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KSTAR Construction and Commissioning

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KSTAR's twelve years project has been officially completed by declaring the first plasma achievement on July 15th, 2008. KSTAR, the first Nb_3Sn-based fully superconducting tokamak device, has come a long path, overcoming many difficult situations. The detailed engineering design and infrastructure setup for R&D have been completed in 2001. In March 2008, after the construction period of seven years, the KSTAR assembly has been completed, by connecting the cryogenic transfer lines between the tokamak and the cryogenic distribution system within six months in the condition of preliminary study. The commissioning on KSTAR has been progressed from April to July, through the following four steps: vacuum, cryogenic cool down, superconducting magnet test, and plasma start-up. KSTAR has successfully passed the vacuum and cool down commissioning at the first trial. As scheduled, the basic environment with the vacuum at 3×10^{-8} mbar and the temperature below 4.5K has maintained without any cold helium leak. Next, all of the superconducting magnets have been conducted using the integrated plasma control system (PCS) for fast current and position control. The first plasma discharge has been initiated under time synchronized operation of the power supplies, the ECH pre-ionization system, the gas-puffing system, and the initial set of diagnostics systems. After about 400 successive test plasma discharges, during which plasma was successfully controlled with a flat-top current of 120 KA, duration of up to 800 ms has been obtained at KSTAR.

All of the commissioning contents, such as objectives, must-check items, target parameters, and commissioning results, will be presented in this paper. Specifically, various histories, such as vacuum, temperature, stress, plasma shot, and machine failure, will be reported.

Keywords: KSTAR, Vacuum Vessel, Nb_3Sn SC Coil, CS Pre-loading, KSTAR Assembly, KSTAR Commissioning, KSTAR First Plasma, ECH pre-ionization, Cool-down, SC transition

1. Introduction

Since the KSTAR (Korea Superconducting Tokamak Advanced Research) project started from the end of 1995 for the development of an advanced superconducting(SC) tokamak to establish a scientific and technological basis for an attractive fusion reactor [1], all related systems have been rigorously developed through early R&D and design phase which was actually terminated in middle of 2002. The R&D and design period provided key technologies and a crucial basis for the actual construction of the machine, which started in early 2002 [2]. The machine construction phase proceeded from 2002 and was finished by August of 2007. During the construction period, various kinds of important construction activity were simultaneously implemented. Among these various areas, the main tokamak system such as i) a vacuum vessel (VV) and cryostat, ii) thermal shields, iii) SC coils and structure, iv) SC interface system including current feeder system, v) machine assembly and system integration was a crucial engineering area of which the quality and schedule could decisively affect the success of the KSTAR construction efforts. All activities related to the systems mentioned above have been successfully carried out by August 2007. As a result, the KSTAR team finally declared the machine construction in September 2007. The integrated commissioning started from March 2008 after 6 months-preparation of final helium distribution box (HDS #2). The integrated commissioning has been successfully progressed without any serious problem and completed in first trial attempt. At last, the KSTAR has been officially completed by declaring the first plasma achievement on July 15th 2008. All commissioning results were verified by a special committee, whose members were nominated by the Minister of Education, Science, and Technology.

Warm-up of the machine started on July 20th was completed by end of August. Warm-up process was

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performed with two steps: forced helium circulation and natural warm-up. Now the machine is in the stage of preventive maintenance and system upgrade for next campaign.

2. History of the Construction

2.1 Vacuum Vessel (VV) and Cryostat

The VV of the KSTAR is one of the most important structures as it provides ultra-high vacuum conditions for the generation and confinement of the tokamak plasma. Therefore, all structures and fabrication techniques for the VV should meet the general requirements as described in detail in the literature [3]. The VV was designed by the end of 2001 to meet the requirements by both the KSTAR staff and by Hyundai Heavy Industries (HHI). The major parameters of the KSTAR VV are illustrated in Table 1.

Table 1. Major parameters of the VV

Parameters	Values
Inner radius of the torus	1.1 m
Outer radius of the torus	2.99 m
Height/width	3.387 m/ 1.880 m
Rib thickness	20 (40) mm
Double wall thickness	50-190 mm
Total weight	72 ton (with support)
Surface area (inner shell)	100 m2 (without port)
Relative permeability	<1.10 (after welding)
Shell thickness	12 mm
Resistance	> 40 μΩ

The cryostat is a single-walled vacuum vessel that provides a vacuum environment for the entire space in which all of the SC magnets and sub-systems are contained. This cryostat structure is mainly composed of large three parts: the base, the cylinder, and the lid. It achieves a target vacuum pressure ($< 1\times10^{-2}$ Pa) to allow the cool-down start of the cold mass. The total weight and height of the cryostat are 180 tons and 8.56 m, respectively. The fabrication of the cryostat started in middle of 2002 by HHI. As the diameter of the cryostat is 8.8 m, as mentioned above, it was impossible for the entire cryostat structure to be transported from the factory to the site. This technical problem was solved through the breakdown of the fabrication of the cryostat system into several sub-units in the factory. These sub-units were finally welded together at the site. Two halves of the cryostat base were completed in the fabrication process at the factory by the end of 2003 and were welded to each other at the site to form the entire base structure by February of 2004. The cryostat cylinder was divided into four quadrants, and the cryostat lid was divided into three pieces of a knuckle and a crown with ports. Both the cylinder and the lid were delivered to the site and were completed through site welding in June of 2004.

2.2 SC Magnet System

As detailed description is explained in the literature [4], the SC magnet system consists of 16 toroidal field coils and 14 PF coils. 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 coil of 7.2 T. The nominal current of the TF coil is 35.2 kA. The PF coil system, which consists of 8 coils in central solenoid (CS) coil system (PF1-4) and 6 outer PF coils (PF5-7), provides 17 Vs and sustains the plasma current of 2 MA for 20 s, inductively. PF1-5 coils use Nb_3Sn CICC in the Incoloy908 conduit and PF6-7 coils use NbTi CICC in a modified stainless steel 316LN conduit. The fabrication procedure of the TF coils is (i)delivery of the CICC in spool, (ii)coil winding using three dimensional continuous scheme, (iii)attachment of joints and helium stubs, (iv)heat treatment in a vacuum furnace, (v) insulation taping on CICC and ground wrap, (vi)impregnation(VPI), and (vii)acceptance test. The joint of TF coil is strand-to-strand joint with solder between Nb_3Sn cable of TF coil and NbTi cable of busline. The last TF coil was finished in the fabrication by January 2006. The PF6 and PF7 coils, which are made of NbTi conductor, have been fabricated at the KSTAR building due to the difficulties in transportation. Fabrication of the 30 superconducting coils was completed by January 2006 with fabrication finish of the PF5U coil.

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 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 8 shows the final machining process and assembly. The 16 TF structures have been finished in fabrication by January 2006. Current feeder system consists of SC buslines with joints, current leads with current lead boxes, and helium lines with electrical isolators. The superconductor of the buslines are made of NbTi strands in circular CICC. The current leads are vapor-cooled type leads, which are made of brass to minimize the helium consumption during zero current. The current lead boxes has been fabricated and installed at the basement pit of the KSTAR tokamak.

2.3 SC Coil Test

A large SC coil test facility has been constructed and the performance test of the full size TF prototype coil, TF00 coil, and a pair of CS model coil were carried out in the test facility [5]. The major objective of the test is to confirm the validity of the design and the fabrication process. The results of the cool-down and current excitation test of the TF00 coil over than 30 kA showed that the TF coil design and fabrication procedure were acceptable. The CS model coil test has been implemented similar procedure of cool-down and current excitation as those of TF00 coil. The peak field measured at coil inner surface was about 8.6 T when charged up to 20 kA.

2.4 Thermal Shields

There are three types of KSTAR thermal shield: a vacuum vessel thermal shield (VVTS), a cryostat thermal shield (CTS), and a port thermal shield (PTS). The main shield panel is fabricated from a 316L plate 3 mm in thickness and a stainless steel pipe with a 7 mm ID. A wall with a thickness of 1.5 mm is welded on the panel. The shield panel has roughly two types of support made of epoxy glass to minimize heat transfer by conduction. As the VVTS is placed in the narrow gap between the TF superconducting magnet and the vacuum vessel, the VVTS panel is coated with silver at a thickness of 10 ㎛ in place of the use of multi-layer insulation (MLI) [6]. The VVTS has a double-pipeline configuration for redundancy. The CTS consists of three parts: the lid TS, the body TS, and the base TS in the cryostat. Each part is toroidally divided into 16 sectors like the VVTS. Its space is such that 30 layers of MLI are used to mitigate the effects of thermal radiation from the cryostat surface to the superconducting coils. There are 72 penetration ports classified into seven types to connect the vacuum vessel body and the cryostat. PTS coated with silver covers these ports. The VVTS fabrication started from the early 2004 and completed by the end of 2004.

2.5 KSTAR Assembly

The KSTAR assembly of which details are described in the lieterature [7] was divided into four stages. The first stage started at the beginning of 2004 and lasted until June of 2004. The first stage assembly included assembly of the cryostat base, gravity support for SC magnets, and main assembly jigs. The second stage started in July 2004 after completion of the main assembly jigs. The second stage included assemblies of major structures such as the VV, VVTS, TF magnets, and VV supports. In March of 2005, the main jig system was partly removed and the VV and VVTS were installed on the tokamak pit. The TF magnets were assembled from April of 2005 to May of 2006. The last sectors of the VVTS and VV, as well as that of the VV supports, were assembled in turn by June of 2006 as the final assembly step of the second stage. The third stage assembly mainly included assembly of all PF and CS coils. After the PF6L, PF7L, PF7U, PF6U coils were installed onto the TF structure in turn, the PF5L coil and the PF5U coil were assembled by October 2006. The CS coils were sub-assembled in the main experimental hall during the assembly period of the PF coils. The CS coil system after the sub-assembly process was finally assembled on the TF magnet system by October of 2006 as shown in Fig. 1. The third stage also covered final installation and system tests for all in-cryostat components of the SC bus line, SC joints, helium piping system, and all of the cryogenic and strain sensors. After most of the in-cryostat components were installed in the third stage, the cryostat cylinder was assembled in early January of 2007, as shown in Fig. 2.

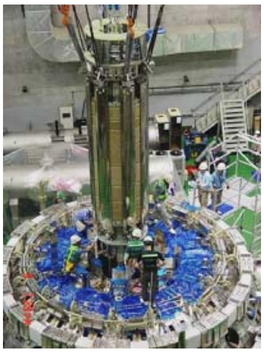


Fig.1 Assembly of the CS

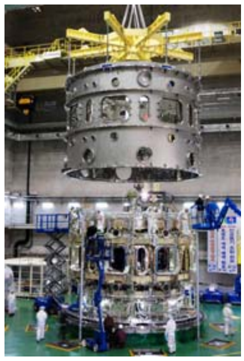


Fig.2 Assembly of the cryostat cylinder

Assembly of the cryostat cylinder provided a condition for the final welding of the VV ports. Subsequent procedures were the assembly of the cryostat lid and the assembly of the vertical ports. Two pumping duct systems for the VV and cryostat were simultaneously assembled during the assembly of the vertical port. As a final step for the assembly, all of the VV ports were blanked for vacuum sealing by the end of April of 2007.

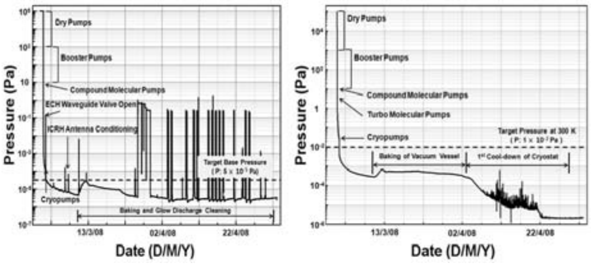
3. Ancillary Systems

In addition to the construction of the main tokamak system, every ancillary system was simultaneously developed and installed to meet the target date of KSTAR first plasma. The 9 kW Helium Refrigeration System (HRS) was finished in system commissioning and final acceptance test by March 2008.

The magnetic diagnostics for the first plasma have been also installed and completed the system test. Other crucial diagnostics such as ECE, single-channel interferometer, visible TV system, H_α monitoring system, and filter-scope were finally ready for first plasma. The ECH system (84 GHz, 500 kW, 2 sec) was also rigorously tested for ECH-assisted pre-ionization using 2nd harmonic [8]. The ICRH system (30~60 MHz, 2 MW, 300 sec) were fully tested with dummy load. However, the ICRH system was utilized ICRH discharge cleaning under TF field within 30 kW owing to the absence of cooling system for the ICRH antenna. The Magnet Power Supply (MPS) was successfully tested with dummy coil at room temperature [9]. As a result, all the system for start of integrated commissioning and first plasma were completed in system installation and self-commissioning before start of integrated commissioning. Figure 12 shows the KSTAR device and all of the ancillary system in the main experimental hall.

4. Vacuum Commissioning

KSTAR has two separate vacuum regions: one is the vacuum vessel for plasma discharge and the other is the cryostat for thermal insulation of superconducting magnets. The main task of the vacuum commissioning is to check the base pressure and leak rate of whole system to guarantee long-term operation. The commissioning was performed with two steps. The first step was taken after the assembly finish in June 2007. In the first trial, the cryostat vacuum was not achieved due to very tiny leak from a bellows in the cooling pipe of the cryostat thermal shields. After repairing the leaked bellows, there were no detectable He leaks on the all of the in-cryostat components. The second step commissioning began in March 2008. Figure 3 shows the vacuum history during the entire commissioning period. As shown in Fig. 3 (a), the primary vacuum reached below 5.0×10^{-5} Pa within 12 hours from evacuation, and the pressure was maintained in the range of 2.5×10^{-6} Pa before baking. While the vacuum vessel is baked up to 100 degree Celsius, the pressure continuously increased to 10^{-5} Pa range. After the baking process, the RF-assisted glow discharge cleaning (GDC) was implemented using hydrogen and helium gas. As shown in Fig. 3 (b), the vacuum pressure of the cryostat also reached 2.5×10^{-4} Pa within one day. In the final leak test in which all the SC magnets and the thermal shield were pressurized to 20 bars, there was no symptom of the helium leak. As the machine was cooled down toward 4.5 K, the secondary vacuum gradually decreased to 2.5×10^{-6} Pa. Especially, the cryostat vacuum drastically decreased at around 40 K. The entire pumping system, including control and interlock unit, were very stably operated through the entire commissioning period.



(a) (b)

Fig. 3 Vacuum history (a) VV, (b) cryostat

5. Cool-down Commissioning

The main tasks in this commissioning step were to check helium cold leak, mechanical stress of cold components, superconducting transition of coils, joint resistances, and operating characteristics of all cryogenic loops. All cold systems were cooled down to their operating temperature within 23 days, without serious trouble disturbing the cool-down process.

5.1 Temperature Control and Helium Cold Leak

The cool-down was carried out by manually controlling the inlet temperature from room temperature to 4.5 K. Figure 4 shows the temperature history of the first cool-down. Temperature was controlled with two limitations not to have excess contraction stress: one was to keep within temperature gradient of 50 K across the coils and structures, and was to restrict temperature difference of 25 K between inlets and outlets. The cryostat pressure decreases smoothly from 2.5×10^{-4} Pa to 2.5×10^{-6} Pa. The helium partial pressure kept around 4.0×10^{-7} Pa until warm-up. To identify whether it had a cold leak, the helium leak rate was measured by changing the pressure of helium gas up to 20 bars. The change of leak rate was not found. This proved that the cryostat did not have a helium cold leak. In any events, the total leak rate was less than 8.9×10^{-9} Pa m^3/s, which was much less than acceptable value of 1.0×10^{-5} Pa m^3/s.

5.2 Mechanical Stress Change

To monitor the structural stress behavior during cool-down, 239 strain gauges were instrumented on the various cold components. They were measured in the range of 15 MPa ~ 93 MPa, which is just within 13 % of the maximum allowable stress. A maximum hoop stress of 93 MPa was observed at the lower outboard leg because there were more constraint structures on the lower part. On the other hand, tensile and compressive stresses were observed in the PF6 and PF7 structures, which were resulted from the relative difference of the thermal contraction between the TF structure and PF coils. Radial displacements of the 4 segmented toroidal ring at 10 K were in the range of 7.66 mm ~ 7.93 mm. Another important issue was to check the preload change of the central solenoid structure. The central solenoid (CS) was mechanically preloaded with 747 tons at room temperature [10]. As shown in Fig. 5, the preload value of CS structure was reduced to 600 tons at 5 K and then back to almost same value after warm-up.

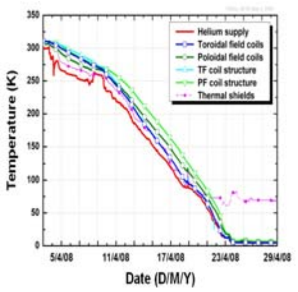


Fig.4 Cool-down history

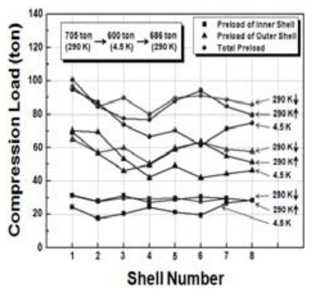


Fig.5 Pre-load change of CS

5.3 SC Transition and Joint Resistance

As the coil temperature went down to 20 K, the transition into superconducting state of the Nb_3Sn coils; 16 TF, and PF1-PF5 coils, was observed by directly measuring the coil voltage drop at a current of 100 A. Subsequently, the superconducting transition of NbTi coils; PF6, 7 coils, was observed as shown in Fig. 6. The transition temperatures of Nb_3Sn and NbTi coils were around 18 K and 9 K, respectively. After the bus-lines were fully cooled, voltage drops were measured at bus-line interval which had 5 or 6 lap joints. The joint resistances were evaluated by linear fitting of the measured I-V curves. Most of the joints have resistances of less than 2 nΩ, which are below the design allowance of 5 nΩ. From this result, it is verified that KSTAR silver-coated lap joints have reliable and uniform performance [5].

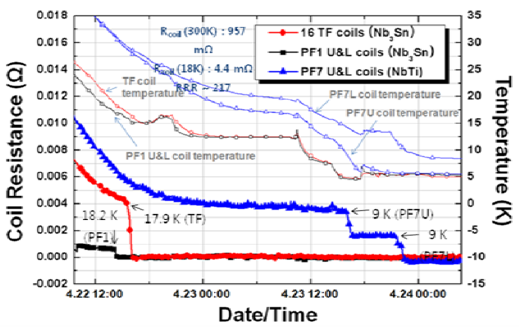


Fig. 6 SC transition of the KSTAR magnets

5.4. Magnet Commissioning

The TF system was tested by increasing the current level in steps. Figure 7 shows operating characteristics of TF magnet. The toroidal magnet was excited to 15 kA corresponding to 1.5 T at R=1.8 m, and has been operated stably with temperature rise less than 0.1 K in current change interval. To investigate the magnetic effect of Incoloy 908, intensive field measurements were also performed [11]. The vertical remnant field measured about 10 Gauss in zero TF current, reduced to 2 Gauss at TF current of 15 kA. The maximum mechanical stress of the TF structure at 15 kA was measured to be about 41 MPa. The quench detection system also operated reliably without any false activation. The maximum detected voltages were less than 25 mV at the instant of current charge started. During the entire commissioning period, no quench was found

Prior to real PF coil test, each power supply was tested with copper dummy coils. The current was controlled by the PCS system which was developed under KSTR-DIII-D cooperation. Control of reference current waveform, fast current change using the blip resistor and mutual inductance effects between adjacent coils were tested with each 7 PF power supply. After the successful performance tests with dummy coils, major tests with the superconducting coils were carried out. After the every single coil test, integrated tests with 7 PF coils were carried out. Seven PF power supplies were operated in a uni-polar condition because there was not a protection circuit. The typical PF current waveform had a 3s ramp-up and a 4s flat-top time before the blip of 100 ms duration. As shown in Fig. 8, blip tests were performed up to changing rate of 17.1kA/s for PF6 and up to 98.9 kA/s for PF3, respectively.

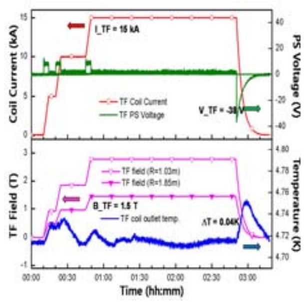


Fig. 7 Operating features of TF magnet

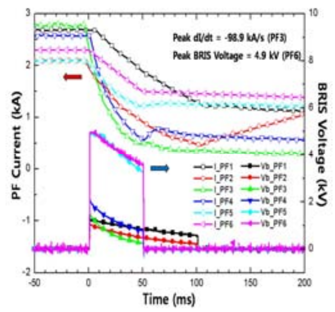


Fig. 8 Blip test results of PF magnets

6. First Plasma Experiments

6.1 Key Features in Start-up

Experiments on the initial field null configurations were performed with two different types of IM scenarios. Usual "conventional mode" scenario to have maximum field null size to get stable initial breakdown was tried. Flux contributions of this mode come mainly from the central solenoids PF1~4 and weakly from PF6~7. The expected loop voltage was ~4.5 V without plasma with flux of 0.89 Wb. The "dipole mode" scenario was developed to get higher loop voltage and poloidal magnetic flux for higher plasma performance. This was achieved by charging-up of the PF6 and PF7, and it increased the available magnetic flux significantly. The loop voltage was 5.1 V with flux of 0.95 Wb. To compensate for the low loop voltage, an 84 GHz ECH system with 500 kW power was utilized as the second harmonic ECH assisted pre-ionization. Pre-ionization by the ECH system was highly reliable. With ECH heating during the current ramp-up, the discharges were less sensitive to wall conditioning. To control the wall reflux during the plasma shots, ICRH-assisted discharge cleaning was implemented during shot-to-shot interval under the TF field.

6.2 Experimental Results

After several tens of breakdown shots, the first plasma was achieved on June 13th (shot 794). Figure 9 shows a plasma image of the shot 794. In this experiment, ECH was very critical system in initiating the discharge. Without the ECH power, plasma could not be discharged. With TF current of 15kA, ECH resonance layer was formed at R=1.8 m [12]. Under the IM conditions of the conventional scenario, the blip resistors were inserted for 100ms. The ECH power was on 30 ms before the applying toroidal loop voltage and lasted for 200 ms with 350 kW power. For this, the force balance with the current ramping was adjusted in feed forward manner. With the dipole mode IM scenario, more initial magnetization and higher plasma current could be obtained. In this mode, plasma current and position could be controlled to get longer plasma durations. As a result, we could achieve maximum plasma current was 133 kA and longest plasma length was 862 ms [13].

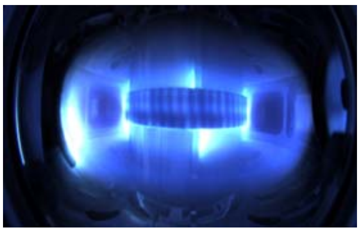


Fig.9 Image of ohmic discharge plasma

7. Conclusion

After about 400 successive test plasma discharges, successfully controlled plasma with flat-top current of 100 kA, duration up to 862ms was achieved at KSTAR. It was verified that the construction and the test results of the past twelve years were very successful through this commissioning. Looking at all of the commissioning results, it is certain that the success and lessons of KSTAR will greatly help with the upcoming construction of the superconducting tokamak. Especially, the engineering and commissioning progress of KSTAR will certainly benefit and contribute considerably to the construction of ITER. The KSTAR now plans to upgrade its power supply, plasma facing components, and heating devices as quickly and feasibly as possible, so that the overall performance of the machine can be greatly improved. The full performance experiments for advanced tokamak physics with a 300 sec long pulse will be exploited within 2012.

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