Superconducting magnet control system of the JT-60SA

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Abstract. The JT-60U is being upgraded to a full-superconducting tokamak referred as the JT-60 Super Advanced (JT-60SA) as one of the JA-EU broader approach projects. JT-60SA will use superconducting magnets to confine the plasma and achieve a plasma current with flat top durations of up to 100 seconds. JT-60SA magnets are cooled by a helium refrigerator, whereby the local flow control is done by a “magnet controller”. During cool down of the JT-60SA, the TF winding pack (WP) and the TF case are connected in series. Since the winding packs of the TF coils (TFWP) has rather high pressure loss, part of the helium flow from the refrigerator needs to bypass them and supplies directly the TF cases and support structures. The magnet controller controls the distribution of the flow. During nominal operation, 876g/s helium are supplied to the TFWP, which is too large for TF case. By introducing a bypass valve for TF case, about 0.1 MPa pressure loss can be saved. Finally the magnet controller has to react on off-normal situations for fail safe operation.

1. Introduction

The JT-60U is being upgraded to a full-superconducting tokamak referred as the JT-60 Super Advanced (JT-60SA) as one of the JA-EU broader approach projects[1]. JT-60SA will use superconducting magnets to confine the plasma and achieve a plasma current with flat top durations of up to 100 seconds in purely inductive mode. The JT-60SA refrigerator will provide supercritical helium at 4.4 K for the superconducting toroidal (TF) field and poloidal field (PF) magnets, 50 K for High Temperature Superconductor Current Leads (HTS-CL), 80 K for Thermal Shields(TS), and 3.7 K supercritical helium for the divertor cryopumps (CP)[2]. During typical plasma discharge scenarios magnets currents have to be ramped and controlled, helium pressures and flow rates in the cooling loops of the coils and structures have to be adjusted and temperature stability of several components has to be supervised. In abnormal situations the magnet system has to be discharged quickly and brought to a safe condition.

A supervising system called “magnet controller (MC)” is being developed to perform an efficient operation by cooperative control together with the refrigerator.

One of the main control functions of the MC is the smooth cool down of the magnet system. During the cool down, temperature differences between different sections of the magnet system and the structures must stay within certain limits and the cooling requirements have to match the refrigerator’s capacity. Helium flow rates have to be split and distributed to the different JT-60SA loops in proportion to the their masses and specific heat capacities.
In case of quench or a command for fast discharge, of a coil the MC triggers the ramp-down of the coil currents by passing the quench signals from the quench detectors to the Supervisory Control System and Data Acquisition System (SCSDAS) and in parallel to the refrigerator system. In this contribution, the current status of the development of the magnet controller is presented.

2. JT-60SA superconducting magnet system

Figure 1 is a whole view of the JT-60SA with the cryogenic users. Figure 1 is a whole view of the JT-60SA basic device. The JT-60SA superconducting magnet system has 18 TF magnets, 6 Equilibrium Field (EF) magnet, 4 modules of Central Solenoids (CS) also shown in Figure 1[3]. All magnets are cooled at 4.4 K and thermally protected by 18 thermal shields cooled at 80 K. 26 HTS CL are used for all magnets with reduced heat load compared to conventional CL. The JT-60SA also has 9 divertor cryopumps cooled at 3.7 K. The whole JT-60SA cryostat is 11.5 m in diameter. Table 1 shows a breakdown of the JT-60SA superconducting magnet system with weights and materials. The refrigerator which will supply helium to the system is already installed on-site and has successfully passed acceptance tests in November 2016.[4]

Table 1. Breakdown of JT-60SA superconducting magnet system.

| Cryogenic user | TF (structure/WP) | EF (structure/WP) | CS (structure/WP) | total | Cryo pump | TS |
|----------------|------------------|------------------|------------------|-------|-----------|----|
| Weight(ton)    | 280/100          | 33/60            | 64/114           | 650   | 1.3       | 100|
| Material       | Stainless steel/Cu | Stainless steel/Cu | Stainless steel/Cu | Stainless steel/Cu | Stainless steel | Stainless steel |
3. Magnet controller

Figure 2 shows the JT-60SA refrigerator process together with all cryogenic users. The JT-60SA refrigerator uses liquid nitrogen pre-cooling and 3 turbines. The refrigerator has a 7 m³ liquid helium damper to smooth pulse heat loads from repetitive plasma shots. It also has another damper supplying the cryopump at 3.7 K, which is evacuated by a Very Low Pressure (VLP) vacuum pump. As shown in Figure 2, the JT-60SA refrigerator supplies helium to five loops, the TF loop (loop1), the PF loop (loop2), the TS loop (loop4), the HTS loop (loop5), and the CP loop (loop3). There are 2 circulators equipped with the refrigerator for the TF loop and the PF loop.

The first function of the magnet controller is the local flow control in the TF loop and the HTS loops, in which the refrigerator and the magnet controller share global and local flow control. In particular, during cool down, the TF loop flow is split into 2 flows by a bypass valve, and the magnet controller controls the mass flow through the bypass valve. A second function is to reduce the pressure loss of the TF case in nominal pulse operation by opening another bypass valve. A third function of the magnet controller is PID control of the HTS-CL return temperature at 290 K and the warm end temperature of the HTS section at 60 K. A fourth function is a transmission of interlock signals from quench detectors to the SCSDAS. The magnet controller transmits a TF or PF quench signal for fast discharge to the SCSDAS to demagnetize the corresponding magnet. The fast discharge demagnetizes a TF and PF magnet in about 10 seconds to result in temperature rise of the magnets.

The magnet controller may also request a slow discharge of TF and PF coils in case of less severe faults such as poor vacuum and refrigerator fault. A slow discharge demagnetizes a TF magnet in 20 minutes. The last function of the magnet controller is to open pressure relief valves when magnet pressure reaches 1.8 MPa after a fast discharge so that warm helium gas can exhaust to the 250 m³ quench tank.

Features of the magnet controller are 1) achievement of an efficient cooling sequence to cool down the TF magnet by controlling the TFWP bypass valve, 2) reduction of TF case pressure loss by the TF case bypass valve. 3) redundant design of quench detectors and detection circuits to secure reliability, 4) trigger of slow discharge as much as possible before fast discharge is triggered by

**Figure 2.** A schematic of the JT-60SA refrigerator and cryogenic users. Devices surrounded by heavy lines are the local target devices which the magnet controller will control.
quench to minimize the magnet temperature rise, allowing fast recovery of the superconducting magnet system for the next pulse operation.

4. Cool down of the magnets
The JT-60SA refrigerator is designed to cool down magnets and the thermal shields in 21 days as shown in Figure 3. One condition is that during the cool down the temperature of the magnets shall be lower than the thermal shield by 20K - 50K in order to trap all impurities on the colder surfaces and maintain the emissivity of the polished TS surface. The second condition is that the temperature differences across different points of the magnet system and its structures shall always stay below 40 K to avoid excessive thermal stresses.

Figure 4 shows the variation of the total mass flow from the refrigerator, and its distribution to the TF magnets, PF magnes and the TS. The mass flow varies in respond to the required cooling speed shown in Figure 3. At ambient temperature, no helium is supplied to the TS due to the emissivity requirement. The helium supply of the TS starts on day 9, and increases with time.

5. Cool down of the TF
Unlike the other loops such as the PF coils and TS, the TF loop has an unique flow schematic. The TF coil consists of the TFWP and the TF case as shown in Figure 5. In order to keep good thermal contact, the TF case has to be firstly cooled to keep applying the pressure towards the TFWP from the TF case. Since the JT-60SA refrigerator has only one circulator for the TF loop, a routing of the flow as shown in Figure 6 is one of solutions to meet this requirement. The magnet controller splits the total mass flow from the refrigerator to the TFWP and the TF case by controlling the bypass valve. At ambient temperature when the cool down starts, the total flow from the refrigerator can not pass the
TFWP due to its large pressure loss. The magnet controller bypasses the excess mass flow by opening the TFWP bypass valve. When the TF is getting colder and its pressure loss is reduced enough, the TFWP bypass valve will be fully closed.

6. TF bypass flow calculation
TF bypass flow is calculated by calculation of maximum mass flow which can pass the TFWP at each temperature. To calculate the mass flow, an empirical friction factor for the JT-60SA TF magnet was used[5]

\[
f = \frac{1}{\text{void}^{0.72}} \left( -0.1023 + 11.5488 \text{Re}^{-0.5523} \right)
\]

where void is void fraction, and Re is Reynolds number.

The mass flow is, then, calculated by formula below

\[
\dot{m} = \sqrt{\frac{2 \rho_{he} A^2 D_h \Delta P}{f L}}
\]

where \(f\), \(L\), \(m\), \(\rho_{he}\), \(A\), \(D_h\) are the friction factor, length of cooling path of conductor, mass flow rate, helium density, cross sectional area, and hydraulic diameter, respectively. In the calculation, the inlet and the outlet pressure was fixed at 1.0 MPa and 0.5 MPa at all temperatures. Parameters used for calculation are shown in Table 2.

| parameter | Value |
|-----------|-------|
| void      | 0.32  |
| A         | 1.26*10^{-4} m² |
| D_h       | 4.54*10^{-4} m |
| L         | 114 m   |

![Figure 6. Bypass valve position in TF loop at start of cool down, and end of cool down.](image)
Calculation results are shown in Figure 7. At the start of cooling at ambient temperature, the TFWP can take only 1/3 of the total flow. The maximum mass flow through the TFWP increases with decreasing temperature. At 80 K, the TFWP maximum flow is equal to the total mass flow. Below this temperature, the TFWP bypass valve is fully closed.

7. Reduction of TF case pressure loss

The TF loop(loop1) has another valve in parallel to the TF case as shown in Figure 8. During the cool down, this valve will be kept closed. In nominal mode, however, much larger amount of mass flow than that of cooling down is supplied to the loop by a circulator. The TFWP is able to take whole flow of 876g/s with the TFWP bypass valve closed at 4.4 K with allowable pressure loss. In a straightforward way, the whole flow can be passed to the TF casings and structures, but the TF case only needs about 1/5 of the whole flow to absorb the heat load. Because there is no need to create excess pressure loss, a dedicated bypass valve called TF case bypass valve is introduced. This valve bypasses 696g/s flow leaving only 180 g/s to the TF casings and structures. By using this valve the pressure loss can be reduced from 120 kPa to 10 kPa during the pulse operation.
8. Control of HTS-CL

The third function of the magnet controller is mass flow and temperature control of the high temperature superconducting current lead (HTS-CL) as shown in Figure 9. The choice for HTS-CL was made to keep the refrigeration load low.

The helium for the HTS CL is provided by the refrigerator at a pressure of 0.4 MPa(a) and a temperature between 48 K and 52 K. The flow rate is controlled at the warm outlet of the current lead by the valve 1. The criterion for the flow control is to maintain the upper end (T2) of the HTS section at around 60 K. The temperature of the warm contact (T1) is controlled to about 290 K by a heater to avoid freezing.

The 50 K control philosophy is different for TF current leads and PF current leads:

- **TF current leads:** During short time standby mode (STM) of the magnet system the flow is maintained at 0.6 g/s. This mode requires the largest heater power to keep the warm end at ambient temperature. When the TF coils are energized the flow is controlled in proportion of the TF current up to the nominal flow of 2 g/s for a current of 25.7 kA. The heater power will be reduced accordingly.

- **PF current leads:** As EF and CS coils are not energized most of the operation time, the mass flow may be kept constant independence of the average current in the PF coil. In practice this flow will be close to 0.6 g/s. During plasma pulses, the PF currents vary within about 200 s. Due to the thermal inertia of the copper heat exchanger of the current leads the mass flow need not to be increased. The heater at the warm connector is activated to keep it at about ambient temperature.

9. Transmission of interlock signals

Figure 10 shows the flow of signals when a quench is detected together with reaction of the refrigerator. In a normal operation, the refrigerator circulates the flow in the loop1. When the quench is detected, quench detectors send the quench signal to the magnet controller. Subsequently, the magnet controller passes the quench signal to the SCSDAS which will eventually command the power supply to trigger fast discharge. At the same time, the magnet controller will send the command to the refrigerator, which will open the bypass valve and close the inlet and outlet valve to the coils to isolate them. To increase reliability, the quench detector and its cabling are redundant as shown in Figure 10. The quench detector (2) will send the quench signal directly to the power supply by a different route from quench signal (1) bypassing the magnet controller.
10. Summary
In the JT-60SA, refrigerant control is shared by the refrigerator for global control and by the magnet controller for local control. In particular, in order to increase cooling efficiency during cooldown and nominal operation of the JT-60SA, two bypass valves were introduced. The maximum flow for the TFWP was calculated applying experimental measurements to specify the size of the TFWP bypass valve.

The control logic of the HTS-CL is different for TF and PF coils. A key of the control is that the mass flow rate can be the constant even for PF during the pulse operation in which the current changes rapidly.

Finally, the magnet controller performs the signal transmission and reaction of the refrigerator in case of a quench, and controls proper reaction of the refrigerator system. Reliability of the magnet controller for quench detection is ensured by a redundant design. The two redundant quench signals follow different signal routes; one goes to the magnet controller; the other goes directly to the power supply to secure reliability.

11. References
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Figure 10. Signal flows and reaction of the refrigerator when quench occurs. Quench detectors and signal circuits are redundant.