Status and Result of the KSTAR Upgrade for the 2010's Campaign

H.L. Yang 1), Y.S. Kim 1), Y.M. Park 1), Y.S. Bae 1), H.K. Kim 1), K.M. Kim 1), K.S. Lee 1), H.T. Kim 1), E.N. Bang 1), M. Joung 1), J.S. Kim 1), W.S. Han 1), S.I. Park 2), J.H. Jeong 2), H.J. Do 2), H.J. Lee 1), S.W. Kwag 1), Y.B. Chang 1), N.H. Song 1), J.H. Choi 1), D.K. Lee 1), C.H. Kim 1), J.K. Jin 1), J.D. Kong 1), S.L. Hong 1), H.T. Park 1), W. Namkung 2), M.H. Cho 2), H. Park 2), J.G. Kwak 3), D. H. Chang 3), S.H. Jeong 3), J.T. Jin 3), S.R. In 3), S.J. Wang 3), S.H. Kim 3), K. Watanabe 4), L. Grisham 5) M. Kwon 1), Y. Gorelov 6), J. Lohr 6) and the KSTAR team

1) National Fusion Research Institute, Daejeon, Korea
2) Pohang University of Science and Technology, Pohang, Korea
3) Korea Atomic Energy Research Institute, Daejeon, Korea
4) Japan Atomic Energy Agency, 801-1, Mukoyama, Naka-shi, Ibaraki 311-0193, Japan
5) Princeton Plasma Physics Laboratory, P.O. Box 451, Princeton, NJ08543, USA
6) General Atomics, P.O. Box 85608, San Diego, CA92186-5608, USA

E-mail contact of main author: hlyang@nfri.re.kr

Abstract. Because the 2010 operation of Korea Superconducting Tokamak Advanced Research (KSTAR) mainly aims to achieve strongly elongated and diverted plasma, all the necessary hardware systems to provide an essential circumstance for the plasma shaping were newly installed and upgraded in 2010. The hardware for the 2010 KSTAR operation comprises in-vessel components and power supplies for superconducting (SC) magnets. The in-vessel components, which contain limiters, divertor, passive stabilizer, in-vessel control coil (IVCC) system, have been upgraded with satisfactory performances. The SC magnet power supplies (MPS) also fully demonstrated their own designed functions during final commissioning for the 2010 operation. In addition to drastic upgrades of the in-vessel components and MPS, there were great progresses in the development of heating and current drive system including neutral beam injection (NBI), electron cyclotron current drive (ECCD), and lower hybrid current drive (LHCD) system to prepare an initial stage for steady-state operation. In this paper, general configuration of the upgraded systems described earlier will be outlined. Moreover, several key performances and test results of the systems will be also reported in summary.

1. Introduction

The Korea Superconducting Tokamak Advanced Research (KSTAR) marked a new epoch in construction of the fully superconducting (SC) tokamaks through successful demonstration on the first plasma and initial operation in past two years [1-2]. However, absence of a few key components that have been omitted in the construction phase is imposing a major limit on the KSTAR operation to move toward its own designed goal: establish a scientific and technological basis for an attractive fusion reactor through steady-state operation [3]. Hence, several actuators were upgraded in 2010. Especially, since the 2010 KSTAR operation mainly aims to achieve strongly shaped and diverted plasma, all of the in-vessel components were newly installed. Although most of the components have been developed to be available only for 20-s operation, it will be a good experience for the in-vessel components to be majorly upgraded for the steady-state operation in the future. Insufficient magnetic flux (~2 Wb) that was originated from current limit in the blip resistor insertion system (BRIS) of the SC magnet power supply (MPS) gave another constriction in the KSTAR operation. Furthermore, separation of each upper and lower poloidal field (PF) coil has been continuously emphasized to enhance the vertical stability for long-pulsed operation. To overcome all the problems

described above, all of the MPS components were fully upgraded prior to start of plasma operation in 2010.
Because plasma heating and non-inductive current drive (H&CD) system will play key roles on steady-state operation and advanced tokamak (AT) operation, it is impossible to overestimate the importance of the H&CD system. Although electron cyclotron heating (ECH)-assisted start up system successfully demonstrated an important result for a smooth start up in the SC tokamaks, insufficiency of several H&CD devices such as neutral beam injection (NBI) system, EC current drive (ECCD) system, ion cyclotron range of frequency (ICRF), and lower hybrid current drive system (LHCD) may decisively impact not only on the 2010 campaign but also on the forthcoming steady-state operation experiments. Therefore, the KSTAR staffs have been struggling with development of the H&CD system, and there were substantial progress in 2010 for the H&CD system development.

2. In-Vessel Components

2.1. PFCs and Divertor System

As shown in Fig. 1, the plasma facing components (PFC) consist of limiters, divertor, passive stabilizer, and NB protection armor. Heat-sink plate of the inboard limiter has a toroidally continuous cylinder-shape, which are made of stainless steel (SS316LN) with internal cooling channels for active water cooling and baking. The plate is covered by graphite tiles that are simply mounted on the plate by bolts. Meanwhile 12 sub-segments among 16 sub-segments of the inboard limiter is covered by graphite tiles, remained 4 sub-segments will be covered with carbon fiber composite (CFC) tiles, on which strong heat influx take place due to the NB shine-through. The divertor system consists of inboard, central and outboard parts. Each part contains 8 heat-sink plates that locate in upper and lower side of the vacuum vessel with up-down symmetry for double-null (DN) operation. Entire area of the heat-sink plates is covered with CFC tiles by bolts to withstand high temperature (maximum 1,200 °C) at a striking point for the case of maximum heat influx of 4.3 MW/m^2. Since the divertor concept with bolted CFC tiles is not sufficient for heat removal from the tiles in long-pulsed operation (300 s), the divertor should be fully upgraded again in 2015 (or 2016) with a new concept of heat removal mechanism, and tile materials.

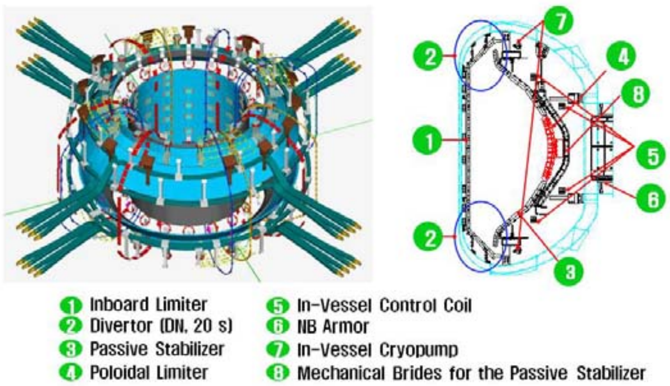

FIG. 1. KSTAR In-vessel components

To enhance plasma performances by exhausting impurities in the plasma, divertor pumping system, which is called as IVCP (In-vessel Cryo-pump) has been developed. The IVCP comprises three layers of concentric pipes, and the total area of 1.01 m^2 in the cryo-pump is cooled by two-phase liquid helium to 4.44 K with inlet pressure of 1.24 bars. The outer and inner thermal shields surrounding the cryo-surface are to be cooled down to 77 K by liquid nitrogen, and are finally surrounded by a radiation particle shield. Estimated pumping speed is to be larger than 25,000 liters/sec for deuterium per each cryo-pump. Since two cryo-pumps are located at top and bottom of the vacuum vessel, total pumping speed of the pumps reaches more than 50,000 liters/sec for deuterium. The cryo-pumps should be quickly regenerated during operation to keep the optimum pumping speed during intervals between every shot. The thermal shields and the cryo-surface were designed to be cooled down within 20 minutes from room temperature to operating temperature. The cryo-surface also should be warmed up to 100 K within 3 minutes and hold the temperature during regeneration period, which is followed by cooling down again to cryogenic temperature within 5 minutes for a next shot. Figures 2 and 3 sequentially show the IVCP and the heat-sink plates of the divertor that were installed in the vacuum vessel.

FIG. 2. In-vessel cryo-pump after installation

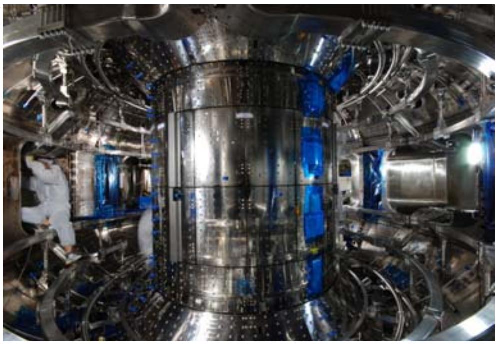

FIG. 3. Back-plate of divertor after installation

The passive stabilizer will play roles both on plasma position control and on MHD instabilities suppression through combinations with active control coils. Two toroidal ring-shaped copper plates made of CuCrZr alloy have up-down symmetry. The upper plate is supported by 12 vertical supports and by four horizontal supports, while the lower plate is supported by 9 mechanical bridges that are connected to the upper plate. Each plate is electrically segmented into four quadrants, and a quadrant is electrically connected to an adjacent quadrant by “gap resistors” to adjust resistance of the passive plate in toroidal direction. Figure 4 shows the passive plates under installation in the vacuum vessel. The poloidal limiter comprises three D-shaped strings to protect launchers of the ICRF and LHCD. Because the KSTAR NBI system is composed of two beam lines, the NB protection armor system also comprises two sets of actively cooled CFC tiles. After termination of the final design, fabrication and installation of the PFC system has been launched in middle of 2009, and all the sub-components were installed in the vacuum vessel in middle of May 2010. Figure 5 shows inside of vacuum vessel with newly installed PFC system. Although several components that are to be covered with CFC tiles in the original design, all of the PFCs were covered with graphite for 2010 campaign owing to relatively low heat flux and short pulsed operation. Especially, the divertor tiles will be replaced as CFC in 2012. Prior to start of 2010 campaign, the PFC system has been baked to 200 °C, and will be verified whether the PFC system is compatible enough for designed baking temperature (350 °C) in 2011.

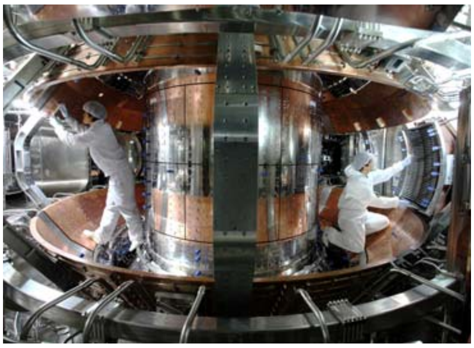

FIG. 4. Passive stabilizer under installation in the vacuum vessel

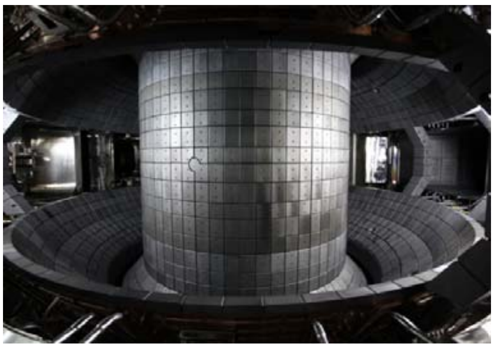

FIG. 5. PFC system with graphite tiles after completion in the vacuum vessel

2.2. In-vessel Control Coil (IVCC)

The IVCC system was developed to take advantages of active control for the plasma position, field error correction (FEC), and that for resistive wall mode (RWM) [4, 5]. More recently, the IVCC is expected to be effectively utilized in suppression of edge localized mode (ELM). This important system adopted a unique concept of segmented coil system to have 16 segments and their support structures [6]. Each segment contains eight water-cooled normal coppers that are partially connected to an adjacent segment in series to form 4 circular coils for position control as shown in Fig. 6, while remained copper conductors are connected to a vertically neighbouring segment to form 12 "picture-frame" coils for the FEC and RWM control. Figure 7 shows the IVCC segments after installation in the vacuum vessel. Because all of the electrical connections, power feed-through cables, and connectors for cooling water are located at outside of the cryostat, there is no internal joint, or connection points in the vacuum vessel. This configuration might substantially enhance reliabilities in operation of the IVCC system. In order to demonstrate the stable operation capability during the 2010 campaign, the integrated commissioning of the IVC coils and power supply was finally performed in July 2010. The maximum applied voltage, current per turn, and pulse length were ±900 V, ±5 kA, and 5 seconds, respectively. As shown in Fig. 8, a measurement of magnetic probes shows the opposite signal and same order of magnitude that clearly implies the upper and lower vertical control coil has been almost ideally connected in anti-series.

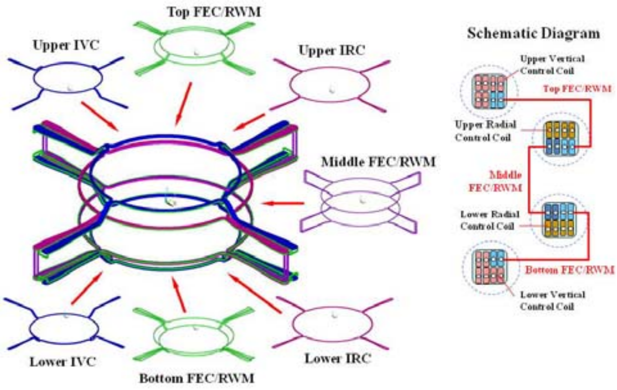

FIG. 6. Electrical connection of the IVCC

FIG. 7. IVCC segments installed in the vacuum vessel

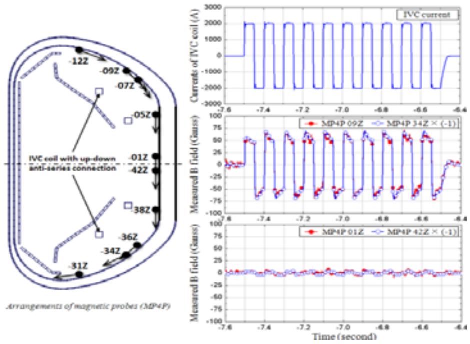

FIG. 8. Result of magnetic field analysis vs. current charging on the IVC coil

3. Heating and Current Drive System

3.1. General Description

The KSTAR heating and current drive (H&CD) system contains NBI and radio frequency RF systems such as ICRF, LHCD, and ECH/ECCD system. The combination of multiple heating and current drive technologies is aiming at providing flexible control functions for current density and pressure profile in the KSTAR operation scenarios; the neutral beam power of 14 MW at 120 keV D0 beam with two beam lines and three ion sources in each beam line, the IC coupled heating power of 6 MW at 30~60 MHz, the LH heating power of 2 MW at 5 GHz, the EC heating power of 0.5 MW at 84 GHz and 110 GHz for start-up, and EC heating power of 3 MW at 170 GHz for the current drive and the MHD mode stabilization, respectively.

3.2. Neutral Beam Injection System

The first NBI system (called as NBI-1) was developed and constructed in order to inject at least 1 MW of deuterium neutral beam in 2010 operation. A bucket type positive ion source, which has been developed by Korea Atomic Energy Research Institute (KAERI) and demonstrated 55 A of hydrogen ion beam at 100 keV with 2-s in the beam pulse [7], was installed onto the beam line system as shown in Fig. 9. More recently, the source was substantially replaced by the new source chamber [8] to enhance arc efficiency in the source chamber. Main vacuum chamber of the NBI-1, and the beam line components that are contained in the chamber were also fully commissioned before start of the integrated commissioning. Figure 10 shows the beam-line of first NBI system. The vacuum chamber includes 16 cryo-pumps, a two-staged gas-cell neutralizer, a bending magnet of which magnetic field integral of 65 kG·cm on the beam path, a rectangular scraper, and a movable single-channel calorimeter, and three ion dump plates to accommodate residual ion beam for full, half, and third components.

FIG. 9. Ion source installed on the beam-line

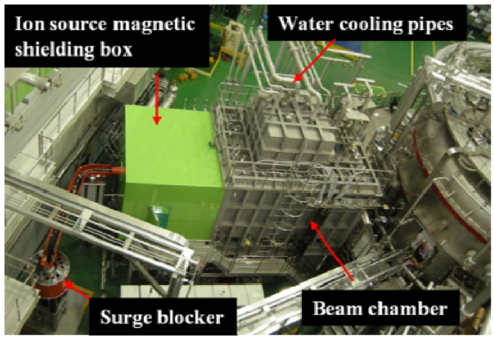

FIG.10. NBI-1 system in experimental hall

All of the power supplies were also completed in the final test for beam extraction up to 90 kV and 54 A in maximum voltages and currents, respectively. Moreover, every cables and devices, which should withstand high voltage (HV) insulation, are also commissioned to 90 kV. After all the sub-components were individually commissioned, the NBI system is now under final test on its performances. The ion source extracted the deuterium neutral beam to 27 A at beam energy of 80 keV. Figure 11 shows an achieved data in the perveance scan, and shows a typical waveform in the beam extraction.

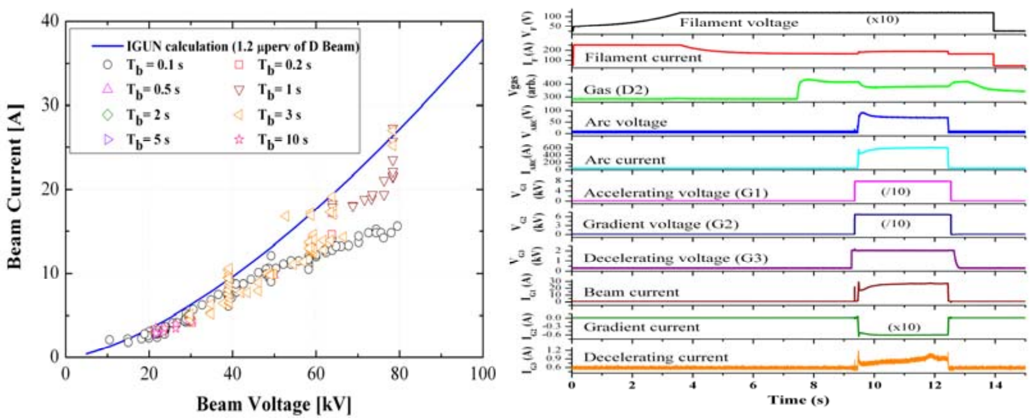

FIG. 11. (Left) The beam perveance data and (right) the waveforms of the 3-s beam extraction with the beam energy of 80 keV and the beam current of 27 A.

Left of Fig. 12 shows the beam divergence of extracted deuterium ion beam at the acceleration voltage of 60 kV varying the arc power from 16 kW to 24 kW. The ion source was proved to have a wide operation range within the beam divergence of 1 deg. which is the KSTAR requirement for the NB injection. The species ratio of the deuterium beam is being analyzed now through the Doppler shifted spectrums as shown in right Fig. 12 (right).

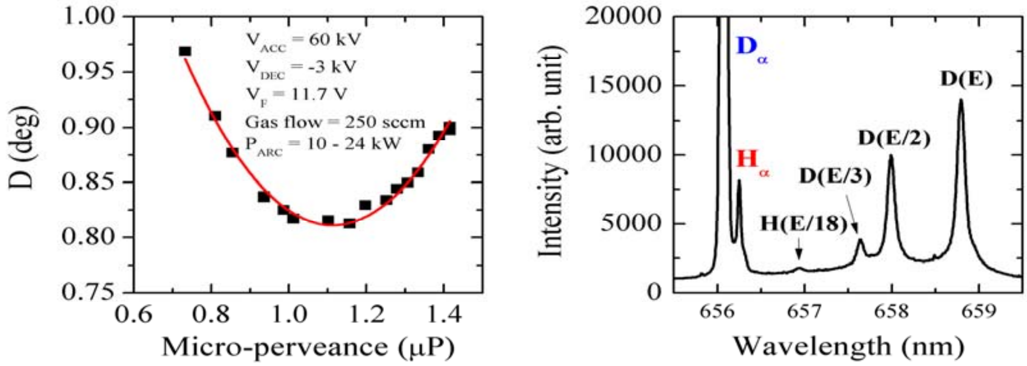

FIG. 12. (Left) beam divergence and micro perveance, and (right) a Doppler shifted spectrum in the beam extraction experiments.

3.3. ECH-Assisted Start up System

Success in the ECH-assisted startup using 2nd harmonic [9] EC wave is expected to provide crucial techniques for reliable start up with relatively low loop voltage (~3 V) in superconducting tokamak devices. The KSTAR ECH-assisted startup system originally utilized 84 GHz gyrotron with a capability of 500 kW and 2 s pulse length. But the gyrotron had a few serious troubles including vacuum leak at the collector, and the tube is still under repair. Hence, a 110 GHz gyrotron, which has specification of 800 kW for 2-s pulse length and 500 kW for 5-s pulse length and diode-gun type with no depressed collector, was loaned from General Atomics (GA). The tube was satisfactorily operated with 250 kW and 3-s pulse length at the terminal dummy load, and the system was essential for the plasma start up using the second harmonic EC resonance at the toroidal magnetic field of 2 T. However, the 110 GHz tube was not capable of higher power due to the power supplies that were originally dedicated to the 84 GHz tube. The 250 kW of ECH power was proven to be quite marginal value for the power threshold for the reliable startup. Consequently, by the gyrotron power supply upgrade in early 2010 and the alignment at the mirror optical unit (MOU), and the 110 GHz ECH system demonstrated more than 400 kW for 2 s at the terminal dummy load that is about 30 meters from the gyrotron.

3.4. ICRF System

The 2 MW ICRF system, which has been developed by KAERI group and mainly utilized for Ion Cyclotron Wall Cleaning (ICWC) in past two years [10], has not been majorly upgraded in the hardware system. However, the ICRF system will be employed for minority heating experiments in 2010 operation in accordance with plasma shaping and much higher coupled RF power.

3.5 ECH/ECCD System

In addition to the ECH-assisted startup system, 170 GHz ECCD is an another important system for Neo-classical Tearing Mode (NTM) control, saw-teeth mode control as well as electron heating and current drive. All of the transmission line components, and power supplies for the 170 GHz gyrotron were already launched in procurement to prepare a 1 MW ECCD system for 2011 campaign. The 170 GHz gyrotron which has been developed by JAEA (Japan Atomic Energy Agency) for pre-prototype of ITER 1MW CW gyrotron will be loaned from JAEA in early 2011 in accordance to the agreement in Korea-Japan collaboration. Test results on the gyrotron they achieved are quite satisfactory to the KSTAR requirements. The 1 MW ECCD launcher is being developed through strong collaboration with PPPL group, and the launcher will be delivered to the site by early start of 2011. Power supplies for the 170 GHz gyrotron are also under manufacturing in the Korean domestic company to meet the ECCD system operation in 2011 operation.

3.6. LHCD System

5 GHz LHCD system of the KSTAR will play key roles in controlling plasma current profiles. The off-axis current driven by the LH waves can create broad or even hollow current profiles required in an ‘advanced tokamak’ scenario by introducing negative magnetic shear [11]. The challengeable engineering issues in development of the LHCD system can be categorized by two research fields. First is the development of 5 GHz CW klystron, and the other is that of steady-state LH launcher to accommodate continuous LH power with good directivities. To basically investigate the issues described above, the initial LHCD system with capacity of 0.5 MW for 2-s is scheduled to be installed in 2011 using the prototype of 5 GHz, 500 kW CW klystron and un-cooled active phased-array waveguide launcher. The prototype klystron, which was fabricated by Toshiba in Japan, was successfully tested at KSTAR site in early start of 2010. The power output we achieved was more than 460 kW for 20-s, and 300 kW for 800-s. The launcher of the initial LHCD system will be composed of 2 arrays, each with 8 waveguides in column with consideration of the power upgrade to 1 MW [12]. For injection of the 5 GHz LH wave into the plasma, an LH launcher was designed based on the 4-way splitter without active water cooling. Each waveguide channel of the splitter is to be welded, and a ceramic vacuum window is mounted on each output waveguide of the splitter for vacuum isolation. After the design completion of the splitter, the fabrication of the test module with one channel is in progress for the preparation of the initial LH launcher in 2011.

4. Magnet Power Supply and SC Current Feeder System

TABLE I: SPECIFICATION OF MPS AFTER FULL UPGRADE

Item	Specification					
	Converter	DCL	BRIS	QP	DCDS	DC Bus-bar
PF1	1kV/25kA	0.4mH/25kA	*3kA→25kA*	2kV/25kA	25kA	25kA
PF2	1kV/25kA	0.4mH/25kA	*3kA→25kA*	2kV/25kA	25kA	25kA
PF3L	500V/25kA	0.4mH/25kA	*3kA→25kA*	2kV/25kA	25kA	25kA
PF4L	500V/25kA	0.4mH/25kA	*3kA→25kA*	2kV/25kA	25kA	25kA
PF5L	1kV/25kA	0.4mH/25kA	*3kA→25kA*	2kV/25kA	25kA	25kA
PF6L	1kV/20kA	0.4mH/20kA	*3kA→20kA*	2kV/20kA	20kA	20kA
PF7	1kV/20kA	0.4mH/20kA	No BRIS	2kV/20kA	20kA	20kA
PF3U	*1kV/25kA*	*0.4mH/25kA*	*3kA→25kA*	*2kV/25kA*	*25kA*	*25kA*
PF4U	*1kV/25kA*	*0.4mH/25kA*	*3kA→25kA*	*2kV/25kA*	*25kA*	*25kA*
PF5U	*1kV/25kA*	*0.4mH/25kA*	*3kA→25kA*	*3kV/25kA*	*25kA*	*25kA*
PF6U	*1kV/20kA*	*0.4mH/20kA*	*3kA→20kA*	*5kV/20kA*	*20kA*	*20kA*
QP: Quench Protector, SDC: Slow Discharge Circuit, SDR: SD Resistor, DCDS: DC Disconnection Switch,						

Due to current limit in the blip resistor insertion system (BRIS) for the PF coils, only 2 Wb of total magnetic flux imposed a major constriction on the KSTAR operation in past two years.

Moreover, lack of power supplies for upper PF coils (PF3, PF4, PF5, PF6) made it impossible for each PF coil to be separated into upper and lower coil. However, all these problems were solved through full upgrade of magnet power supply (MPS) system in early 2010. Table 1 summarizes the final specification of the MPS, in which shadowed cells represent upgrade in 2010. According to new installation of the upper PF power supplies, corresponding four sets of SC current leads and SC bus-lines were also additionally installed and commissioned in overhaul period before start of 2010 operation. Moreover, the grid power for the MPS has been updated from 50 MVA to 100 MVA to validate all of functions of the MPS.

5. Summary

This paper outlined status and plan in development of in-vessel components and heating systems. All the in-vessel components were installed inside vacuum vessel for 20-s operation. The PFCs were entirely covered with graphite tiles that were baked to 200 °C, and several components including the divertor will be partially replaced as CFC tiles in 2012. The IVCC system was also installed in the vacuum vessel and commissioned for vertical position control in 2010 campaign. In-vessel cryo-pump was pre-installed for divertor pumping experiments in 2011. First NBI system is now under integrated system commissioning for 1 MW injection in 2010 campaign, and preparation of the 170 GHz ECCD and the 5 GHz LHCD systems is being actively progressed for 2011 campaign.

Acknowledgement

The Korean Ministry of Education, Science and Technology under the KSTAR project contract supported this work.

References

[1] BAK, J.S., YANG, H.L., et al., "Overview of Recent Commissioning Result of KSTAR," 22nd IAEA Fusion Energy Conference, (2008) FT/1-1.

[2] OH, Y.K., et al., "Commissioning and initial operation of KSTAR superconducting tokamak", Fusion Eng. and Des. **84** (2009) 344-350.

[3] LEE, G.S., et al., "Design and construction of the KSTAR tokamak," Nuclear Fusion, **Vol. 41**, (2001) p1515

[4] LEE, G.S. Lee, IVANOV, D.P., et al., "Advanced Physics and Plasma Control with Segmented In-vessel Control Coils in the KSTAR Tokamak", ITC2001, Japan, 2001.

[5] JHANG, HOGUN, et al., "Simulation studies of plasma shape identification and control in Korea Superconducting Tokamak Advanced Research", Fusion Eng. and Des. **54** (2001) 117–134.

[6] KIM, H.K., YANG, H.L., et al., "Design features of KSTAR in-vessel control coil", Fusion Engineering and Design, **84** (2009) 1029-1032.

[7] OH, BYUNG-HOON, et al., "Long pulse beam extraction with a prototype ion source for the KSTAR neutral beam system", Rev. of Sci. Inst., **79**, 02C101 (2008)

[8] Dairaku, M., et al., "Development of a plasma generator for a high power NBI ion source," JAEA Technology 2008-091 (2008) (in Japanese).

[9] BAE, Y.S., et al., "ECH pre-ionization and assisted startup in the fully superconducting KSTAR tokamak using second harmonic", Nucl. Fusion **49** (2009) 022001.

[10] KWAK, JONG-GU, et al., "Commissioning the ICRF system and an ICRF assisted discharge cleaning at the KSTAR", Fusion Engineering and Design **85** (2010) 169-173

[11] MAILLOUX, J., et al., "Progress in internal transport barrier plasmas with lower hybrid current drive and heating in JET (Joint European Torus)", Phys. Plasma **9** (2002) 2156.

[12] PARK, S., et al., "Development status of KSTAR 5 GHz LHCD system", Fusion Engineering and Design **85** (2010) 197-204.