

## Commissioning Results of the KSTAR Superconducting Magnet System for the First Plasma Operation

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**Abstract.** The KSTAR device is a tokamak with a fully superconducting (SC) magnet system, which enables an advanced quasi-steady-state operation. Initial operation of the KSTAR SC magnet system has been accomplished for the first plasma discharge operation. The SC magnet system consists of 16 toroidal field (TF) coils and 14 PF coils, magnetic structures, SC buslines, current leads, and monitoring and protection system. One of the uniqueness of the KSTAR device is using the Nb<sub>3</sub>Sn superconductor both in 16 TF coils and in 10 PF coils except 4 PF coils made of NbTi. The objectives of the commissioning of the superconducting magnet are to verify the engineering reliability of all the superconducting magnets at the operating conditions and to develop the operational controllability for the successful plasma startup. The target parameters of the initial operation are TF coil current of 15 kA, PF coil current up to 4 kA and PF blip and feedback control using plasma control system (PCS).

All the superconducting magnets were operated reliable without any severe failure to preventing the first plasma operational target. The TF magnet was operated reliably up to 15 kA for 8 hours and the temperature rising of TF magnet is less than 0.1 K. There was no quench during operation including slow and fast discharges. As the PF commissioning, the controllability of each power supply has been tested by using dummy copper load and each SC PF coil. After the individual test of the PF coil and power supply, integrated control was accomplished for the field null formation and for loop voltage generation to meet the first plasma discharge. The ac losses of the several PF coils have been measured by applying the single trapezoidal current and dc biased sinusoidal current with various ramp rate. The hysteresis loss of PF1 coil was less than 180 mJ/cc and the time constant of the coupling loss was less than 50 ms after 500 pulse operations. The field distortion by the Incoloy908 material in the superconductor was measured and modification in the PF coil current scenario has been adopted also. By the feedback control of the plasma current and position, the plasma current could be sustained up to 860 ms under the limited volt second of 1.1 Wb.

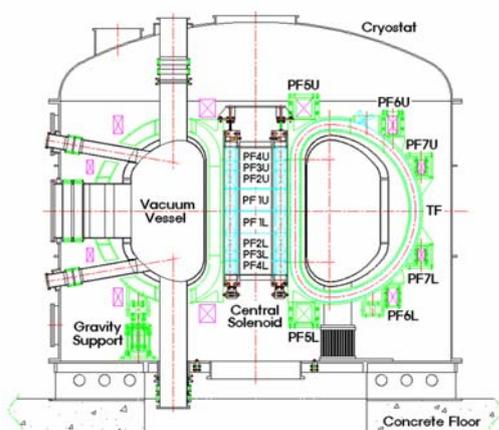


FIG. 1. Configuration of the KSTAR superconducting magnet system

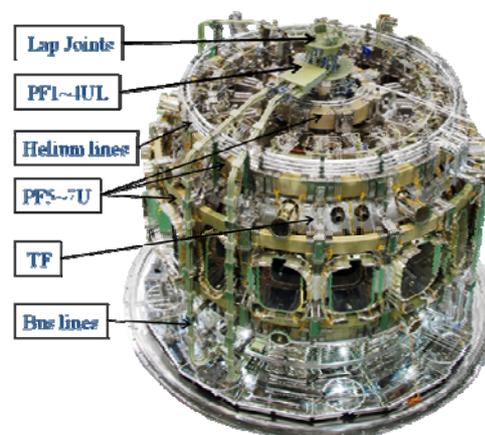


FIG. 2. Bird eye view of the KSTAR superconducting magnet system

## 1. Introduction

The KSTAR device is a tokamak with a fully superconducting (SC) magnet system, which enables an advanced quasi-steady-state operation [1, 2]. Initial operation of the KSTAR SC magnet system has been accomplished for the first plasma discharge operation. The SC magnet system consists of 16 toroidal field (TF) coils and 14 PF coils, magnetic structures, SC buslines, current leads, and monitoring and protection system. The TF coil system is designed to provide a magnetic field of 3.5 T at the plasma center, with a peak flux density at the TF coils of 7.2 T and the stored energy is 470 MJ. The nominal current of the TF coils is 35.2 kA with all the coils connected in a series. The PF coil system, which consists of 8 coils in the central solenoid (CS) coil system (PF1–4) and 6 outer PF coils (PF5–7), provides the plasma current of 2MA for 20 s, inductively. The TF and PF1–5 coils use Nb<sub>3</sub>Sn cable-in-conduit conductors in an Incoloy 908 conduit and PF6–7 coils use NbTi CICC in a stainless steel 316LN conduit [3]. The configuration and the bird eye view of the KSTAR magnet system are shown in Figures 1 and 2. In the initial operation phase, to reduce the burdens in the magnet system both in mechanical and in electrical, the target current of TF and PF coils were limited up to 15 kA and 4 kA respectively. ECH pre-ionization system was adopted to reduce the loop voltage required for the plasma discharge. The commissioning campaign consists of a set of performance-testing activities which verified sub-system operation and overall system integration. The objectives of the commissioning are to demonstrate that the performance tests and system checks are in accordance with the design specifications, that they meet the performance criteria, and to identify any issue that would prevent device operation and plasma experiments. In this paper, the commissioning results of the magnet system are introduced.

## 2. Commissioning before Magnet Cool-down

### 2.1. Field measurement in vacuum vessel

To investigate the electrical connection of each coil and to survey the magnetic field error inside vacuum vessel, field survey using hall probe array has been accomplished under the coil current up to 100 kA before the coil cool-down. When TF coil is charged, the measured field was almost same as the calculation, but for the single PF coil charged situation, the measured vertical field was about 30 % less than calculation. It comes from the field distortion by the magnetic material in TF coil winding, which are composed approximately 38 % in volume. While the TF magnets were charged up large currents, Incoloy 908 was magnetized in the toroidal direction, and its contribution to the poloidal magnetic field was highly reduced [4].

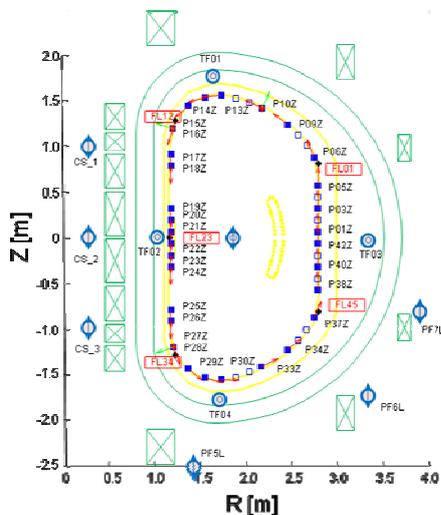


FIG. 3. Location of the magnetic field measuring sensors

### 2.2. Power supply control with dummy load

Each power supply has been tested for using the plasma control system (PCS) by connecting a

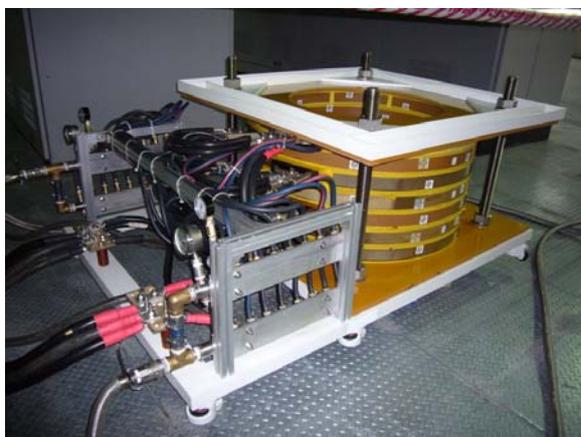
dummy copper load and each SC coil. Before the cool-down, a high-inductance dummy load with 29mH inductance and 50 m $\Omega$  resistance which consists of 7 circular solenoid coils stacked vertically and connected in series was prepared for single power supply qualifications as Figure 4. Using 4kA-capable blip resistor system (BRIS), the ability to adjust the slew rate of the coil current was tested up to -30kA/s for a 320V power supply. It has been found that the power supply is capable to adjust the coil current reduced up to -20kA/s during the blip phase by exerting additional (+) PS voltage to the load when the inherent  $dI/dt$  is about -30kA/s at the 3kA level. All the power supplies were tested one by one. Step response tests showed that there is a communication delay of 5 milliseconds in average.

To verify the mutual interaction issues of the strongly coupled solenoid coils, the electric connection of the 30mH dummy load had been changed: the first upper 4 rings were serially connected to the PF1 power supply and the rest 3 below them were connected to the PF3 power supply. The effect on the current control by the mutual inductance between loads could be measured. All the power supply operated reliable according to the PCS control command [5].

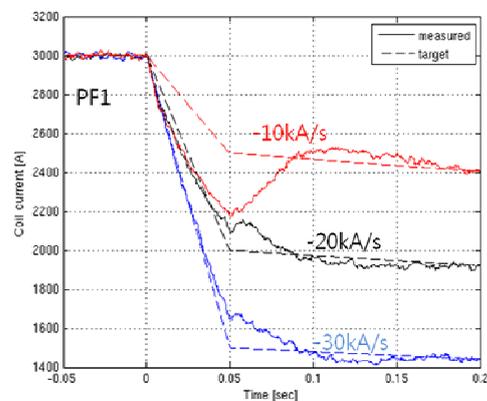
### 3. Commissioning after Magnet Cool-down

#### 3.1. SC magnet inspection

As standard procedures for coil inspections prior to the high current operation, superconducting phase transition measurements, joint resistance measurements, and coil insulation tests were conducted. Each coil resistance was monitored during cool-down. The relative resistance ratios (RRR) of all coils were over 100 and this meant that the copper in the superconducting cable could act as a stabilizer in case of coil abnormal operation. The superconducting phase transition also occurred at the temperature of about 18 K for the Nb<sub>3</sub>Sn coils and about 10 K for the NbTi coils. These results show that all the coils were superconducting and far from quench at the normal 4.5 K operating temperature. For the joint resistance measurements, a standalone power supply with a current rating of 1 kA was used. The resistance was calculated by slope measurements of the signals based on an applied current variation from + 1 kA to - 1 kA. For the TF joints, additional measurements were conducted using the TF power supply in the range of 10 kA. To eliminate the power supply's control signal noise in the measurement, the resistance was measured after the converter



(a)



(b)

FIG. 4. Dummy coil for the PF power supply performance validation (a) and the variation of the  $dI/dt$  by changing the additional converter voltage in PF power supply (b)

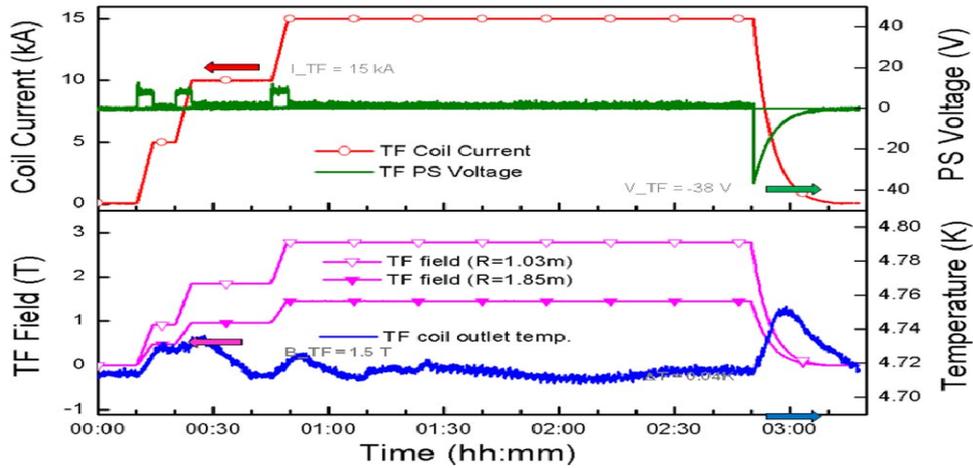


FIG. 5. Current operation and related temperature rising of the TF magnet system

turned off and the coil was in a persistent operation mode with slow current decay through the bypass diodes in the power supply. The measured results showed that the joint resistance was less than  $3 \text{ n}\Omega$ . The dielectric strength of each coil was measured before and after cool-down. The insulation was stable under a  $6 \text{ kV}$  test voltage.

### 3.2 TF magnet operation test

The TF magnet power supply uses an insulated gate bipolar transistor (IGBT) type convertor and has a rating of  $40 \text{ kA}$ . Since the IGBT convertor could not apply negative voltage, an additional slow discharge resistor was prepared for the current discharge of the TF coil after plasma experiments. For the initial operation the current of the TF power supply was tested up to  $15 \text{ kA}$ . As a protection system of the superconducting magnets, a quench detection system was developed. In the event of a quench occurring in the magnets, the quench detection system triggers a quench protection circuit inside the power supply.

The TF system was tested by increasing the current level in steps. Following step testing the TF system operated stably for 8 hours at  $15 \text{ kA}$ . The thermo-hydraulic and magnetic parameters also were measured for the operating conditions. Figure 5 shows the TF magnet operation features. The current was maintained at  $15 \text{ kA}$  for 2 hours and discharged using a slow discharge system. The magnet operated stably with the temperature rising less than  $0.1 \text{ K}$  during the current charge and discharge periods. The field inside the vacuum vessel measured by movable Hall probes was accurate within  $0.5 \%$  compared to calculations. The measured mechanical strain of the TF structure at a TF current of  $15 \text{ kA}$  was about  $210 \mu\epsilon$  and equivalent stress was about  $42 \text{ MPa}$ . From this result, the stress at the rated current of  $35 \text{ kA}$  was estimated to be about  $160 \text{ MPa}$ . If the  $93 \text{ MPa}$  stress measured during the cool-down is added, then the total stress is expected to be about  $253 \text{ MPa}$  at  $35 \text{ kA}$ . This is much less than the material operational criteria of  $700 \text{ MPa}$  and in accordance with the magnet design specification. The quench detection system also operated reliably. During the current charging and discharging time, the detected signal was less than  $25 \text{ mV}$  and well below the trigger condition of  $50 \text{ mV}$ ,  $2 \text{ s}$  [6].

### 3.3 PF magnet operation test

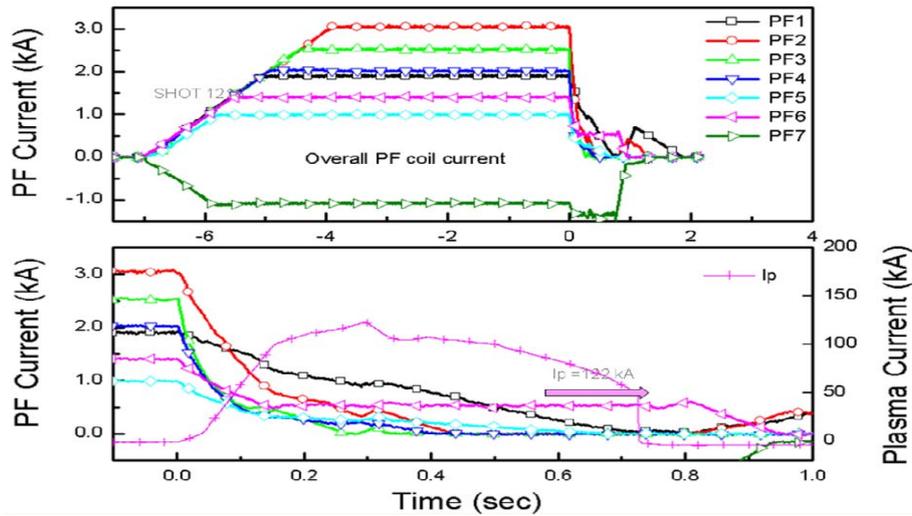


FIG. 6. Current operation and related temperature rising of the TF magnet system

After each power supply test using the dummy coil, a power supply test with the superconducting coils was conducted. Major test items were reference current controls, BRIS operation tests, adjustment of the current ramping speed, step response tests, and protection mode tests. During the power supply control tests, a magnetic diagnostic signal detection and analysis was also conducted. To analyze the Incoloy908 effect on the field with currents in the PF1 and PF7 coils, the magnetic measurements were compared with and without the TF current. The measurement results showed that the remnant field was about 40 Gauss in the case of zero TF current. But with 15 kA TF current, the remnant field was in the range of a few Gauss.

After the individual coil tests, an integrated test for 7 PF coils was conducted. In the initial operation, all the power supplies were operated in a unipolar condition. Figure 6 shows one of the power supply control signals for the plasma discharge. The overall current rampup was started about 7 s before the blip phase (BRIS active phase), and the blip duration was about 150 ms.

### 3.4 AC loss measurement

There are two kinds of ac losses, one is the hysteresis loss which depends on the material type

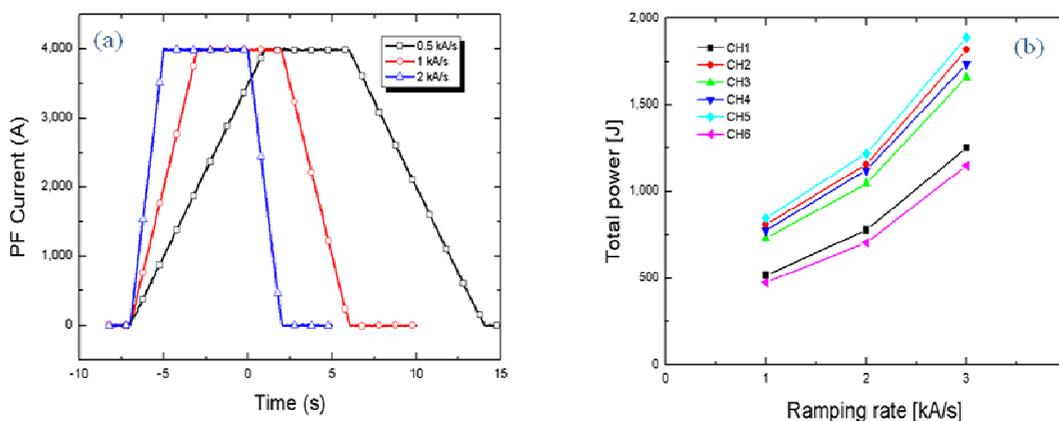


FIG. 7. AC loss measurement by changing the trapezoidal current ramp rate in PF1 coil

and the other is the coupling loss which depends on the inter-strand contact resistance and cabling. In an environment of slowly varying currents or fields, the hysteresis loss is dominant, but in an environment of high frequency currents or high field strengths, the coupling loss can be dominant. For KSTAR operation at currents up to 2 MA and long pulses up to 300s, the ac losses can be a very important factor in deciding the operational capability. Measurements of the ac losses in the KSTAR PF magnet system are difficult because of lack of installed sensors. So, two kinds of method for ac loss measurement have been conducted.

First one is a conventional measuring method using single pulse operation with trapezoidal waveform and integrated heating on each channel of the PF1 according to ramp rate variation as shown in Figure 7. By the results hysteresis loss of the coil was calculated to be less than 180 mJ/cc for +/- 1.3 T field swing. The effective Nb<sub>3</sub>Sn filament diameter is about 16 μm. The comparison of the coupling loss of PF1 was as follows, the coupling loss time constant,  $\tau$ , by trapezoidal method was about 62.5 ms at the initial operation time and about 50 ms after 2 month's operation. It could be expected that the mechanical detachment between strands from many pulses resulted in the reduced coupling loss. When the tests are at a low current of around 500 A, there could be uncertainties due to power supply controls or magnetic material effects.

So another method of ac loss measurement was developed which has been adopted in the KSTAR CS model coil [7, 8]. Figure 8 shows the current waveform for the PF1 AC loss. An AC current of 0.5 kA is applied for 600 s with a DC biasing current of 2 kA. The frequency was changed from 0.1 Hz to 0.2 Hz. The figure shows that thermal parameters reached a steady-state condition after 350 s. When compared with sinusoidal method, the measured time constant was about 35 ms. In the trapezoidal test, the error could come from the uncertainty at low current. Another interesting result is that the coupling time constant of the PF6 coil is also about 33 ms even though it has NbTi conductor. These results could come from the adoption of chrome coating on all three kinds of strands, Nb<sub>3</sub>Sn, NbTi, and copper. These results show that the KSTAR construction has advantages for various operational capabilities especially high speed PF6 coil operation as in the first plasma operation .

The superconducting magnet commissioning was completed without any severe problems in spite of the fact that individual cool-down tests were not conducted prior to assembly.

#### 4. Conclusions

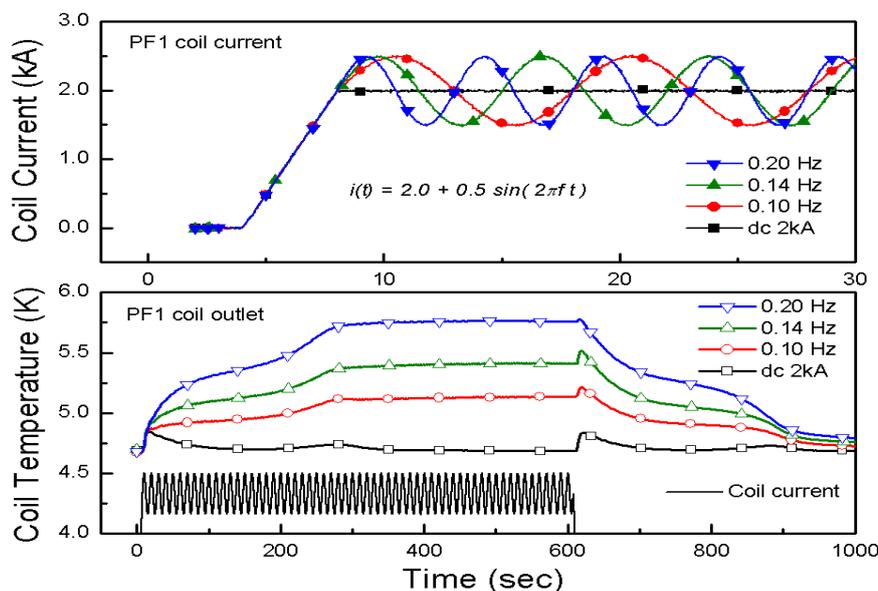


FIG. 8. AC loss measurement by changing the frequency of the dc biased sinusoidal current in PF1 coil

The commissioning of the KSTAR superconducting magnet was reliable without any severe failure preventing the device operation and plasma experiment. The key achievements of the initial operation of the superconducting magnets are as follows;

- The effect of the Incoloy908 material in the Nb<sub>3</sub>Sn superconductor was verified and the handicap for the plasma discharge was solved by the modification of the coil current scenario.
- All TF magnets were operated reliable in thermal and mechanical aspects at the current level up to 15 kA for 8 hours.
- Magnet power supply was operated reliable for the whole period of commissioning.
- The PF power supply control using the plasma control system was reliable for the single coil commissioning and for the integrated feedback control for the plasma discharge up to 860 ms.
- The ac loss measurement at the limited current shows that the ac loss was in the acceptable range and degradation of strand coating is negligible.
- Quench detection system based on the voltage measurement was operated reliable.

The reliability of the magnet system under the increased coil current will be measured according to the operational plan. In the next campaign, the magnet commissioning under the rated TF coil current of 35 kA will be conducted. The operation procedure and results of the Nb<sub>3</sub>Sn superconducting magnet could be the benchmark for the future superconducting tokamak device including the ITER.

### Acknowledgement

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### References

- [1] G. S. Lee, et al., "Design and construction of the KSTAR tokamak," Nuclear Fusion, vol. 41 (2001) 1515.
- [2] J. S. Bak, et al., "Status of the KSTAR tokamak construction," Fusion Engineering and Design, vol.81 (2006) 2315.
- [3] Y. K. Oh, et al., "Completion of the KSTAR construction and its role as ITER pilot device," Fusion Engineering and Design, (2008).
- [4] H. Yonekawa, et al., "KSTAR magnetic field measurement at room temperature and remnant field evaluation," submitted to ASC2008 conference and will be published in IEEE Trans. on Applied Superconductivity.
- [5] S. Hahn, et al., "Plasma control system for the day-one operation of KSTAR tokamak," submitted to 25<sup>th</sup> SOFT (2008) P3.23.
- [6] Y. Chu, et al., "Quench detection based on voltage measurement for the KSTAR superconducting coils," submitted to ASC2008 conference and will be published in IEEE Trans. on Applied Superconductivity.
- [7] Y.K. Oh, et al., "Status of the KSTAR superconducting coil fabrication and test," Proc. of fourth IAEA TM on SSO, PS-FT7 (2005).
- [8] S. Lee, et al., "AC loss characteristics of the KSTAR CSMC estimated by pulse test," IEEE Trans. on Applied Superconductivity, vol. 16 (2006) 771.