Performance of the LHD cryogenic system during cooling and excitation tests

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***Abstract*—Performance of the LHD cryogenic system in the first year's operation was described making importance on the recovery process after the normal transition of the helical coils. During the excitation tests of the LHD superconducting coils up to 2.75 T, the normal zone propagation was observed in the helical coil and the emergency shut-off of the coil power supplies was carried out. 2,700 ℓ of liquid helium evaporated from the helical coils. The coils and the helium refrigerator were separated automatically and the helium refrigerator could keep its steady state operation. After the pressure and flow rate of the recovery gas from the helical coils were settled down to the normal state, the coils were connected to the helium refrigerator and the cooling was restarted. The system could return to the steady state in which coil excitation is enabling, by only three and a half hours.**

***Index Terms*—cryogenic system, superconducting coils, large-scale, LHD, emergency**

I. INTRODUCTION

The Large Helical Device (LHD) is a superconducting, heliotron type, experimental fusion device, which has the feature of current-less and steady state plasma confinement. The construction of LHD was completed by the end of 1997 as an eight-year project for the phase I experiment [1]. The LHD cryogenic system succeeded in 6400-hours operation in the first year, and proved its high reliability [2].
The first cycle operation of LHD started on February and ended on June in 1998, and the second cycle operation started on August and continued to the end of 1998. Each cycle consists of a purification, cool down, steady state, and warm-up operation. It took 670 hours for 1st cycle and 569 hours for 2nd cycle to cool down the total cold mass of 822 tons at 4.4 K and 34 tons at 80 K.

The plasma experiment was started on March 31, 1998 as planned. Two experimental campaigns were successfully completed in 1998. The numbers of coil excitations and plasma discharges were 252 and 7132, respectively. High-performance plasmas with temperature as high as 2 keV and energy confinement times as long as 0.23 seconds have been achieved by neutral beam heating. Long pulse operation has also been explored up to 22 seconds for neutral beam heated plasmas and 2 minutes for electron cyclotron heated plasmas.

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II. FEATURES OF THE LHD CRYOGENIC SYSTEM

The LHD cryogenic system consists of the helium (He) refrigerator, the superconducting helical and poloidal coils, the supporting structure, the LHD cryostat, the control-valve-boxes, the superconducting bus-lines, the current-leads cryostat and the cryogenic transfer-lines as shown in Fig. 1. The helical coils are cooled with pool boiling liquid helium. The poloidal coils are cooled with forced flow supercritical helium (SHe). The supporting structure and the superconducting bus lines are cooled with forced flow two-phase helium and the liquid helium is used for the current leads. The 80 K radiation shields of the LHD cryostat are cooled with forced flow 40 K – 80 K helium gas. The He refrigerator simultaneously has cooling capacities of 5.65 kW at 4.4 K, 20.6 kW from 40 K to 80 K and 650 L/h liquefaction. The total heat loads under steady state condition were 1940 W + 650 L/h (3.0 T) at 4.4 K and 12.1 kW at 80 K. The measured heat loads were almost the same as the final design values, which were about half of the cooling capacities.

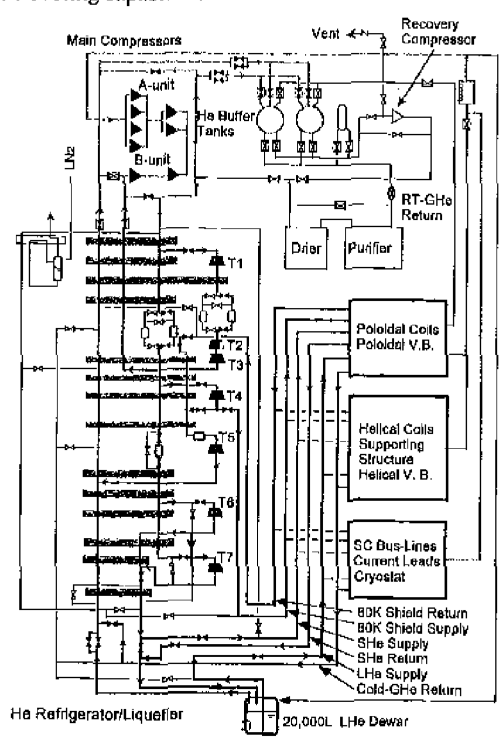

Fig. 1. Flow diagram of the LHD cryogenic system.

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III. Emergency program for the coil quench

The emergency sequence programs, corresponding to a power failure, apparatus faults, a coil quench and a successive emergency shut-off of the coil power-supplies and so on, are installed into the LHD cryogenic control system (LHD-TESS) [3]. The protections of apparatus and recovery in a short time period are possible by the function of them. Whenever any one of superconducting coils or superconducting bus-lines quenches, all coils are disconnected from the power supplies and connected to the dump resisters. The transport currents of the coils are discharged exponentially with a time constant of 20 seconds. These events of a coil quench and a subsequent emergency current shut-off are abbreviated to 1Q. The cryogenic system has to be protected in the case of the quench, which results in evaporation of a lot of liquid helium and rapid raise of coil pressures due to Joule heating and/or AC losses. The coils are automatically isolated from the He refrigerator with 1Q-signal by the emergency sequence program. The coils are protected from the dangerous pressure buildup by the relief valves. On the other hand, the He refrigerator can keep its steady state operation for a quick recovery.

Figure 2 shows changes of a cooling flow for the poloidal coils before and after a coil quench emergency program (1Q). The doted lines in the figure indicate a cooling flow in the steady state and the bold solid lines indicates a changed cooling flow after 1Q. In the steady state, the upper and lower poloidal coils are connected in series and the SHe is supplied from the He refrigerator and returns to it. After 1Q, the poloidal coils are disconnected from the He refrigerator by closing the coil inlet and return valves. The poloidal coil inlet is directly connected with the discharge of the turbines # 6 and # 7 in the He refrigerator, and the bypass line is prepared in order to prevent the damage of the turbines by the rapid pressure variation. Therefore, the inlet valve (V1) and the return valve (V2) were closed with 60 seconds ramp speed, while a bypass valve (V3) is opened simultaneously. Outlets of upper and lower poloidal coils (V4, V5) are connected to the buffer tank in order to release and keep the coil pressure same as that of the buffer tank. The liquid helium (LHe) supply valve (V6) to the SHe heat exchanger (HX) is also closed in order to disconnect the coil and the 20,000 ℓ LHe Dewar.

Figure 3 shows changes of a cooling flow for the helical coils before and after 1Q. In the steady state, the liquid helium is supplied to the helical coils with pool boiling from the bottom of the coils. Low-quality two-phase helium supplied from the LHe Dewar is cooled by a heat exchanger installed in the vapor-liquid-separation reservoir at the helical valve box (H-VB), it turns into the single-phase liquid helium, and is supplied to the helical coil and the supporting structure. After 1Q, the helical coils are isolated from the He refrigerator by closing the coil inlet valve (V1, V2) and outlet valve (V3). Once the pressures in the helical coils exceed the limits, the multi-stage pressure relief valves operate. There are two kinds of program-controlled pressure relief valves; two recovery valves (the operating pressure of 0.137 MPa) are connected to the room temperature (RT) recovery line, two release valves (0.157 MPa) are connected to the vent line. Ten spring-loaded safety valves (0.181 MPa) and ten rupture disks (0.216 MPa), are also set up in the helical coil header. The inlet valves for the supporting structure and shell arms are also closed to isolate then from 20,000 ℓ LHe Dewar. The outlets of the supporting structure and the vapor-liquid-separation reservoir are connected to the RT recovery line.

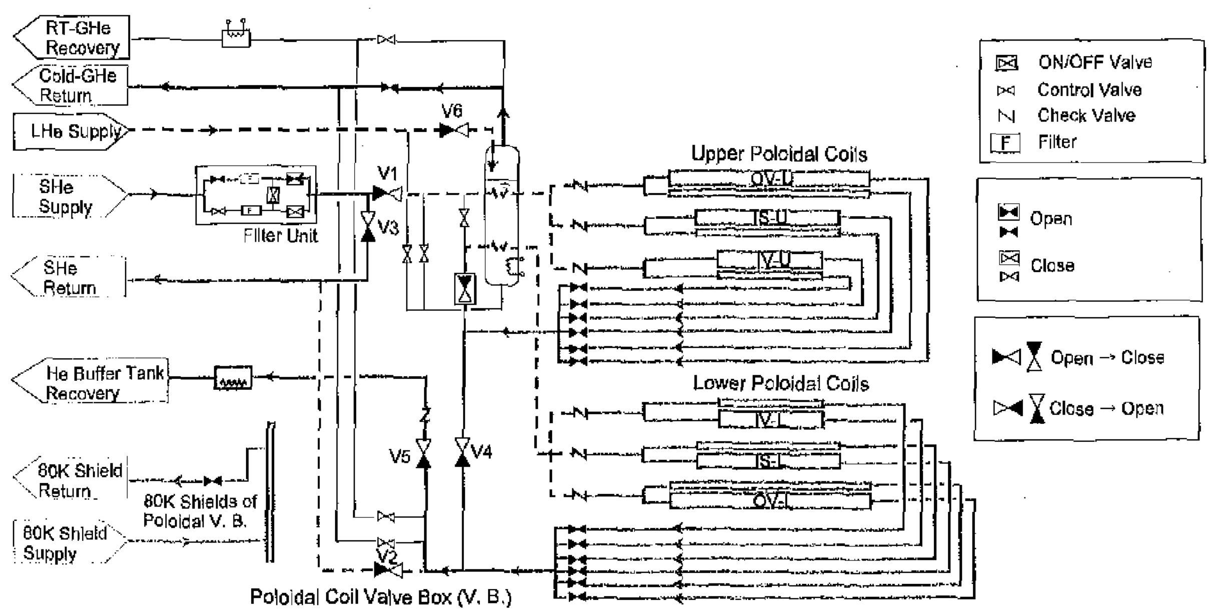

Fig. 2. Changes of a cooling flow for the poloidal coils after a coil quench emergency program (1Q).

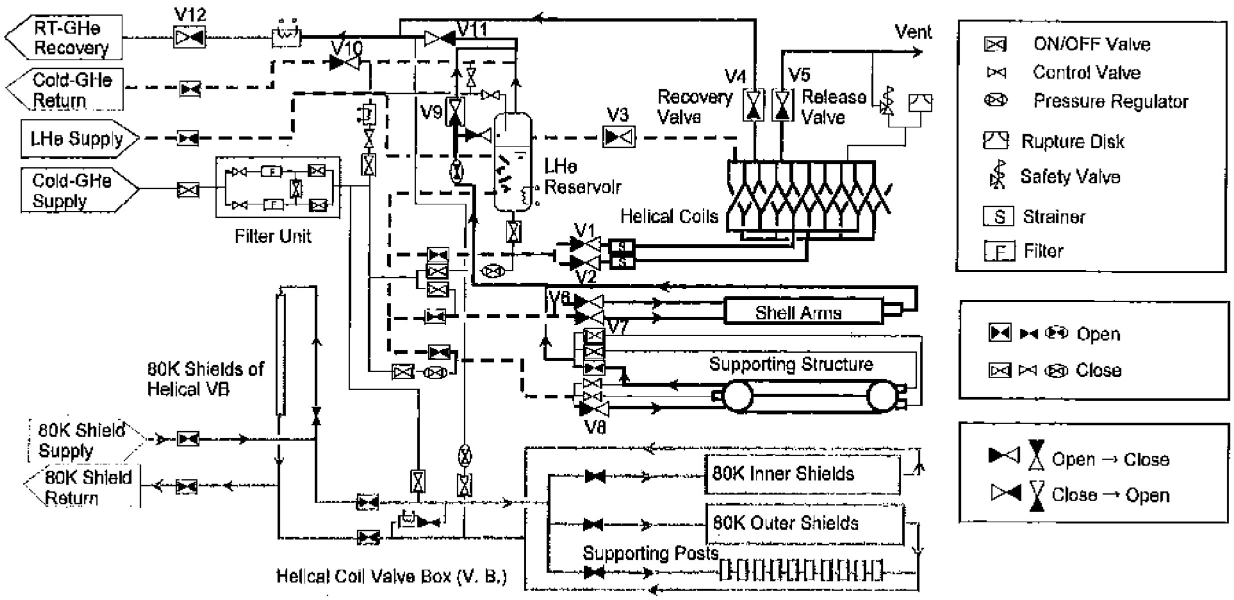

Fig. 3. Changes of a cooling flow for the helical coils and the supporting structure after 1Q.

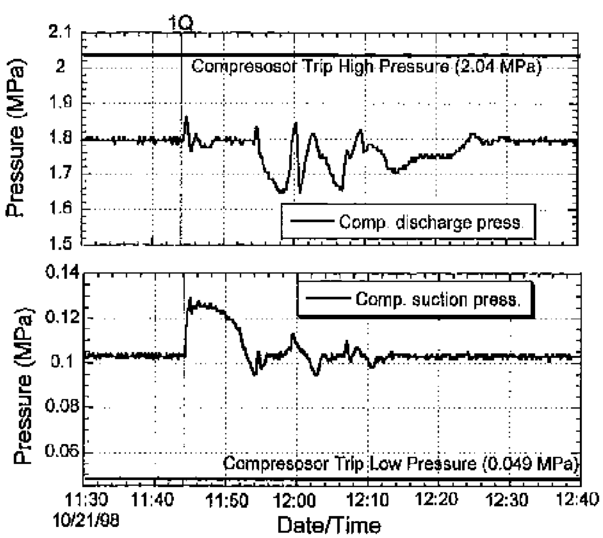

Fig. 4. Fluctuation of the main compressors inlet and outlet pressures

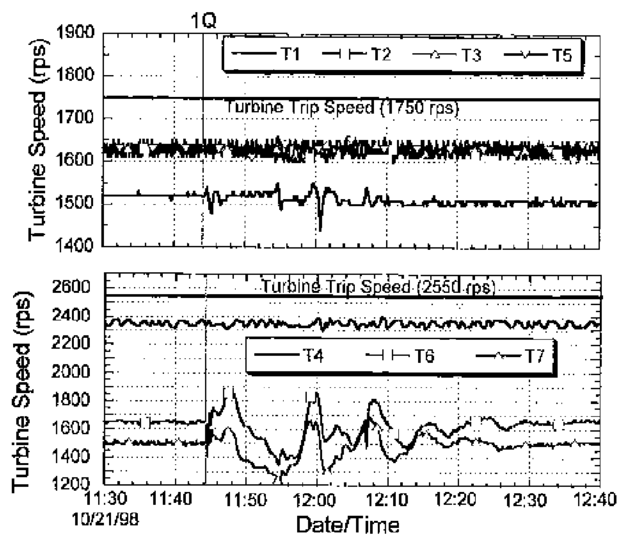

Fig. 5. Fluctuation of the turbine rotational frequencies.

IV. Performances During Excitation Tests

A. Emergency process due to the coil quench

During the excitation tests of the LHD SC coils up to 2.75 T, normal zone propagations and a subsequent coil quench were observed in the helical coil and the emergency shut-off of the coil power supplies (1Q) was carried out [4, 5]. The coils were isolated from the He refrigerator automatically by the 1Q emergency sequence program. Figure 4 shows the fluctuation of the suction and discharge pressures of the main compressors when 1Q occurs. Although the compressor suction and discharge pressures were fluctuated, there was additional coverage in the suction-pressure lower limit and the discharge-pressure upper limit in which the compressors carry out a trip. Figure 5 shows the variation of the turbine rotational frequency at the time of 1Q. Due to the rapid pressure changes after 1Q, the rotational frequencies of turbines #6 and #7 were fluctuated greatly, however, there was a margin in the upper limit in which the turbines carry out a trip. From these data, the He refrigerator was able to continue the steady state operation after 1Q without any trips of turbines and compressors. Figure 6 shows the pressure rise of the helical coil outlet header after 1Q. Pressure rise of the helical coils was restrained less than 0.177 MPa by the function of the recovery and release valves. The total operating time of the release valves, which opened 2 times, was 17 seconds, and the evaporating helium gas of 900 Nm^3 exhausted within 1 minute.

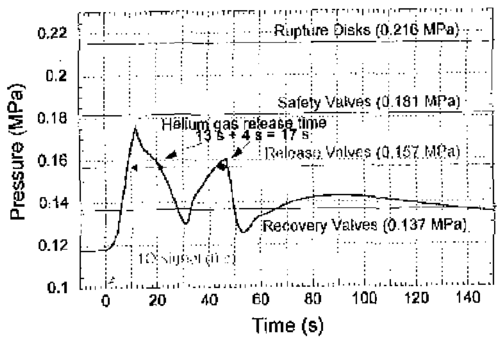

Fig. 6. Pressure rise of the helical coil header after 1Q.

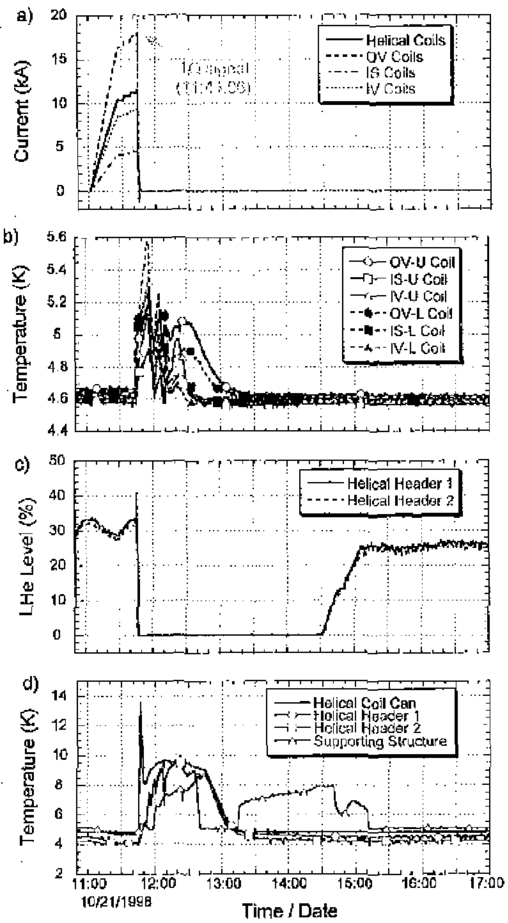

Fig. 7. Recovery characteristics after 1Q, a) Coil currents, b) Poloidal coils outlet temperatures, c) Helical coil header liquid helium levels, d) Helical coils & Supporting structure temperatures.

B. Recovery process

Figure 7 shows the characteristics during the recovery process from 1Q; outlet temperatures of the poloidal coils, liquid helium levels of helical coil header, temperatures of the helical coil cans and the supporting structure. The events from the 1Q occurrence to the restoration on October 21, 1998 are listed in Table 1. 2,700 ℓ of liquid helium evaporated from the helical coils. 1,000 Nm^3 of the evaporated gas was recovered to the helium buffer tanks, while 900 Nm^3 was exhausted into the air. And, the supplement of the exhausted helium gas and purification were completed at 10:50 of the next day.

Table 1. Events from 1Q occurrence to the restoration

11:44	1Q-signal occurrence He refrigerator and coils were separated
11:55	Helical coils returned to the normal pressure Evaporated liquid helium was 2,700 ℓ Recovery gas 1,000 Nm^3, exhaust gas 900 Nm^3
11:56	Poloidal coil SHe cooling restarted
12:25	Supporting structure cooling restarted
12:33	Helical coils LHe supply restarted
13:25	Poloidal coil outlet temperatures recovered
15:05	Helical coil header LHe level recovered
15:12	Supporting structure temperatures recovered LHD cryogenic system restored to the coil-excitation-enable-condition

V. Summary

After the normal transition of the SC coils and the emergency shut-off of the coil power supplies, it could be restored to the coil-excitation-enable-state only in three and a half hours by the function of the LHD cryogenic system corresponding to the emergency process. Pressure rise of the helical coils was suppressed less than 0.177 MPa by terms of the recovery and release valves operations, which were programmed in the LHD cryogenic control system (LHD-TESS).

Acknowledgment

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