Current Status and Facility Operation for the 3rd KSTAR Campaign

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Abstract. KSTAR began high magnetic field (Toroidal Field: 3.5T) plasma operations with longer time and more reliable performance, which required implementation of a safe and stable KSTAR operation including superconducting magnets. Reliable tokamak operation was conducted to achieve the goal for the 2010 KSTAR campaign to produce a D-shaped plasma with the targeted current of 500 kA maintained for 5 seconds in duration. The cryoplant is one of the most important systems among KSTAR's utilities because it supplies liquid helium to the superconducting magnet, which requires continuous operational capabilities to maintain a cool-down of the system. The final goal of operating the KSTAR Integrated Control System (KICS) is to perform the roles of tokamak operation and plasma experiments with sustained stability, higher availability and security. Systematic and integrated KSTAR operational procedure is also required in order to unify various individual systems.

1. Introduction

The 3rd campaign operation of the Korea superconducting tokamak advanced research (KSTAR) device in 2010 has been successfully performed. KSTAR is a fully superconducting magnet device operated as a steady-state capable advanced tokamak. One of the important missions of the 3rd campaign is to achieve a plasma current of 500 kA with 5 seconds in duration and to produce a D-shaped plasma. In-vessel control coils (IVCC) have been installed for plasma position control and in-vessel cryopumps for divertor pumping. For conditioning of the in-vessel vacuum environment, the 2010 KSTAR campaign included plasma facing components (PFC) baking operation with a maximum temperature of 225℃ to improve the wall condition of the vacuum vessel. A hot nitrogen gas baking system was additionally employed to bake the PFCs passive stabilizer. The vacuum conditions required for the vacuum vessel and the cryostat were achieved successfully even though the vacuum area was much increased from last year. The toroidal field (TF) magnet has achieved continuous operation of 2 hours with 35 kA, which is a record for the longest time and the highest current among existing tokamaks. The rise in temperature during high current TF magnet testing was only 1.5 K, however when the PF magnet current changed with 10 kA/s, the temperature increase reached 8.2 K mainly due to AC losses. Control systems were upgraded and added in order to provide a reliable control environment, and to contribute to achieving the goal of reliable performance plasma and supporting international collaboration work.

2. Tokamak Operation for Reliable Performance Plasma

2.1 Vacuum Operation

The vacuum conditions required for the vacuum vessel and the cryostat were achieved before starting the cool-down. The target pressures of the vacuum vessel and the cryostat at room temperature are 5×10^{-7} and 1×10^{-4} mbar, respectively. The main pumping system for the vacuum vessel and cryostat is composed of turbo molecular pumps (TMP) and two cryopumps [1]. Before the plasma experiment, the pressure of the vacuum vessel and the cryostat respectively reached about 6.0×10^{-8} mbar and 5.1×10^{-8}. Figure 1 shows the pumping down curve of the vacuum vessel and cryostat.

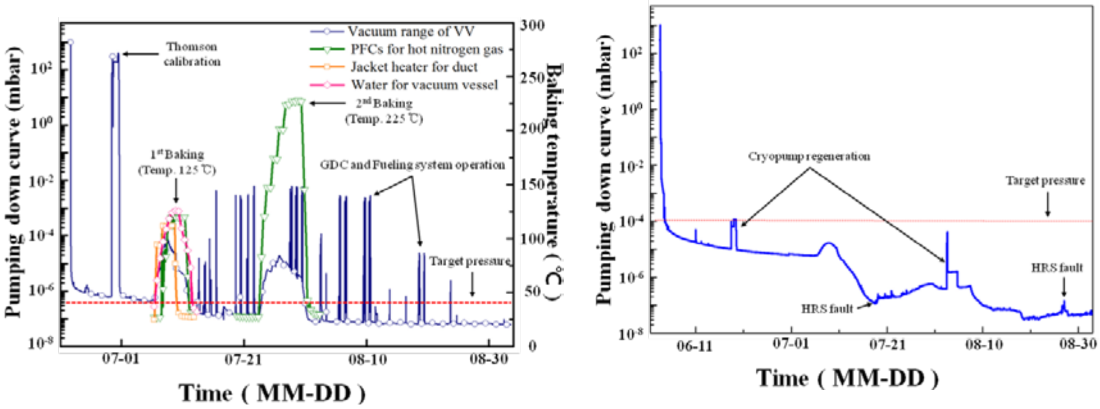


FIG. 1. Pumping down curves of the vacuum vessel & the cryostat in the 3rd KSTAR campaign.

The vacuum vessel consists of a stainless steel vessel with the inner volume of 100 m^3 and the surface area of 80 m^2, and a pumping duct with the inner volume of 14 m^3 and the surface area of 38 m^2, respectively. The surface area of PFCs increased from 1.54 m^2 (KSTAR 1st

(a) KSTAR 1st campaign (2008) (b) KSTAR 2nd campaign (2009) (c) KSTAR 3rd campaign (2010)
FIG. 2. Step-by-step installation of Plasma Facing Components from 2008 to 2010

campaign) to 54 m^2 (KSTAR 3rd campaign) as shown in FIG. 2. The Cryostat has 38,000 m^2 of total surface area including that of the multi-layer insulation (MLI) for the cryostat thermal shields, a volume of 480 m^3, 5,000 welding points, 72 welded bellows, and helium lines of almost 2 km in length. In the 3rd KSTAR campaign, the baking for the vacuum vessel was performed twice: During the first baking operation, three baking systems - a water baking system, a jacket heater baking system, and a hot nitrogen baking system - were operated simultaneously to clean all the surfaces of the vacuum vessel, the PFCs, and the pumping duct.

The maximum temperature of the baking is about 120 ~ 130 ℃ for 24 ~ 36 hours, respectively. For the second baking operation, only PFCs were baked at a temperature of about 225 ℃ for 65 hours. In order to measure the out gassing rate as a function of baking temperature, no GDC was performed until the temperature reached the target temperature (225 ℃). D_2 and He GDCs were performed sequentially at the target temperature. The most dominant gas species in the vacuum vessel were mass 18, 44 and 28 before baking, after the 1st baking, and after the 2nd baking, respectively. The mass 18 (H_2O) decreased from 1.91×10^{-3} mbar·ℓ·s^{-1} to 1.25×10^{-5} mbar·ℓ·s^{-1} after the baking operation. However, the mass 2 (Hydrogen) increased from 6.17×10^{-5} mbar·ℓ·s^{-1} to 1.33×10^{-4} mbar·ℓ·s^{-1} due to the increasing number of hydrogen particles detached from the surface of PFCs by the hot nitrogen baking (maximum temperature at 225 ℃). The mass 18, 28, 44 were sufficiently removed in the process of vessel baking. Table 1 shows the out gassing rates through three campaigns from 2008 to 2010. The out gassing rate at the 3rd KSTAR campaign was more than four times larger than the 1st KSTAR campaign due to the increasing surface area of PFCs. However, the out gassing rates per unit area decreased in the 3rd campaign. This means that the baking system prepared for the 3rd campaign proved to be effective in removing impurities.

Campaign	PFC surface (unit :㎡)	Out gassing rate (unit : m·bar·ℓ·s^{-1})	Per unit area (unit : m·bar·ℓ·s^{-1}m^{-2})	Baking system
1st (2008)	1.54	1.43 ×10^{-4} (M28 dominated)	9.31× 10^{-5}	• Water baking operation (100 ℃)
2nd (2009)	11	1.93 ×10^{-4} (M02 dominated)	1.75 ×10^{-5}	• Water baking operation (130 ℃) • Jacket heater baking operation (120 ℃)
3rd (2010)	54	6.49 ×10^{-4} (M28 dominated)	1.20 ×10^{-5}	• Water baking operation (130 ℃) • Jacket heater baking operation (120 ℃) • Hot nitrogen gas baking operation (225℃)

Table 1: Out gassing rates measured at each of the KSTAR campaign from 2008 to 2010

2.2. Cool-down Operation

To keep the superconducting (SC) magnet coils of KSTAR at proper operating conditions, not only the coils but also the other cold components, such as thermal shields (TS), magnet structures, SC bus-lines (BL), and current leads (CL) [2] must be maintained at their respective cryogenic temperatures. A helium refrigeration system (HRS) with an energetic equivalent cooling power of 9 kWh at 4.5 K without liquid nitrogen (LN_2) pre-cooling has been manufactured and installed for this purpose. Minor modification of a maintenance process and a Distributed Control System (DCS) of the TS circuit were conducted in the 3rd KSTAR campaign in order to develop the optimal operation scenario of the KSTAR magnet cooling scheme. During the maintenance period of KSTAR, some of the cooling circuits of KSTAR had been modified and might have been contaminated. To remove the air and moisture impurities in the cooling circuit, a careful conditioning job was performed. The impurity level in the helium circuits at KSTAR decreased to below 1 ppm after the conditioning job. Table 2 shows the results of the conditioning job. The cool-down of KSTAR was started on the 8th of July after the conditioning job was completed. When the HRS and KSTAR were connected, the cooling circuit of KSTAR and the HRS were cleaned again using the external purifier and the WCS during the early stage of cool-down. When the KSTAR temperature reached 200 K, the oil pump on the WCS failed and thus cool-down was stopped. After the oil pump was repaired, cool-down continued from the 7th of August at the 270 K of KSTAR magnet temperature. KSTAR was cooled-down to 4.5 K in 18 days after the restart of the HRS. On the 19th day of the cool-down period, HRS stopped again due to an electrical power outage because of a lightning strike to the electrical wire. HRS was resumed after 48 hrs and has continued uninterrupted. The PF 7 magnet of KSTAR increased to 32 K during the disconnection of the helium supply. The cool-down result of 2010 KSTAR campaign is shown in figure 3. The temperature peaks and the helium flow decline on the 20th and 21st day of cool-down were the influences of the electrical power outage. Figure 4 shows comparison of cool-down at KSTAR from 2008 to

Items	Pumping/Filling	Dewpoint	Criteria
TF Structure	7 times	-74.9 ℃	< -65 ℃
Thermal Shield	15 times	-75.0 ℃	
Current Lead	10 times	-75.1 ℃	
TF Coil	7 times	-74.3 ℃	
PF Coil	7 times	-74.5 ℃	
PF Bus Line	7 times	-71.6 ℃	
TF Bus Line	7 times	-71.0 ℃	

Table 2. Result of the KSTAR cooing circuit conditioning

2010. The 1st campaign of KSTAR in 2008, took 23 days to cool-down KSTAR and during the 2nd KSTAR campaign, 33 days were needed for KSTAR to cool-down because of the 3rd turbine failure at the HRS. When the 3rd turbine failed in 2009, the temperature of the thermal shield (TS) increased to ~ 300 K and that of the KSTAR SC magnets increased to 65 K. The last step of the cool-down is to start-up the supercritical helium (SHe) circulators. The SHe circulators are installed on each TF and PF helium circuit which circulates more than 300 g/s of supercritical helium.

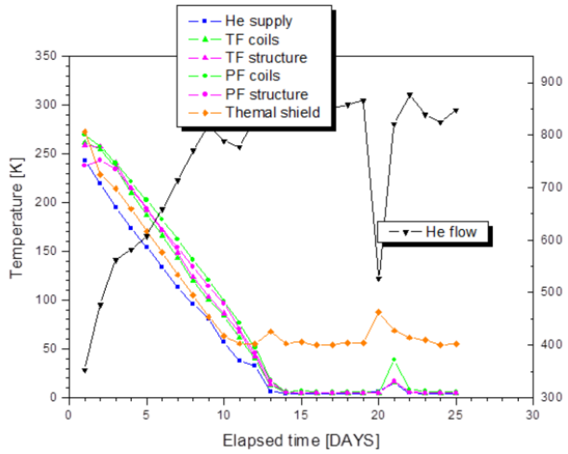


FIG. 3. The result of the KSTAR cool-down in 2010

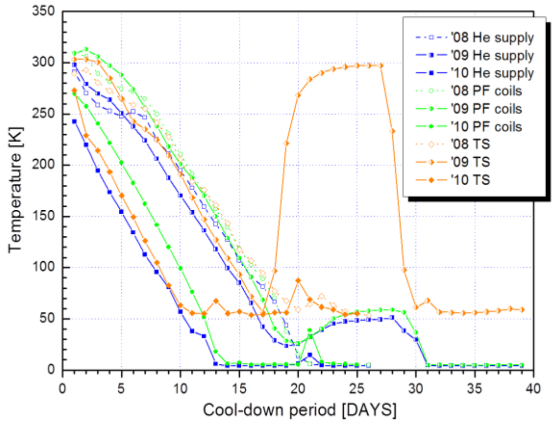


FIG. 4. Comparison of the cool-down results from 2008 to 2010

2.3 Magnet Commissioning and Tokamak Monitoring

The Tokamak Monitoring System (TMS) for the monitoring of the temperature and mechanical deformation of the superconducting magnet system [3] and the Quench Detection System (QDS) for the detection of quench events were carefully inspected before operation. The radial displacement depicted in FIG. 5 showed the shrinkage of the TF supporter with about 8 mm inward the radial direction has been almost the same during the last three cool-down operations of the KSTAR. After checking the superconducting to normal transition of all coils and bus lines during the cool-down, the joint resistances were assessed by measuring the voltage across each bus having several joints while supplying 0 ~ 1 kA to the coils. The results satisfied the design requirement that the resistance of a lap joint should be less than 5 nΩ. The Quench Detection System (QDS) [4] used the voltage-based detection as the primary method. The helium properties such as temperature, mass flow rate, and pressure can be used for secondary quench detection. Before applying large current, the QDS were adjusted to make inductive voltages almost zero and to respond only to quenches. Afterward, the TF magnet was

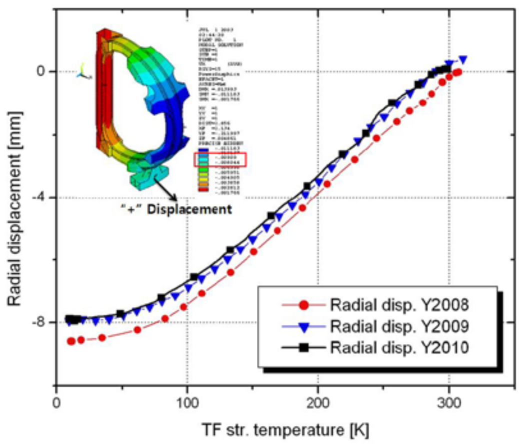


FIG. 5. Radial displacement of the TF supporter (Toroidal Ring).

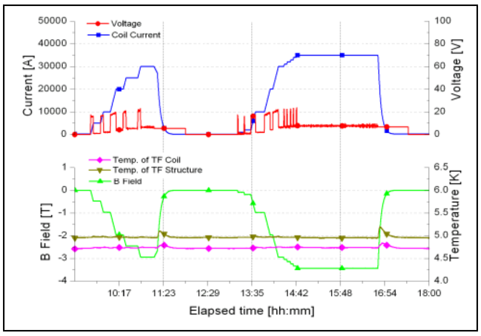


FIG. 6. TF current excitation ; The magnetic field at the center of the vessel & the variation of the coil temperature.

charged up to 35 kA, which was the target current of this campaign. It produced 3.5 T at the center of the vacuum vessel. As shown in FIG. 6, coil temperatures were maintained stably and the magnetic fields measured at the vessel were the same as the designed ones. From experimental results so far, the TF coils, under a large current, operated continuously for a long period with the temperature margin at more than 4 K. The measured maximum mechanical strain of the TF structure during charged up to 35kA was about 760 με and its equivalent stress was 152 MPa, which is lower than the operational criteria of 500 MPa that is two third of the yield strength of stainless steel, 750 MPa. The strain of the TF structure with respect to TF operating currents had the same characteristics for the last three campaigns as shown in FIG. 7. It was clear that the TF structure had sufficient margin at its rated operation. This steady-state monitoring of the structural behavior can be used as a barometer for inspecting the integrity of the magnet structure. For the 3rd KSTAR operation, the maximum current supplied to the PF coils was limited to 10 kA, which is still less than the designed current. Each PF coil was individually tested with various current waveforms before the coupled operation of all the PF coils. Figure 8, shows that the temperature increase was approximately 1.5 K when the PF 1 coil was charged up to 10 kA with ramp-up & down rates of 1 kA/s. However, in the operation shown in FIG. 9, the temperature rose up to 13.3K from 4.6 K when the current changing rate was 10 kA/s in the zero crossing and the ramp-down periods. AC losses due to di/dt undoubtedly caused the conductor temperature to rise. However, temperature rise should be limited so that the conductor can be in a superconducting state. During the individual test, the temperature rise,

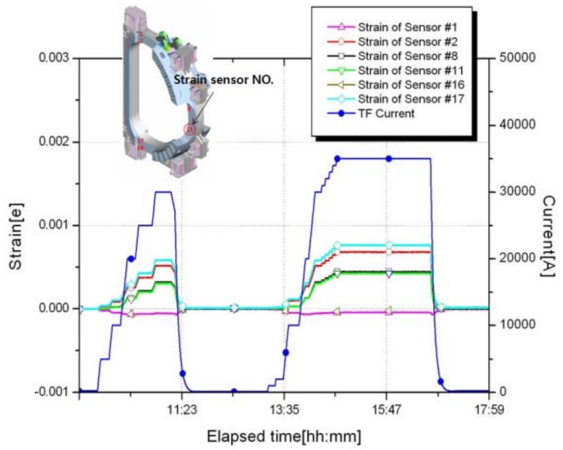


FIG. 7. Strain measurement for the TF coil charge (Active-dummy strain gage were installed on the TF case)

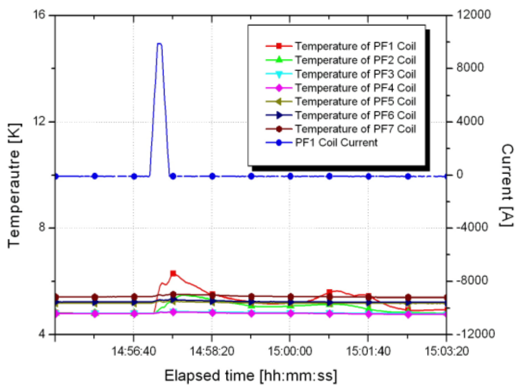


FIG. 8. 10 kA current charging to PF 1 coil and its related temperature increase (Shot # 2503).

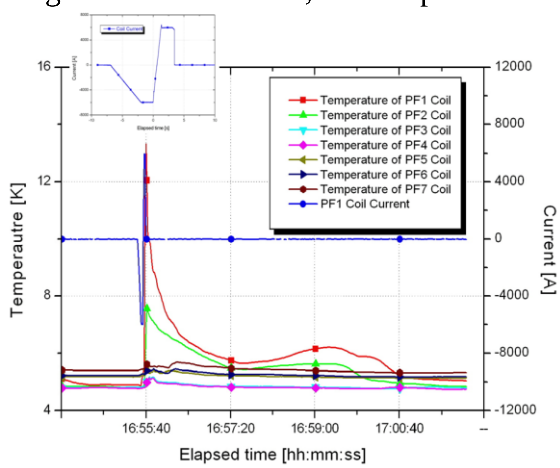


FIG. 9. Fast current changing to PF 1 coil and its temperature variation (Shot # 2517).

especially in PF 1 coil, was higher than estimated. Hydraulic analysis including AC effects has been carried out in order to find the optimal operational conditions. As one of the possible ways to reduce the temperature rise, the helium flow to the PF1~2 coils increased from 65 g/s to 90 g/s. The maximum temperature rise was reduced from 13.3K to 12.3K (shot #2526) with the same scenario as shot #2517. Engineering limits such as maximum current changing rates of the PF coil operation and improvement of the hydraulic circuits should be developed for the optimal operational condition of the KSTAR plasma.

Acoustic emission (AE) generated by the TF coil structures is monitored with 4 cryogenic AE sensors in order to evaluate the mechanical deformation and shearing of the structures, which may be induced by thermal contraction and electromagnetic forces. The cryogenic AE sensors of NF AE-901DL-A with a natural frequency of 140 kHz were tightly fixed at the bottoms of the TF8 and TF16 coil structures or the toroidal ring by using GFRP mounting structures for electrical insulation as shown in FIG. 10. The envelopes of the sensor output voltages, which have been amplified by 40 dB with the pre-amplifiers at the bottom of the tokamak, were detected by using the discriminators with a discharge time constant of 0.1 ms in the TMS low voltage signal conditioning room. The envelopes in much lower frequencies than the natural frequency of the AE sensors were continuously sampled at a sampling rate of 100 kHz by using the digitizer of NI PXI-4462, and then every 5 samples were averaged in order to reduce aliasing noise. The measurements during AE events, which included higher peak voltages than threshold voltage, were archived into the local data storage of the data acquisition controller of NI PXI-8105. The interlock system was upgraded and operated for safe plasma experiments by integrating newly-developed, replaced and existing devices into the unified interlock system. Device operation and maintenance procedures were modified to optimize the operation efficiency and to reduce processing errors.

FIG. 10. AE sensor on the TF coil structure

3. KSTAR Integrated Control Systems

The final goal of operating the KSTAR Integrated Control System (KICS) is to perform the roles of tokamak operation and plasma experiments with sustained stability, higher availability and security. Major work in the field of the KSTAR control system for the 2010 campaign are summarized as follows; (a) to develop plant control & monitoring systems and their interfaces for the newly installed plant systems such as PFC, NBI-1, IVC power supply, power supplies for PF3~6 upper coils, etc., (b) to develop data acquisition systems for newly installed diagnostics and to expand data channels of the existing DAQ systems, (c) to improve the environment for remote access and data sharing, and revise the access policy, (d) and also to enhance the availability and reliability during operation of the integrated control system by standardizing, optimizing, duplicating, etc.

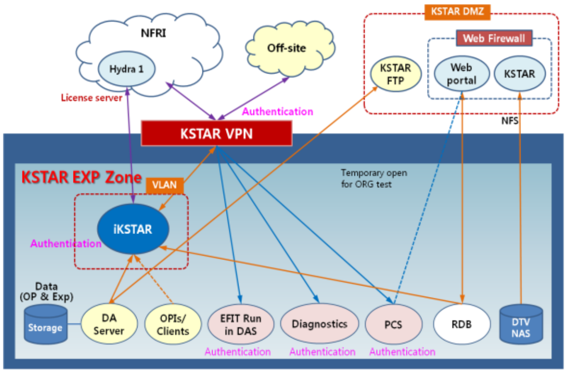
3.1 Upgrading Plant Control and Diagnostic DAQ Systems

For achieving the goal of the 2010 campaign, many plant systems have been upgraded and newly installed. These systems included a PFC monitoring system (PMS), a neutral beam injection system (NBI-1), a power supply for IVCC, and power supplies separated for PF3~6. Newly introduced diagnostics included a Thomson scattering system (TS), ECE imaging system (ECEI), Charge exchange spectroscopy (CES), IR visible bolometer (IRVB), etc. The PMS was comprised of 6 PLCs and an Experimental Physics and Industrial Control System (EPICS) IOC server to measure temperature from 203 sensors positioned at divertor, limiter and NB armor. The NBI-1 control system was a quite complicated system because it must be in charge of beam line, gas injection, CP & vacuum, cooling water, power supply and data acquisition. The IVC power supply and separated PF3~6 power supplies ran in VME system similar to the existing systems, so we expanded the control system to integrate these systems.

Different from the other systems, the coil power supply should be regarded in the view of sequential operation of tokamak and real-time feedback control. First, we changed a shared-memory communication used for real-time feedback control, the coil power supply systems and a central controller. Finally, 32 types of plant system I & Cs, which were composed of 110 subsystems with about 50,000PVs, functioned in the 2010 operation. During the campaign, the plant systems generated about 6GB of data daily. This number slightly increased in comparison with the last campaign. The major diagnostic tool for the 2010 experiment was the Thomson scattering system using a single Nd:YAG laser with 2J pulse energy and a pulse width less than 10 ns. The difficulty in DAQ system development was to find technology to measure extremely narrow pulse signal and we decided to use a conventional method to convert charge-to-digital signal after gating narrow pulse. We also developed data acquisition systems for soft x-ray array (SXR) and Mirnov coil (MC) to have full integration with a EPICS-based central control system and a MDSplus data system. In accordance with the increase of sensors, a magnetic diagnostic DAQ system was expanded to have an additional cPCI system to measure a total of 576 data channels. In the end, 25 types of diagnostic systems with about 10,000 MDSplus tag participated in experiments and produced several TBs experimental data that was dramatically increased because diagnostic systems operated with mega-sampling rate such as ECEI started to operate.

3.2 Enhancing the Environment for Remote Access and Data Sharing

Although collaborators to participate in and co-research for KSTAR experiments have grown rapidly, infrastructure for remote participants has not been sufficiently prepared. Before this campaign, we established a dedicated KSTAR Virtual Private Network (VPN) for secure access, and a gateway server named as iKSTAR for data service and operation information sharing. Also, we installed a KSTAR FTP server for data sharing with remote collaborators, and this service first was utilized for General Atomic in the US. In addition, some improvements were performed in KSTAR web services by upgrading web pages, consolidating several services accounts, and enhancing a web firewall.



Fi Fig. 11. Configuration of service for remote access

3.3 Improving Reliability and Availability of the Control System

The final goal for the control system is to achieve non-interrupted operation for supporting high performance plasma experiments. Therefore, we have elaborated on increasing availability step-by-step during the campaign by standardizing, optimizing, duplicating, etc. In order to standardize the control system, we first made and released the control system development guidelines to define architecture, platform, software, a naming convention and procedure. Also, a software standard framework was developed which was used for almost all data acquisition systems regardless of hardware platform. This approach reduced the incidences of faults due to sequential violation by operators and abnormal operation conditions, and at least could identify which part failed. Next, efforts have been made to secure stable EPICS Channel Access because intermittent disconnections had been experienced during the prior campaigns. All multiple IOCs were removed in a single plant server by merging them, which was regarded as a main cause for unstable connection. Also, CA gateway was optimized by load balancing, upgrading, optimizing the system parameters, and, as a result, CA connection aren't a cause of failure in the operation of the control system any more. Finally, redundancy was built for computing servers to be in charge of data archiving, service, analysis, and backup, and also commissioned a fail-over module which was developed to hand over their functions to a redundant server when faults happened. Moreover, a utility program was developed to supervise the entire control system including EPICS IOCs, computing servers, storage systems, networks, and even temperature of a computing room and an equipment room where the computing servers, central control systems and operator's servers are located.

Summary

The 3rd campaign operation of KSTAR device in 2010 has been performed successfully. The vacuum conditions required for the vacuum vessel and the cryostat were achieved even though the vacuum area was much increased from last year. High current and long period steady-state operation of TF magnet testing was performed successfully. The temperature rising during high current TF magnet testing was only 1.5 K, however when the PF magnet current changed with 10 kA/s, the temperature increase reached 8.2 K mainly due to AC losses. The high field operational results of the superconducting tokamak could be used as fiducial data for ITER and other superconducting magnet devices. The operational results of superconducting magnet protection technology in high magnetic fields could be used in other high current devices including ITER. The EPICS based KSTAR control system could be a reference of the ITER control system and also could suggest the KSTAR control system as a standard for superconducting tokamak control systems. Development of an optimum operation scheme for the helium refrigeration system will be a reference for superconducting magnet cooling systems.

Acknowledgement

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