Overview of Recent Commissioning Results of KSTAR

J. S. Bak, H. L. Yang, Y. S. Kim, Y. K. Oh, I. S. Whang, Y. S. Bae, Y. M. Park, K. W. Cho, Y. J. Kim, K. R. Park, W. C. Kim, M. K. Park, T. H. Ha and the KSTAR Team

National Fusion Research Institute, Daejeon, Korea

e-mail contact of main author: jsbak@nfri.re.kr

Abstract. KSTAR is an advanced tokamak with fully superconducting coils for the steady state plasma research. 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. The commissioning on KSTAR has been progressed from March to July 2008, through 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. All of the subsystems have been tested and showed to satisfy the design requirements. All of the magnets were cooled down to 4.5 K stably and then charged successfully without any serious faults. The first ohmic plasma was achieved on June 10th. The breakdown was successfully achieved at B_t = 1.5 T at 1.8 m. After several tens of breakdown shots, the first plasma of more than 100 kA has been successfully achieved on June 13th 2008. At the plasma start-up stage, it was verified that the key issues for the breakdown and the current ramp-up are: the null field, breakdown electric field, toroidal field, gas pressure, blip duration, ECH pulse length and impurity control. This first plasma commissioning has demonstrated that KSTAR has been successfully constructed and is ready for operation. All of the commissioning progress, including various problems and interesting test results, are summarized in this paper. Furthermore, details on the individual subsystem commissioning results will be presented in the KSTAR-related paper at this conference.

1. Introduction

KSTAR, 12 year's 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 major milestone and sequence of overall commissioning are described in details in Reference 1. The purpose of commissioning is to test each subsystem and linked subsystems after device assembly, and to demonstrate that systems are in accordance with the design values and meet the performance criteria. The final target of first plasma is to achieve current of 100 kA in pulse duration of 100ms at a magnetic field of 1.5 Tesla. The commissioning on KSTAR consists of these four steps: vacuum, cryogenic cool down, superconducting magnet test, and plasma start-up. Table 1 summarizes the verifying items at each commissioning step. The vacuum, cool down, and magnet commissioning steps were progressed very smoothly, without any serious difficulties. After these three commissioning steps on KSTAR, the first ohmic plasma was successfully achieved on June 10th on KSTAR, with the collaboration of General Atomic. In several discharges, a modest peak of 107 kA in pulse duration of 213 ms was achieved at a 1.5 T TF field. After the parameters for reliable breakdown and current ramp-up were optimized, the maximum plasma current was ramped up to 133 kA with rate of about 0.85 MA/s by pre-programmed control. Then, more than 400 shots were repeated with the feedback control of the plasma current and position. Finally, the plasma was extended to 862ms duration at a level of 100 kA current. 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 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.

TABLE I: KSTAR COMMISSIONING REQUIREMENTS AND RESULTS.

Step	Item	Unit	Requirement	Result
Vacuum	Base pressure of VV	Pa	5.0×10^{-5}	3.0×10^{-6}
	Base pressure of CR	Pa	1.0×10^{-2}	3.0×10^{-6} @5K
	Total leak rate	$Pa\cdot m^3/s$	1.0×10^{-5}	1.6×10^{-8}
Cryogenic cool-down	Inlet temperature of TFC	K	less than 5	~ 4.5
	Inlet temperature of PFC	K	less than 5	~ 4.5
	Inlet temperature of CTS	K	about 60	~ 60
	Inlet temperature of VVTS	K	about 100	~ 100
	Temperature control	K	< 50	< 50
Superconducting magnet	Superconducting transition	K	-	Nb3Sn : ~ 18
		K	-	NbTi : ~ 10
	Electrical insulation	MΩ	100	TF: 3000, PF: 3000
	Joint resistance	nΩ	5	0.5 ~ 2
	TF current charging	kA	15	15
	PF current charging	kA	2 ~ 4	2 ~ 4
	Blip rate	kA/s	10 ~ 100	10 ~ 100
	B_{TF}	T	1.5	1.46 (R=1.8m)
Plasma start-up	Loop voltage	V	3.5-4	4.2
	ECH pre-ionization	-	400 kW, 200 ms	450 kW, 200 ms
	ICRH discharge cleaning	-	30 kW, 0.2 ~ 10 s	30 kW, 10 s
	Plasma current	kA	100	133
	Plasma duration	ms	100	862

2. Vacuum Commissioning

KSTAR has two separate vacuum regions: one is the primary vacuum of vacuum vessel for plasma discharge and the other is the secondary vacuum of 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. Vacuum 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 1 shows the vacuum history during the entire commissioning period. As shown in Fig. 1(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 carried out using hydrogen and helium gas. Then, gas fueling system linked to plasma control system was tested. The ICRH discharge cleaning was routinely operated between shots. As shown in Fig. 1(b), the secondary vacuum for cryostat also reached 2.5×10^{-4} Pa stably within one week. 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 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. Many peaks on curve of Fig. 1(b) were caused by the burst of trapped air of bus-line insulation parts, which were cured by gas-bag impregnation method. These peaks were gradually disappeared below 15 K. The entire pumping system, including control and interlock unit, were very stably operated through the entire commissioning period.

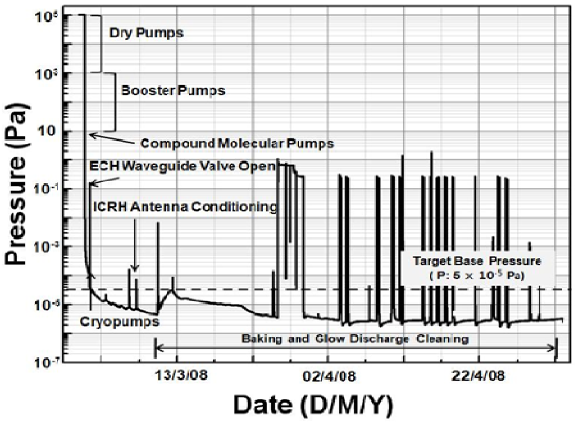

FIG. 1(a) Primary vacuum history

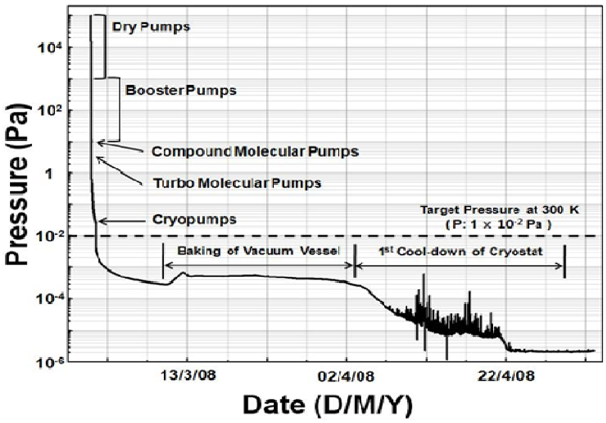

FIG. 1(b) Secondary vacuum history

3. 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.

3.1. 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 2 shows the temperature history of the KSTAR 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 [2], and two, to restrict the temperature difference of 25 K between inlets and outlets. During the cooling down process, the total and partial pressure of residual gas in the cryostat were monitored as shown in Fig. 3. 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 process. 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. If a cold leak existed in the cryostat, the helium partial pressure at 5 K should have increased rapidly because of the high density of the supercritical helium. 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 [3].

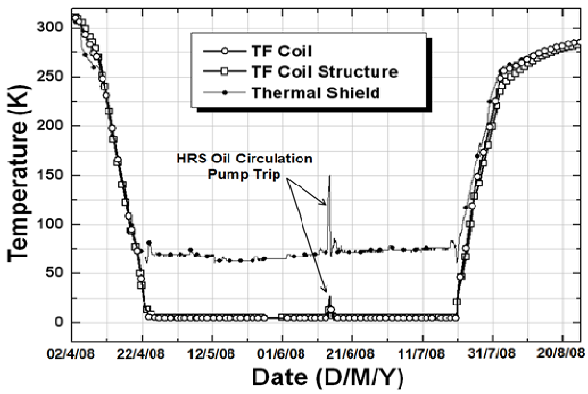

FIG. 2 KSTAR temperature history

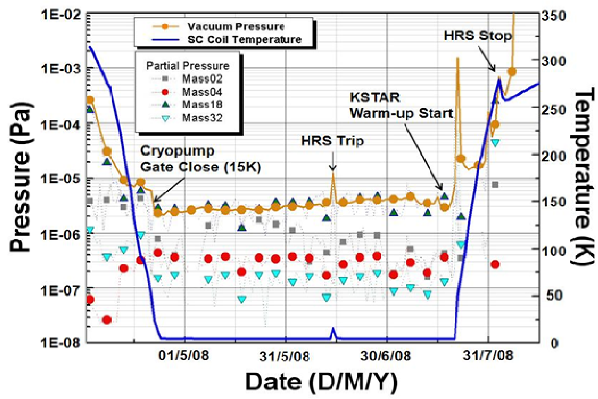

FIG. 3 Vacuum behavior during cool-down

3.2. Mechanical Stress Change

To monitor the structural stress behavior during cool-down, 239 strain gauges were instrumented on the various cold components. The variation of stresses in TF structures are shown in Fig. 4. 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 750 tons at room temperature [4]. 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.

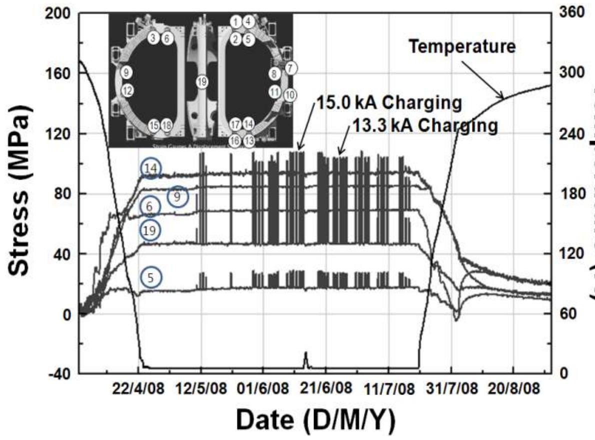

FIG. 4 Stress change of TF structures

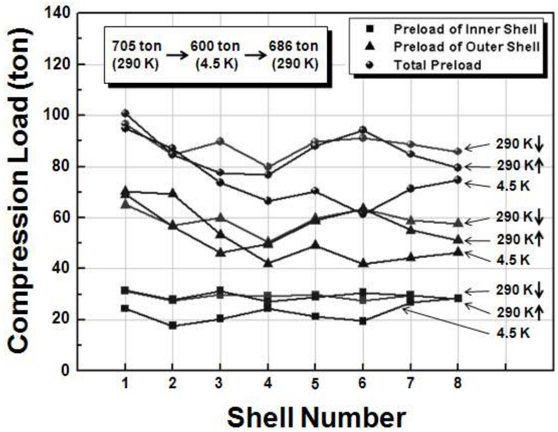

FIG. 5 Preload change of CS structure

3.3. Superconducting 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 10 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. Table II shows the resistance measurement for 136 lap joints. 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].

3.4. Stability of Cryogenic System

Operation of the helium cryogenic system has been progressed from April 3rd to August 2nd 2008, without any critical troubles. Even though the helium refrigerator system (HRS) was interrupted twice by electrical failure, HRS could be restarted quickly and smoothly without disturbing the cool-down process. In a continuous operation of 4 months, there were no problems, such as blocking of turbines or the coil inlet filters, chocking of control valves, decrease in the heat exchanger efficiency, nor a vacuum or helium leak etc. One major interruption occurred due to a fault of a compressor oil pump. The total recovery time back to the normal condition was 1 day. Some minor problems, such as thermo-acoustic oscillation of some of the piping, bad thermal anchoring of a few temperature sensors, and vibration of the warm compressor, will be improved after the system warm-up for the next campaign.

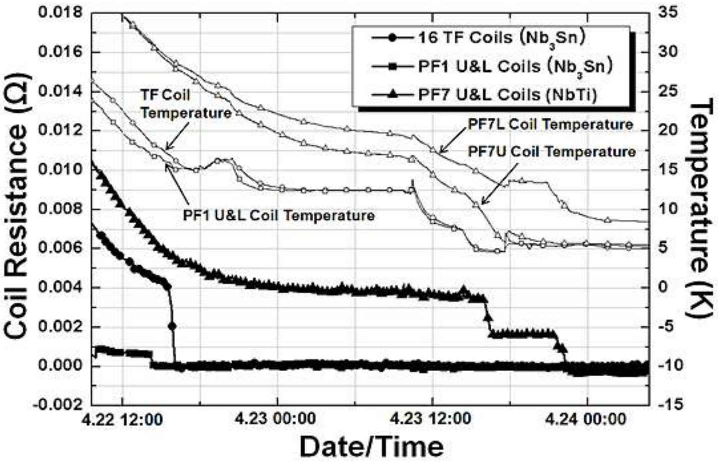

FIG. 6 SC transition of KSTAR magnets.

Bus-line		# of Joint ICB	# of Joint OCB	Average Resistance [nΩ / joint]
TF	(+)	4	4	1.85
	(−)	4	4	
PF1	(+)	2	3	2.23
	1L to 1U	3	-	
	(−)	3	3	
PF2	(+)	3	3	1.53
	2U to 2L	3	-	
	(−)	2	3	
PF3	(+)	2	3	1.69
	3L to 3U	5	3	
	(−)	3	3	
PF4	(+)	2	3	1.45
	4L to 4U	5	3	
	(−)	3	3	
PF5	(+)	2	3	2.09
	5L to 5U	5	3	
	(−)	3	3	
PF6	(+)	3	3	0.08
	6U to 6L	6	3	
	(−)	3	3	
PF7	(+)	3	3	0.51
	7U to 7L	2	-	
	(−)	3	3	

TABLE II: JOINT RESISTANCE.

4. Magnet Commissioning

The main task of integrated commissioning of superconducting magnet was to test whether all the superconducting magnets, interface systems, and its power supply could stably operate under specified operation conditions, as well as to check the controllability of each power supply. The TF coil was tested up to 20 kA because of limitation of switching capability for the fast quench protection circuit. The PF coils were tested up to 4 kA with corresponding power supplies without the fast quench system. The current charging and discharging test for all coils were successfully performed in May 2008. Especially, this commissioning result is very meaningful because any coils of KSTAR have not been tested at the cryogenic condition before the assembly. In actual test, interface parts were elaborately tested than magnet itself. The operation of all superconducting coils was very stable in thermal, mechanical, and electrical respect, without any quench or defects.

4.1. TF Magnet Test

The TF system was tested by increasing the current level in steps. Figure 7 shows the 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. The magnetic field inside the vacuum vessel was measured by movable Hall probes and was in good agreement within 5 % compared to calculations. To investigate the magnetic effect of Incoloy 908, intensive field measurements were also performed [6]. The vertical remnant field measured about 10 Gauss in zero TF current, reduced to 2 Gauss at TF current of 15 kA. In addition, it was confirmed that most of the hysteresis observed in the magnetic measurements was eliminated as the TF magnet was once saturated by current charging. The maximum mechanical stress of the TF structure at 15 kA was measured to be about 41 MPa. The maximum stress at the rated current of 35 kA is estimated to be about 160 MPa. Therefore, the total stress at 35 kA is expected to be about 240 MPa, including the cool-down effect. It was verified that this value is much less than allowable criteria of 700 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.

4.2. PF Magnet Test

Prior to real coil test, each power supply was tested with copper dummy coils. The current was controlled by the PCS system which was developed under KSTR-DIIID 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. Must check items included the reference current control, BRIS operation tests, current ramping speed, step response tests, and protection mode tests. After the every single coil test, integrated tests with 7 PF coils were carried out. 7 PF power supplies were operated in an unipolar 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 that of 98.9 kA/s for PF3, respectively.

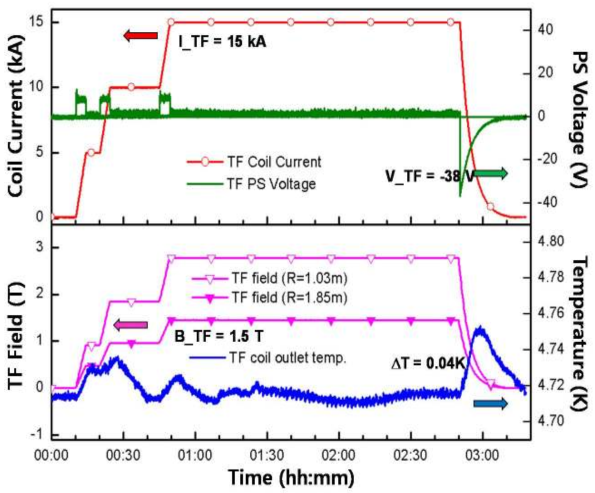

FIG. 7 Operating features of TF magnet.

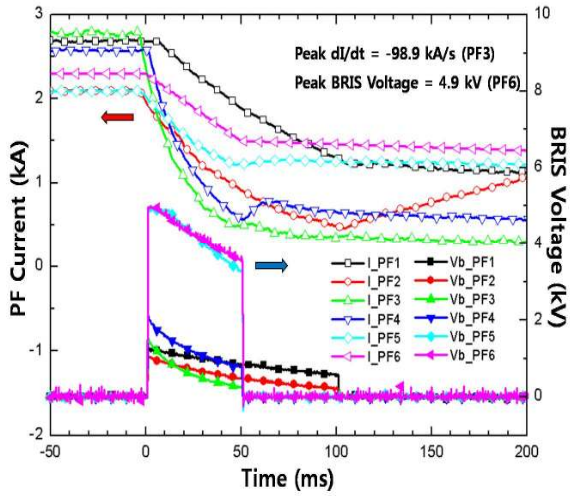

FIG. 8 Blip test results of PF magnets.

5. Plasma Start-up Commissioning

The purpose of this commissioning step was to demonstrate that the all integrated tokamak sub-systems can make a plasma discharge by the synchronized operations. This commissioning process began from the check of magnetic field configuration. Base on the field measurement results by movable Hall probe and a 2D numerical model considering the magnetization effects of Incoloy 908, a KSTAR-specific operation scenario has been developed to get optimized breakdown conditions

5.1. Key Features in Start-up

Experiments on the initial field null configurations were performed with two different types of IM scenarios. First, usual "conventional mode" scenario to have maximum field null size so as 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 loop voltage was ~4.5 V without plasma with flux of 0.89 Wb. Second, the "dipole mode" scenario was developed and used to get higher toroidal loop voltage and poloidal magnetic flux to get higher plasma performance. This was achieved by charging-up of the outer PF coils, 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, and insufficient wall conditioning, an 84 GHz gyrotron with 500 kW power was used as the second harmonic ECH assisted pre-ionization system [7]. 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 helium discharge cleaning was routinely applied during the shot-to-shot interval under the TF field. Typically, helium discharge cleaning with 30kW~53kW power (33MHz, 1.0 x10^{-2} Pa) for 5 minutes between shots (1-sec pulse per every 10-sec) have been implemented.

5. 2. Experimental Results

Figure 9 shows the plasma shot log tested during the commissioning period. As shown in Fig. 9, it took about one week to seek the optimized current ramp-up condition. After several tens of breakdown shots, the first plasma of more than 100 kA was successfully achieved on June 13^{th} (shot 794). The detailed characteristics plasma parameters of shot 794 were described in Reference 8. ECH was very critical 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. 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 shown in Fig. 10. Maximum plasma current was 133 kA (shot 976) and longest plasma length was 862 ms (shot 1127).

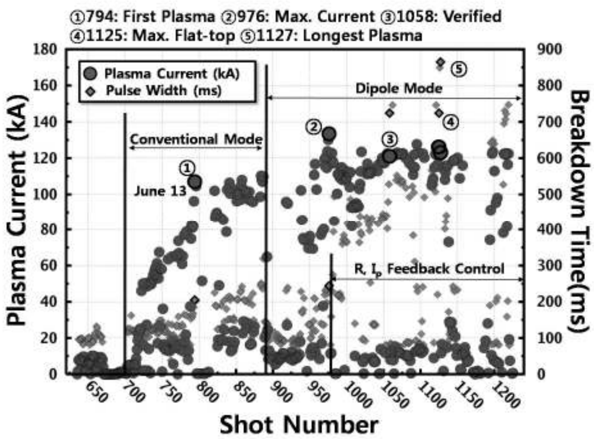

FIG. 9 Plasma shot log for the first plasma.

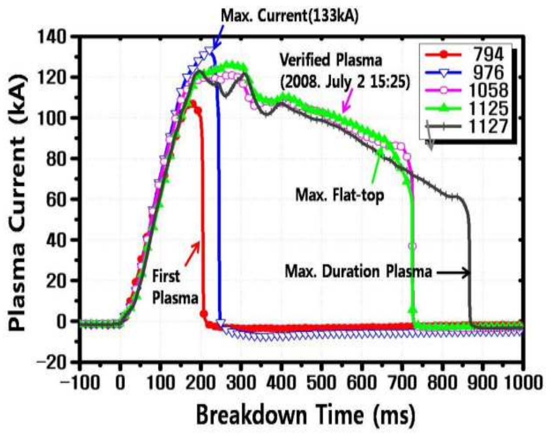

FIG. 10 Representative shots.

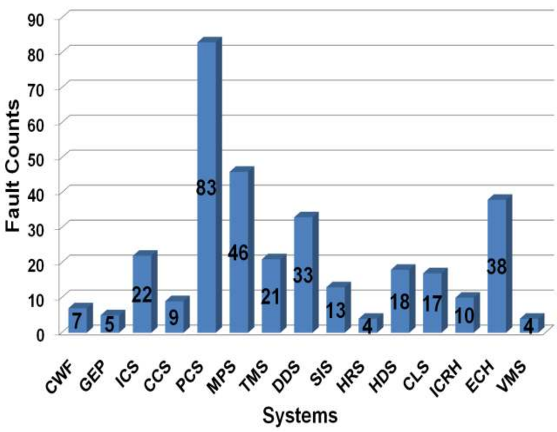

FIG. 11(a) Fault events during commissioning.

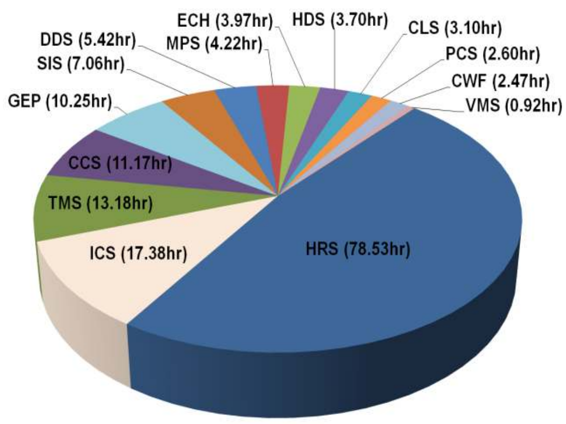

FIG. 11(b) Machine interrupt time.

6. Machine Failure Analysis

During 4 months of operation, 330 fault events occurred. These events included all possible failures, such as hardware malfunctions, software faults, electrical failure, operation mistakes, sequence violations, and so on. Figure 11 shows the statistics of fault events and interrupt time of individual sub-system. The major cause of interrupt was trip of helium refrigerator system. All other short interrupts were mostly caused by some signal processing and some sequence control. The recovery time for helium refrigerator system was relatively longer than the other ones. Despite of 330 fault events, total interrupt time is only 164hours, and all subsystems have operated successfully with the machine availability of 94 %.

7. Conclusions

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. In fact, in the first plasma commissioning stage, everything proceeded amazingly well. 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 success of the KSTAR can be contributed to its exhaustive quality control, meticulous inspection, and well-organized scheme. 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.

Acknowledgment

This work is supported by the Ministry of Education, Science, and Technology.

References

[1] OH, Y.K., et al., Commissioning and Initial Operation of KSTAR Superconducting Tokamak", 25th Symposium on Fusion Technology, 2008, O8-3.
[2] WEISEND, J.G., Handbook of Cryogenic Engineering, Taylor & Francis, 1998.
[3] KIM, K.P., et al., "Overview of the KSTAR Vacuum Pumping System", 25th Symposium on Fusion Technology, Rostock, 2008, P3-81.
[4] SA, J.W., et al., "Assembly results of the KSTAR CS Coil system", 5th IAEA TM on SSO, Daejeon, 2008.
[5] PARK, Y.M., et al., "Commissioning of the KSTAR Current Feeder System", Applied Superconducting Conference, Chicago, 2008, 3LPD08.
[6] YONEGAWA, H., et al., "KSTAR Magnetic Field Measurement during the Commissioning Results and Remnant Field Evaluation", Applied Superconducting Conference, Chicago, 2008, 3LPD05.
[7] BAE, Y.S., et al., "First Experimental Results on Second Harmonic ECH Pre-ionization and Heating KSTAR First Plasmas", US-EU-JPN RF Heating Technology Workshop, San Diego, 2008.
[8] KIM, W. C., et al, "Start-up of KSTAR Tokamak", International Congress on Plasma Physics, Fukuoka, 2008.