

CONFERENCE PRE-PRINT**PERFORMANCE OF JT-60SA SUPERCONDUCTING
MAGNET OPERATION IN INTEGRATED
COMMISSIONING TEST**

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Abstract

In the full superconducting tokamak JT-60SA, the first plasma was successfully realised during the first operation series. In order to obtain this result, the suitable operation procedure of magnet system, temperature and coil current control was essential. In the same experiment series, it was able to generate the plasma that has 1.2 MA of plasma current in maximum. However, PF coil current was up to 5 kA in this operation, and maximum currents were 10 kA in the single coil excitation test performed before the plasma experiment series. In the next operation series, the nominal current (20kA) operation will become the main purpose for PF coils system to produce the high-performance plasmas. Aiming to this, various improvement procedure was considered from the viewpoints of the procedure of energizing the coils, or the coil protection method.

1. INTRODUCTION

The JT-60SA tokamak has a full superconducting magnet system that consists of 18 Toroidal Field (TF) coils, four modules of Central Solenoid (CS), and six circular Equilibrium Field (EF) coils [1–4]. As shown in Fig.1, the superconducting coils surrounded by the thermal shields were installed in the cryostat. Around the cryostat, the components that cool the coils down were set, 5 current read boxes (CTB), 11 valve boxes (VB) and the cryo-line including the piping of coolant. The first cool-down operation of magnet system for an integrated commissioning test started in October 2020. The TF coil was operated in the nominal current (25.7 kA), and PF coils were operated up to 5 kA, individually. After EF1 incident had occurred in March 2021, we tried to increment the insulations of magnet systems, terminals, feeders, and current leads with high temperature superconductor (HTS-CL). After insulation work, we perform the global Paschen test (GPT) that was done after pumping the cryostat out and controlling the pressure inside the cryostat. If any discharges were observed, we tried to reinforce the insulation again and GPT was performed [5,6]. OP-1 was started after the several repetitions of insulation works and tests, the first plasma was successfully produced in October 2023. Operation of coils was also advanced in this series; TF coil that were already reached the nominal operation status was possible to be operated during several hours, and PF coils were 10 kA operation in the single operation, and 5 kA in the plasma operation. From early 2024, in-vessel component and additional heating system are being installed in JT-60SA to produce the high-performance plasmas with 5.5 MA of plasma current and D-D operation. For this purpose, nominal operation of PF coils, 20 kA of maximum current, is necessary. To achieve the nominal current operation in the next campaign (OP-2), we are trying to take some action, especially the improvement of safety of devices.

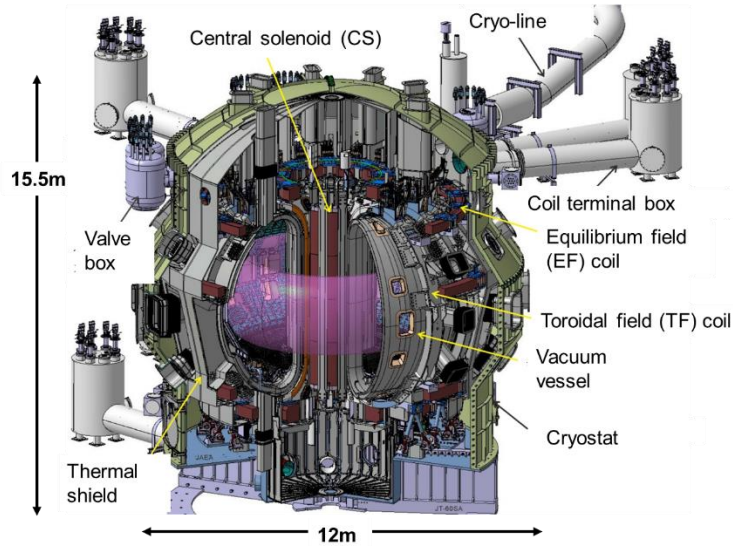


FIG. 1. The schematic view of the magnet system and the concerning equipment in JT-60SA.

2. INTEGRATED COMMISSIONING ~ OP-1 SERIES

2.1. Energization tests of coils after first cool down

From October 2020, as the integrated commissioning of JT-60SA tokamak, the first cool-down test was started, and operation of power supply and coil energization tests were performed after it was confirmed that all coils became superconducting state. In early 2021, TF coil was successfully operated in 25.7 kA [5,6].

In this series, displacement of TF coils was observed. Fig.2 shows the distributions of radial displacement of TF coil case. In the case of 25.7 kA, radial displacement became around 8 mm. This value was near the estimated value by FEM calculation, 9.1 mm. TF coil consists of two parts, coil case and OIS. During TF coils excitation, radial displacement of TF case induced by the hoop force was absorbed by the slipping into OIS. In this structure, OIS was not moved during coil energization, so that splice plates between OIS to fix the TF coils did not receive the large stress due to the hoop force. the displacement of OIS was small. Therefore, there is no inconsistency between the mechanical stiffness of the real TF coil system and the designed one.

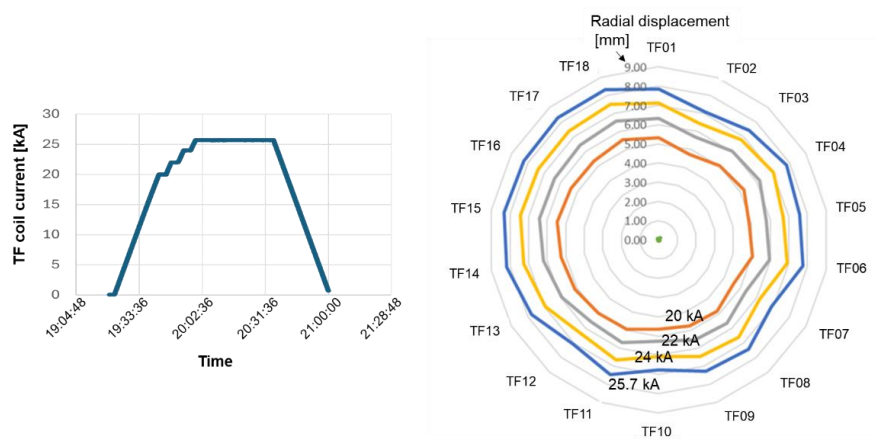


FIG. 2. Time evolution of TF coil current and the displacement of TF coils in the experiment of TF coil energization.

Energising test of PF coils was also performed till 5 kA. However, this commissioning campaign was terminated due to the short circuit incident at the terminal of EF1 coil during EF1 operation [7]. From August 2021, we started to enhance the insulation structure of terminals for every coil to rise Paschen tightness. 36 joints of TF coils, 48

joints of CS/EF coils and feeders were targets, and HTS (high temperature superconductor) current leads (26 locations) were also enhanced. Every joint has cable extraction part for the quench detection, so that these parts were filled with charged resin. After this series of work, summer 2022, we carried out GPT was carried out after pumping out inside the cryostat. In this period, other weak points were found into the parts of coils, cooling pipes, feeders, and conductor extraction parts, so that insulations of these points were additionally enhanced aimed to OP-1 including the first plasma production.

2.2. OP-1 series

The 2nd cool-down operation of the magnet system started in June 2023 as the start of experiment series OP-1. To mitigate forces due to thermal contraction difference, temperature of the magnet system should be controlled to keep the temperature difference among magnets less than 10K during cool-down operation. The temperature indicated in Fig.3 is a calculated temperature from magnet winding resistance. The temperature differences of each magnet system, TF coils, EF coils, and modules of CS, are successfully operated within the criteria as summarised in Table 1 [8–11].

TABLE 1. MEASURED DIFFERENTIAL TEMPERATURE IN THE GROUP OF CS, EF AND TF COILS DURING FROM 300K TO 80K.

Coils	Measured value	Allowable value
CS1~4	5.0K	< 10K
EF1~6	7.1K	< 10K
TF1~18	5.6K	< 10K

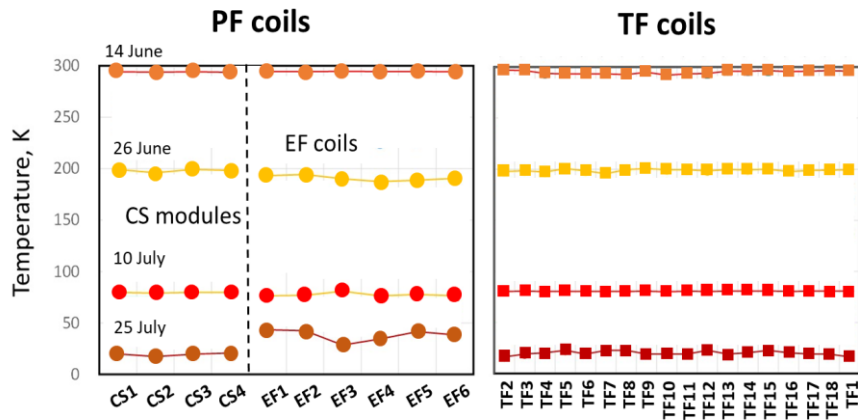


FIG. 3. Time evolution of temperatures of each coil during 2nd cool down.

In this series, single coil energising test of PF coils was performed up to 10 kA which is half of the nominal current. These tests were not performed for EF2 and CS3 coils due to the problem of insulation.

In order to expand the operating area to the nominal current, it is important that the mechanical strength as designed is guaranteed. For this purpose, the deformation of the coil due to the hoop force induced by the coil energization was measured by the displacement gauge installed on each PF coil, and it is confirmed that the mechanical stiffness was as designed by comparing it with the calculated evaluation.

Each EF coil has the radial displacement gauges that were installed every 120 degrees in three TF coil sections (TF01, TF07 and TF13). Since all PF coils are installed on TF coils, the measured displacement is relative to the TF coil. To ensure the redundancy, two displacement gauges are installed in each location. The support of the displacement gauge is set on the TF coil side, and the needle tip of the measuring element touches the support structure (clamp) of the EF coil. The coil is deformed by the electromagnetic force caused by the magnetic field created by itself or other coils during energization. In the case of a single energized body, the amount of deformation is only the radial displacement caused by the hoop force.

At the top of the CS assembly, the displacement gauges are installed in the same sections as the gauges for the EF coils to measure the displacement in three directions: radial, toroidal, and vertical. When the winding pack of a CS module widens radially by its own hoop force, the energized module shrinks in the vertical direction due to the Poisson effect. Here, vertical displacement values are adopted to evaluate the deformation of a CS module.

The results of the displacement measured in the single coil excitation tests of EF1 coil, EF6 coil and CS1,2,4 modules are shown in Fig.4. The calculated displacements of each PF coil were evaluated by the finite element method (FEM) model. Since the displacement is depended by the hoop force that is proportional to the square of the coil current, the calculated value is expressed as a quadratic curve of the coil current. All coils show that are quite close to the measured displacement and the calculated values represented by solid lines.

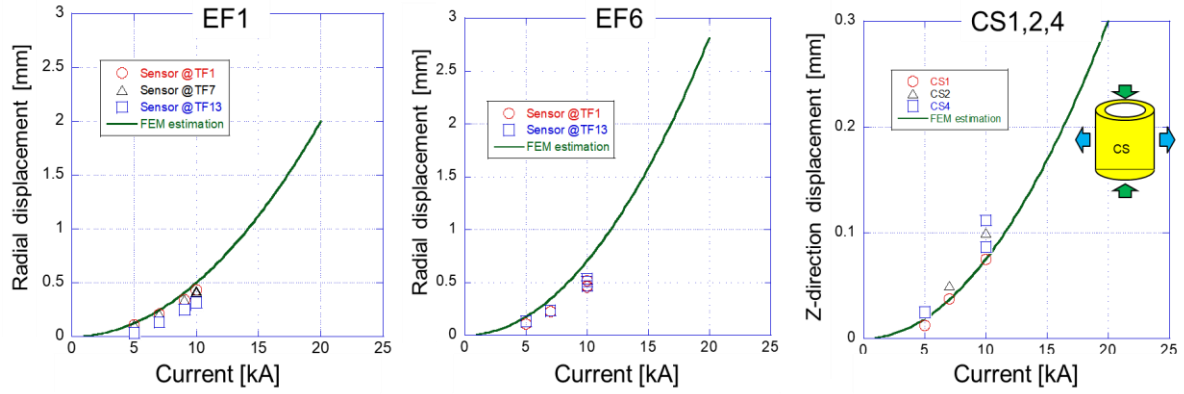


FIG. 4. Radial displacement of EF1 and EF6 coils and z-direction displacement of CS in the series of the single coil excitation test. Solid line shows the prediction of the displacements estimated by FEM.

For the plasma operation of OP-1, the mixture operation of TF and PF coils was performed, and the first plasma was successfully produced. In this series, toroidal deformation of TF coil induced by the over-turning force was observed as shown in Fig.5. There are 3 toroidal displacement gauges in the TF coil system. Measured value of the toroidal displacement was match the calculated value by FEM.

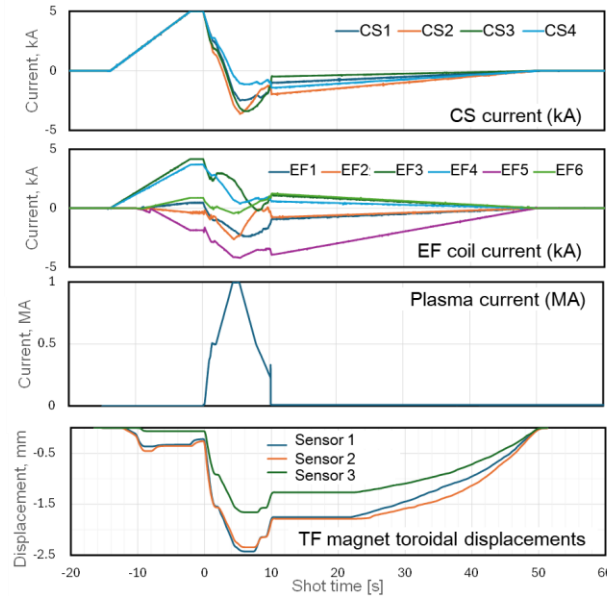


FIG. 5. Time evolution of PF coil and plasma currents and the toroidal displacement of TF coils in a plasma shot in the case of 23.3kA of TF coil current.

During OP-1, the current of PF coil was limited to 5 kA, which is 1/4 of the nominal current, and the magnetic flux that could be supplied was also 1/4 of the rated flux. The plasma current could also reach up to 1.2 MA,

which is roughly 1/4 of the rated 5.5 MA. Since it was possible to realize a plasma current proportional to the amount of magnetic flux, it was shown that the JT-60SA was able to operate as designed. By operating the coil up to 20 kA in the next operation series (OP-2), the careful operation will be needed because the realised operational area is still limited as shown in Fig.4.

3. IMPROVEMENT OF THE CONCERNING EQUIPMENTS AIMED TO 20KA OPERATION OF PF COILS

For the operation in the nominal coil current in the next campaign, we are trying the following actions.

- Enhancement of insulations of joints and He inlets of EF coils
- In-situ insulation reinforcement of He inlets/outlets on CS modules
- Revised the controller of the quench detection (QD) system.
- Installation of the cold cathode gauges (CCG).
- Decreasing the voltage during the coil operation.
- Coil operation scenario in the single energization.

3.1. Enhancement of insulations of joints and He inlets of CS and EF coils

We could realize the first plasma and MA-class plasma under the condition that the operation voltage was limited in the basis of the result of the global Paschen test (GPT) performed before OP-1 series. The operation current was also limited due to the allowable voltage. In the next series, the PF coils will have to be operated up to the nominal current, so that it is necessary to increase the insulation performance of PF coils.

3.1.1. EF coils

To increase the insulation performance, especially Paschen tightness, we carried out the insulation enhancement for the casing of pancake joints (PJ) of EF1, EF2, and EF3. In addition, the inlets of EF1, EF2, EF3, and EF4 were also performed. PJ of EF4, EF5 and EF6, and inlets of EF5 and EF6 was not done because these locations were hard to access and Paschen tightness of EF4,5,6 was relatively better than the other coils. Pancake joints were covered with FRP plates to protect the joint parts, but these locations were doubtful that Paschen tightness was not enough. We mainly used the charged resin to fill the electrical path to avoid the discharge under the Paschen condition.

The reinforcement procedure of the inlets was (1) additional GK tapes were wound around the piping that was extracted from the winding pack, and (2) the charged resin was installed (plastering) around the inlet and elbow parts of the extracted piping.

For the reinforcement of the PJs, we passed the following steps:

- (a) Step 1 : FRP plates that consists of several parts was unified with Glass and GK sheets.
- (b) Step 2 : Gaps between each FRP plates was filled by the charged resin. (plastering)
- (c) Step 3 : Gaps between winding pack and FRP plates was filled by the charged resin. (mould casting)
- (d) Step 4: Overlapping Glass/GK sheets was installed between the winding pack and FRP plates to unify the winding pack and FRP plates.

The examples of insulation reinforcement are shown in Fig.6.

3.1.2. CS module

In the period of the global Paschen test performed before OP-1, we found the discharge points on the surface of CS module. To resolve this problem, the method of the enhancement of insulation had to be considered. As an “in-situ” work, we applied the method that resin was splayed on the surface of the targets to fill the electrical path. The number of targets were 100 locations of He inlets/outlets and 21 locations of the cable extraction part. For the cable extraction parts, the charged resin was also installed before the splay work. From April to July, this work was performed, and we confirmed that all targets were covered by the resin by checking with the endoscope.

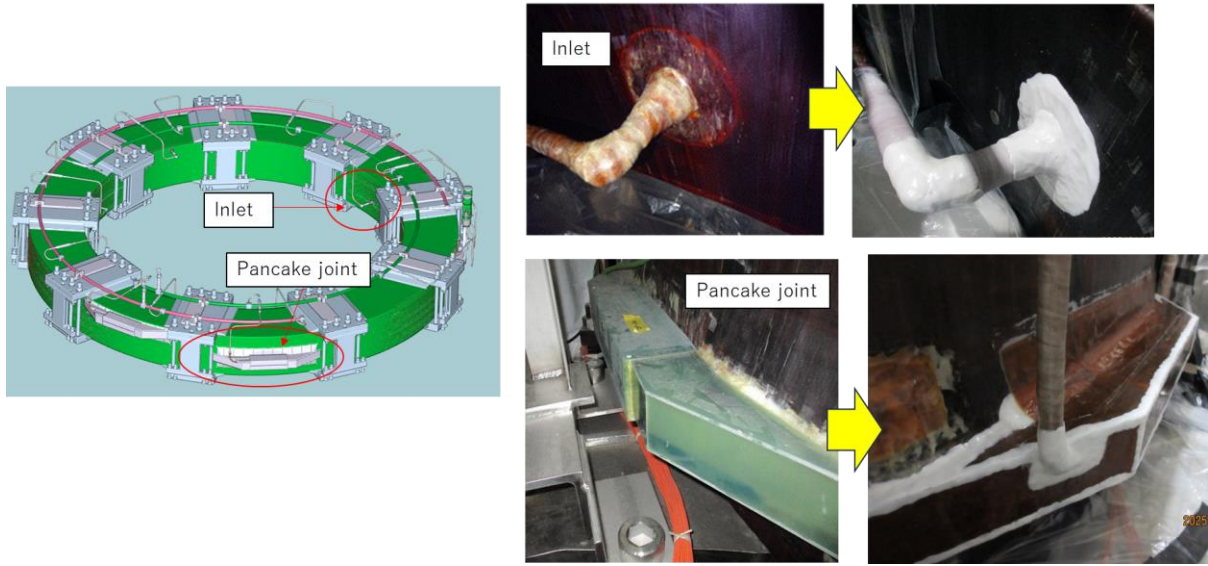


FIG. 6. Examples of insulation reinforcement with the charged resin against a He inlet (upper) and a pancake joint cover (lower) for EF coil.

3.2. Devices for the coil protection

It was tried that the coil protection devices were also improved aimed to 20 kA operation of PF coils.

The quench detection (QD) system was one of the important tools of the coil protection. In the PF coils, the pickup coil was set into the winding pack, and a bridge circuit was applied to cancel the difference between the inductive voltage generated in the coil and detects the resistive voltage. Two types of variable resistors were prepared: a coarse resistor with a fluctuation range of 0-100 k Ω and a fine-tuned resistor with a range of 0-1 k Ω . Adjustment of them was remoted from the outside of torus hall where is the radiation control area. During the coil energization test before OP-1 series, as shown in Fig.7, the balance of voltages became good for all PF coils when the coil current lineally changed [12]. However, relatively large noise remained when second-order differentiation about time of coil current did not become zero. To resolve this, variable capacitors are additionally installed in the filter part of the operation amplifier of QD system as shown in Fig.7, and these variable capacitors are also possible to be controlled remotely. Recently, we checked the signals for the test amplifier system that this improvement was adopted, so that we could get perspective to cancel the spike noise [13].

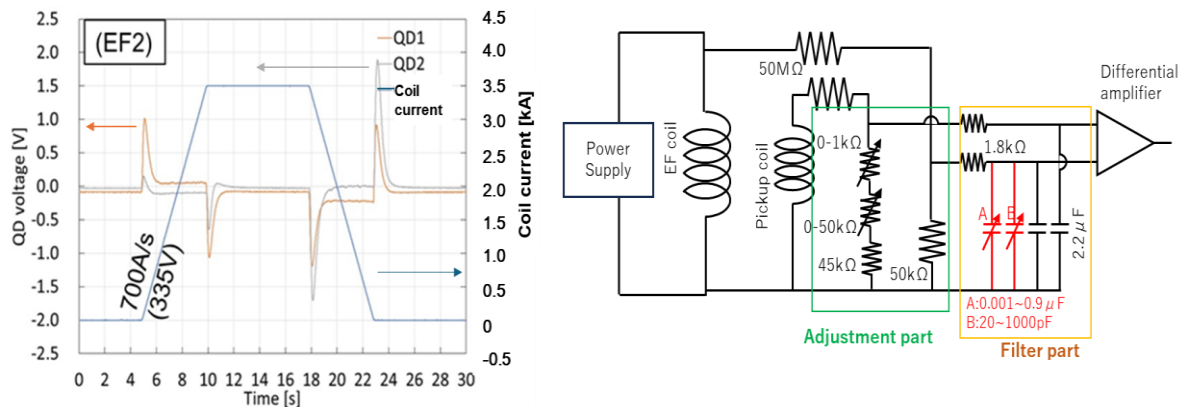


FIG. 7. Signal of QDs during the adjustment during a coil excitation (left). Schematic diagram of the circuit of QD amplifier (right).

As another device to protect the magnet devices, the cold cathode gauge (CCG) is installed to monitor the situation of vacuum in the cryostat [14]. CCG is able to be operated in the cryogenic temperature, so that this device is adopted for the interlock before the pressure around the superconducting coils raise to the Paschen condition

induced by any leakage incident. In OP-1, 10 locations of CCG were installed in the upper side of cryostat, mainly around EF coils, and 11 gauges of them were installed in the lower side of the cryostat. From OP-2, 12 gauges will be placed on upper and lower sides of the cryostat. In addition, 5 gauges will be installed in each CTB [15].

3.3. Operation of PF coils

In OP-2, every PF coils will be tested under the condition of nominal current. These tests will be performed with the single coil. For each coil, its current will be increased gradually up to 20 kA. After a series of current condition, HV test will be done to confirm that the coils have no damage. In this series, movement of coils will be monitored to confirm that no mechanical problems occur in the energized coil.

As a future work, for the power supply of the coils, dumping resistance of the protection circuit will be revised to decrease the over/under shooting of current. Therefore, the voltage during the coil operation will be decreased. This will create a margin in the operation voltage and expand the range of plasma operation, as well as the reinforcement of insulation.

4. SUMMARY

The first plasma in JT-60SA was successfully achieved in 2023. Most of PF coils was successfully operated with 10kA in maximum. Recently, upgrading work is in progress toward the operation of high-performance plasmas. In order to realize this purpose, nominal current operation is needed for PF coils, so that we are trying the following actions:

- Enhancement of insulations of joints and He inlets of PF coils are progressed.
- For QD system, we have the prospect of cancelling out the remaining noise by adding the capacitor.
- To keep the safety of the magnet system, CCG additional installation is performed.

In the next experiment series (OP-2) that will be started in 2026, currents of PF coils will be gradually increased with monitoring the coil deformation, and HV test for a PF coil will be performed after each step of current of PF coils.

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