# KSTAR Assembly and Vacuum Commissioning for the 1st Plasma

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**Abstract.** The Korea Superconducting Tokamak Advanced Research (KSTAR) device site assembly was completed by May 2007. During the assembly period, several key technologies were developed to assemble the superconducting tokamak and its ancillary systems. As will be described in this paper, we encountered several problems and difficulties that mainly stemmed from the uniqueness of the superconducting tokamak, but all the problems were successfully solved and the assembly was satisfactorily completed on schedule. The vacuum commissioning was the first step of the integrated machine commissioning. Since the commissioning was strongly related to verifying the feasibilities of the KSTAR assembly strategies, the commissioning result was an important indication for quality assessment in the assembly. The commissioning results verified that the KSTAR assembly was successfully performed, and provided an essential condition to start the machine cool-down. In addition to the basic vacuum test, the vacuum commissioning included wall conditioning and a gas fueling test for the 1st plasma. As a result, the wall conditioning and the fueling system adequately supported the 1st plasma campaign.

## 1. Introduction

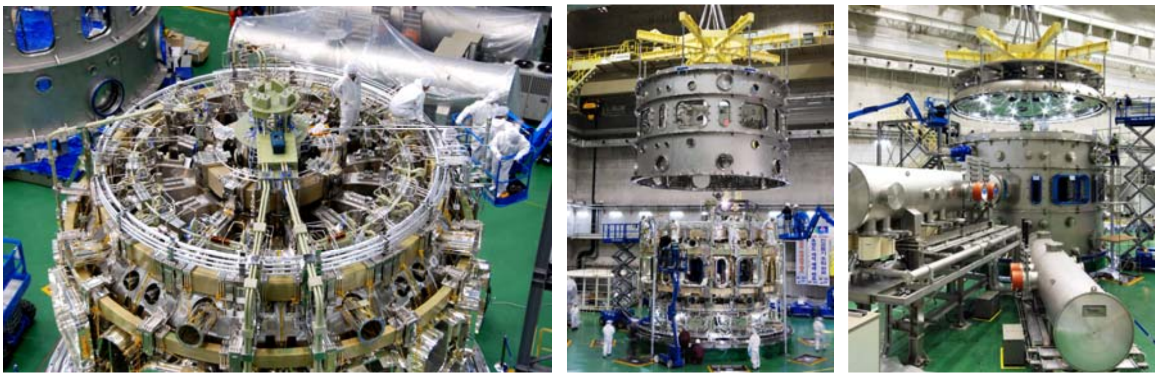
Since the Korea Superconducting Tokamak Advanced Research (KSTAR) project was kicked off from the end of 1995 to develop an advanced superconducting tokamak for the establishment of the scientific and technological bases for an attractive fusion reactor [1], the KSTAR team at last achieved the 1st plasma [2] on June 13th, 2008 after more than twelve-years of strenuous efforts. Among the many engineering aspects [3] for the KSTAR project leading to its success, the KSTAR assembly also decisively contributed to the success owing to its wide and complex work scope. Successful completion of the KSTAR assembly provided a fundamental environment for the integrated machine commissioning and the 1st plasma which acted as a final qualifying process for the KSTAR assembly strategies. There were several key features and unique assembly concepts first adopted in the KSTAR assembly, which have been finally analyzed through the integrated commissioning phase. The integrated commissioning started with the vacuum commissioning, for which the main mission was achievement of low vacuum pressure and a check of the vacuum tightness for the cool down start and the 1st plasma campaign. The final vacuum commissioning result shows that the target criteria were successfully achieved in both the vacuum vessel (VV) and the cryostat.

The vacuum commissioning also included the VV wall conditioning and fueling experiments. The wall conditioning process continued from the vacuum commissioning stage to the 1st plasma experiments. The gas fueling system was fully commissioned before the start of the 1st plasma experiment. As a result, the fueling system provided a crucial tool for the successful 1st plasma experiment. In this paper, an overview of the KSTAR assembly including its history, key features, and the difficulties met in the machine assembly stage will be introduced. This paper also includes a summarized report on the comparison between the several designed assembly strategies and the results we achieved through the integrated commissioning stage. Moreover, the general configuration and operational results of the wall conditioning and the gas fueling system will be finally introduced in this paper.

## 2. KSTAR Assembly

### 2.1 Procedure and History

As described in the detailed procedure in Ref. [4], the KSTAR assembly was implemented in four stages. The first stage that began from the start of 2004 to June 2004 included assembly of the lower parts such as the cryostat support, the cryostat base, and the gravity supports for all superconducting (SC) magnets. During this period, the main assembly tool system that is described also in Ref. [4] was also constructed. The second stage started in July 2004 after completion of the main assembly tools system. This stage covered assemblies of the most important major structures such as that of VV, VV thermal shield (VVTS), toroidal field (TF) magnets, and VV supports. After the TF magnet system was assembled and finally aligned, the last sectors of the VVTS and VV, and the eight-leaf spring type VV supports were assembled in turn by June 2006 as a final assembly step of the second stage. The third stage mainly comprised assemblies for all poloidal field (PF) and central solenoid (CS) coils. The PF6L, the PF7L, the PF7U, the PF5L, the CS coils, and the PF5U coils were installed in turn on the TF structure by October 2006. The third stage covered the final installation and system tests for all in-cryostat components such as the SC bus lines, various kinds of joints, the liquid helium supply and return piping system, and all the sensors. Figure 1 (a) shows all of the assembled PF coils with most of the in-cryostat components. The fourth stage started in early 2007 with final assembly of the cryostat cylinder and its thermal shield surrounding all of the in-cryostat components as shown in Fig. 1 (b). Installation of the cryostat cylinder provided the conditions for final welding of the median, slanted, and B&C ports of the VV. Subsequent procedures were the assembly of the cryostat lid and its thermal shield as shown in Fig 1 (c), which was followed by the assembly of the top vertical ports of the VV. Two pumping duct systems for the VV and cryostat were simultaneously assembled during the vertical port assembly. As a final step for the machine assembly, all of the VV ports were blanked for vacuum sealing by the end of April 2007.



*(a) (b) (c)*

*FIG. 1 KSTAR Assemblies in 2007 (a) Final Inspection for the PF coils and In-cryostat components (b) assembly of the cryostat cylinder (c) assembly of the cryostat lid*

## 2.2 Key Features and Results

### 2.2.1 Radial & Vertical Offset in the SC Coil Assembly at Room Temperature

Because all of the SC coils should be assembled at room temperature and would thermally contract at cryogenic temperature, it was very important for the thermal contraction of the SC coils to be accurately estimated. Comparisons of analysis and calculations of the thermal contraction showed that the TF structure would thermally contract by 8.2 mm in the radial direction at the outermost boundary of the gravity support (7.5 mm at the center of the support), and by 5 mm at the average vertical position at the equatorial mid-plane of the machine in the vertical direction. Therefore, the SC coils were assembled with additional displacements of 7.5 mm outward and 5 mm upward, respectively, from the original designed position to compensate for the contraction. Table 1 and Fig. 2 show the radial contraction at the outermost edge of the gravity support for both the analysis and the measured values. The maximum deviation between analysis and measurement was 0.54 mm, which indicates that the calculation was correctly performed and the assembly concept chose a reasonable strategy.

| TR No. | Radial displacements (mm), @ 11K | | | |
|---|---|---|---|---|
| | Sensor Indication (Reset at 311 K) | Contraction from 293 K | FEM analysis | Deviation |
| TR 01 | -8.59 | -7.93 | -8.2 | -0.27 |
| TR 02 | -8.26 | -7.67 | -8.2 | -0.53 |
| TR 03 | -8.33 | -7.66 | -8.2 | -0.54 |
| TR 04 | -8.26 | -7.71 | -8.2 | -0.49 |

TABLE 1: RADIAL DISPLACEMENT OF THE TF

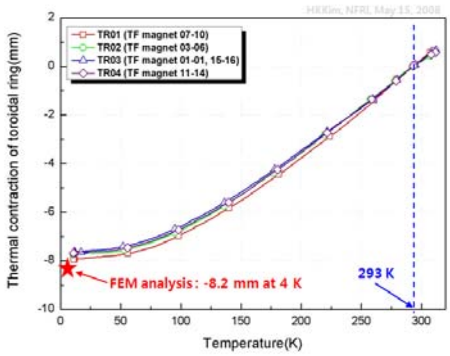



*FIG. 2 Radial displacement of the TF structure during cool- down*

### 2.2.2 Assembly Concept of the TF Magnets

A unique feature in the KSTAR assembly was assembly of the TF magnets [5]. The 337.5$^{o}$ sector of the VV and the VVTS were completed through site welding. After final installation of the VV and VVTS, each of the sixteen TF magnets passed through the 22.5$^{o}$ gap of the VV. Each of the sixteen TF magnets was rotated around the VV to the final position with help of a special tool system to accurately control the TF magnet positions owing to the narrow clearance between VVTS and TF magnets. This concept has several advantages as follows:

(i) Individual handling and alignment of the TF magnets minimized the assembly tolerance in spite of the welding distortion of the VV in the site welding
(ii) Minimized the site welding point and uncontrollable welding distortion of the VV
(iii) Localized the non-destructive test (NDT) and vacuum leak test point to VV sector 3

The assembly concept of the TF magnets was satisfactory, and the assembly tolerance for the TF met the tight requirement (allowable assembly tolerance: less than ±1mm) [6]. As the tolerance was measured at room temperature for the geometrical axis, the actual error field in the presence of the TF field should be measured to finally identify the feasibility of the assembly tolerance. The geometrical displacement measurement of each TF magnet after cool down showed that the relative displacement of the TF system was negligible, but a quantitative analysis of the error field was not implemented in the 1$^{st}$ plasma experiment. The error field analysis will be carried out in the next campaign in 2009 with various methods including electron beam trajectory measurements [7].

### 2.2.3 Vacuum Leak Test of the VV in the Site Welding

After the VV is surrounded by the VVTS and TF magnets, it is almost impossible for the VV to be repaired in the event of a vacuum leak at the site-welding seams. Therefore, the most critical path in the assembly was to verify that the vacuum tightness of the VV was achieved. The sectors 1 (180° sector) and 2 (157.5° sector) were individually tested for vacuum leaks at the factory utilizing the double-walled configuration of the VV [8]. This method was similarly adopted after site welding of the VV to form the 337.5° sector. Figure 3 shows the 337.5° sector under helium leak test. However, this method could not be applied for the site welding of the VV sector 3 (22.5° sector). If any defect exists in the outer wall of the sector 3, there is no chance to repair it due to the existence of the VVTS and the TF magnets. This required that every welding point on the outer wall should be tested before the start of welding of the inner wall. Small chambers attached along the welding seam by rubber sealant provided localized vacuum condition as shown in Fig. 4. All the welding seams of the VV sector 3 outer wall were successfully tested for vacuum leaks with various combinations of small chambers and by spraying helium from the outside of the outer wall.

*FIG. 3 VV 337.5° sector under leak test*

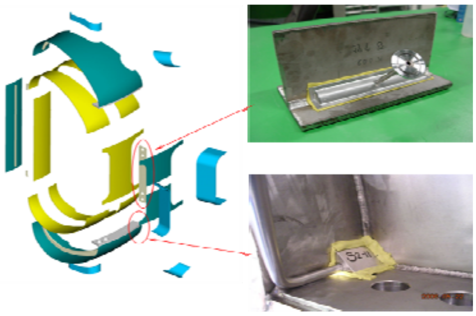


*FIG.4 Vacuum chambers for leak test on the sector 3*

2.2.4 Assembly of the Port Modules

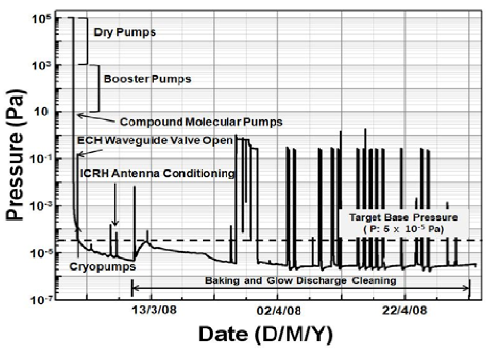
Each of the 72 ports of the VV was assembled onto the VV as a module of port and bellows assembly through a tunnel in the pre-installed port thermal shields. The most important aspect for this assembly concept was that both of the port stubs on the VV and on the cryostat should coincide with each other. The VV and the cryostat were carefully monitored in the fabrication and assembly tolerances for this purpose, and the port modules had 10 mm of additional margin in length for the case of an excessive distance between the two port stubs exceeding the designed port length. The port modules were finally fabricated on site to accurately fit the port to the stubs. Nevertheless, some ports inevitably lost a wall thickness of as much as 3 mm from the initial 12 mm in the welding of the port to the stubs due to excessive lateral displacement that could not be accommodated by site fabrication.

2.2.5 Pre-loading in the Sub-assembly of the CS Coil and Structure

Because the CS coils must be sustained by compressive force and friction between each coil, applying a pre-load during the room temperature assembly was one of the most important issues. The principle of pre-loading is to use the differential thermal expansion between the coil stack and the structure. The issue was partly solved by applying a pre-load of up to 749 tons to the CS stack with thermal expansion of the CS structure by heating the structure, which was followed in turn by adjustment of the spacers and cooling the structure back down to room temperature. The target value of the pre-loading (1,300 tons) was not achieved because of excessive heating of the coil due to the heat radiated from the adjacent structure. More than additional 100 tons of pre-loading was expected after cool down to cryogenic temperature due to the different thermal contraction between the coil stack and the structure. However, the strain measurement result after cool down was in the reverse direction to the expectation. More thermal contraction in the coil stack than that in the structure resulted in a relaxation of the pre-load from 749 tons to 700 tons, which is 54% of the required value. This result seems to stem from an under-estimation of the thermal expansion coefficient of the coil stacks, and from the uncertain properties of the non-metallic materials including the G-10 rings between the adjacent coils [9]. The main concern is whether the coil stacks remain in a vertical compressive state from the insufficient pre-loading. Several analysis reports showed that the coil interface still locally preserves the compression state under the worst case scenario, which means that the CS coils are safe in the operation phase. However, further careful investigations should be made to assure the machine safety in the operation phase.

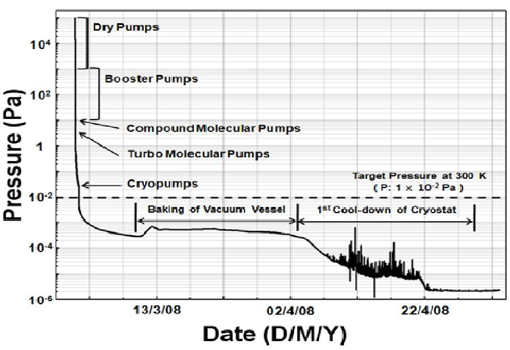
### 3. Vacuum Commissioning

As the final step for the quality verification of the KSTAR assembly and the first step for the integrated machine commissioning, the first vacuum commissioning started in June 2007 after the assembly finish. The main mission of the commissioning was to achieve the target base pressure in both the VV (< $5\times10^{-5}$ Pa) and the cryostat (< $1\times10^{-2}$ Pa), respectively, for the 1st plasma campaign and the start of the cool down. The other important task was to check the leak rate of the whole system, and to repair any leak point in case of a tiny leak being found. The base pressure in the vacuum vessel reached $5\times10^{-6}$ Pa in the first trial, and no detectable leak was found when the sensitivity of the He leak detector was maintained at $5\times10^{-11}$ Pa·m$^3$/sec. The vacuum pressure in the cryostat also reached $5\times10^{-3}$ Pa in the first attempt. However, the He partial pressure continuously increased when the thermal shield was pressurized to 25 bars. This was clear evidence of tiny leak in the cryostat thermal shield. It took almost three months to pinpoint the leak point, and the leak point was found in a small bellows for the cryostat thermal shield. After the bellows was removed and replaced, there was no symptom of He leakage for all components contained in the cryostat. The second vacuum commissioning started from March 2008. Figure 5 shows the vacuum history during the whole commissioning period. As shown in Fig. 5 (a), the base pressure of the VV reached below $5.0\times10^{-5}$ Pa within 12 hours from the start of the evacuation, and the pressure was maintained in the range of $2.5\times10^{-6}$ Pa before baking. While the VV was baked up to 100 degree Celsius, the pressure continuously increased up to the $10^{-5}$ Pa range. After the baking process, RF-assisted glow discharge cleaning (GDC) was carried out using hydrogen and helium gas for 24 hours and 72 hours, respectively [10]. As shown in Fig. 5 (b), the vacuum pressure of cryostat also reached $2.5\times10^{-4}$ Pa stably within one day.




*(a)*

*FIG. 5 (a) Vacuum history of the vacuum vessel*




*(b)*

*FIG. 5 (b) Vacuum history of the cryostat*

For the final confirmation of vacuum tightness at room temperature, all cryogenic circuits including superconducting magnets were pressurized to 20 bars with helium gas. In this final leak test, there was no evidence or symptom of a helium leak. As the machine was cooled down toward 4.5 K, the cryostat vacuum gradually decreased to $2.5\times10^{-6}$ Pa. Especially, the cryostat vacuum drastically decreased at around 40 K. Many peaks on the curve of Fig. 1(b) were caused by the bursts of trapped air from bus-line insulation parts, which were cured by a gas-bag impregnation method. These peaks gradually disappeared below 15 K.

In addition to the GDC, ion cyclotron resonant heating (ICRH) discharge cleaning was routinely performed between shots at a TF field of 1.5 Tesla in the 1$^{st}$ plasma experiments. Figure 6 shows the He plasma generated by the ICRH system. The ICRH discharge cleaning was operated between plasma shots for 5~10 minutes with less than 30 kW RF power. The working gases were hydrogen and helium, and typical gas pressures were $2.5\times10^{-5}$ ~ $2.2\times10^{-4}$ mbar. However, the impurity removal rate showed that the ICRH discharge cleaning was not effective by comparison to the GDC [11]. The ICRH discharge cleaning should be further investigated in the next campaign with increased RF power after active water cooling for the antenna is prepared. The gas fueling system consisted of two gas dosing valves for the discharge cleaning and one Piezo valve for the fast gas puffing with a 1 msec. time response. The Piezo valve was controlled by the plasma control system (PCS) for feed-forward or for feedback density control in the 1$^{st}$ plasma experiments. Figure 7 shows a typical sequence of gas fueling in the first plasma experiments. The primary gas puffing was applied for pre-filling to the middle of the $10^{-3}$ Pa range, which was followed by additional secondary gas puffing at the moment of the PF blip. Although there were several minor troubles in controlling the gas puffing system, both the hardware and the control system for the fueling system operated well and adequately supported all experiments in the 1$^{st}$ plasma campaign.

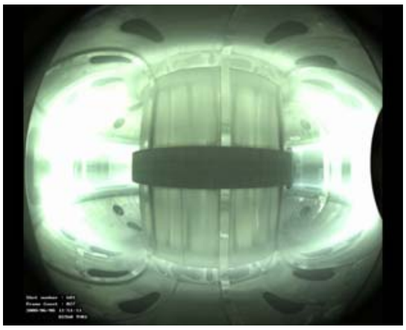


*FIG.6 View of the ICRH discharge cleaning*

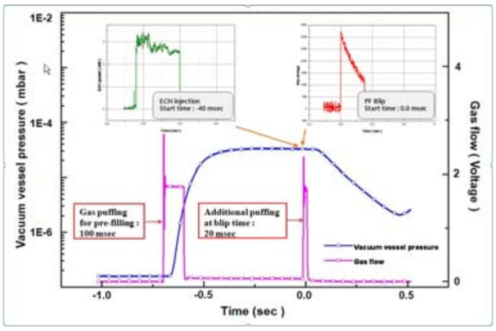



*FIG. 7 Gas puffing sequence in 1$^{st}$ plasma campaign*

## 4. Conclusions

The KSTAR assembly has been successfully completed in quality and schedule in spite of its technical difficulties. The assembly was finally verified in the quality and in the newly adopted strategies through integrated machine commissioning and the 1$^{st}$ plasma campaign.

The results proved that all the assembly work performed well. The technologies and experiences achieved through the assembly period are expected to provide a few fundamental guidelines for superconducting tokamak construction. The vacuum commissioning result was also very satisfactory, and verified that all the engineering aspects in the KSTAR construction were quite adequate for the designed requirements. Nevertheless, we also found several unexpected results in the assembly that should be further investigated for machine safety. These will be updated, modified, and partly repaired in the operation stage to achieve machine safety and to accumulate the key technologies for superconducting tokamak construction in the future.

**Acknowledgement**

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