Reliable long-term operation of superconducting bus lines for the LHD

journal or publication title	Journal of Physics Conference Series
volume	1857
page range	012014
year	2021-04-19
URL	http://hdl.handle.net/10655/00012932

doi: 10.1088/1742-6596/1857/1/012014

Reliable long-term operation of superconducting bus lines for the LHD

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Abstract. The Large Helical Device (LHD) is an experimental device for helical type fusion plasma in National Institute for Fusion Science and plasma experiments over 150,000 shots have been successfully conducted during twenty long-term plasma experimental campaigns. The LHD has two kinds of superconducting magnets and nine flexible superconducting bus lines with an average length of 55 m, which are utilized as a part of the current feeder system between the coils and the power sources. The superconducting bus lines consist of a pair of aluminum stabilized NbTi/Cu compacted stranded cable insulated electrically and coaxial five corrugated stainless steel tubes with two layers of vacuum insulations. The nominal current is 32 kA and the withstand voltage is 5 kV in 77 K gas helium. From the first experimental campaign, the superconducting bus lines have been stably operated at steady state by using automatic control. It is also confirmed that the status of the superconducting bus lines are kept good thanks to appropriate maintenances. As the results, the reliable operation of the superconducting bus lines has been achieved during the plasma experimental campaigns without any serious failure and the total operational time of the steady state cooling is approximately 58,000 hours.

1. Introduction

The Large Helical Device (LHD), which was completed in 1998, is an experimental device for helical type fusion plasma in National Institute for Fusion Science [1-2]. Plasma experiments over 150,000 shots were successfully conducted during twenty long-term plasma experimental campaigns for 22 years. The LHD has two kinds of superconducting magnets, which are a pair of helical coils and three pairs of poloidal coils. In many fusion experimental devices, current leads for superconducting magnets are designed to be close to the devices [3-5]. In the case of the LHD, current leads are located apart from the LHD and close to power sources by utilizing nine flexible superconducting bus lines between the coils and the current leads as a part of the current feeder system in order to expand the space for pumping system, heating devices, diagnostics apparatuses and any other equipment around the LHD (see figure 1). The application of the superconducting bus lines also leads to reduction of electrical power consumption for the power sources [6].

From the first experimental campaign, the superconducting bus lines have been stably operated at steady state by using automatic control [7]. Also, the problem of annoying ice, covering on the terminals of the current leads, was solved by controlling the temperature of the terminals by heaters automatically [8]. Moreover, the superconducting bus lines were protected by switching to the fault protection mode even if the rapid current discharge with the time constant of 20 seconds occurred and the current feeder system was separated from the cryogenic system of the LHD [9]. The reliable operation of the superconducting bus lines has been achieved during the plasma experimental campaigns without any serious failure thanks to optimized operational method and appropriate maintenance between experimental campaigns. In this paper, the present status of the superconducting bus lines are reported and the operation control method and preventive maintenances for the stable and reliable operation are also discussed.

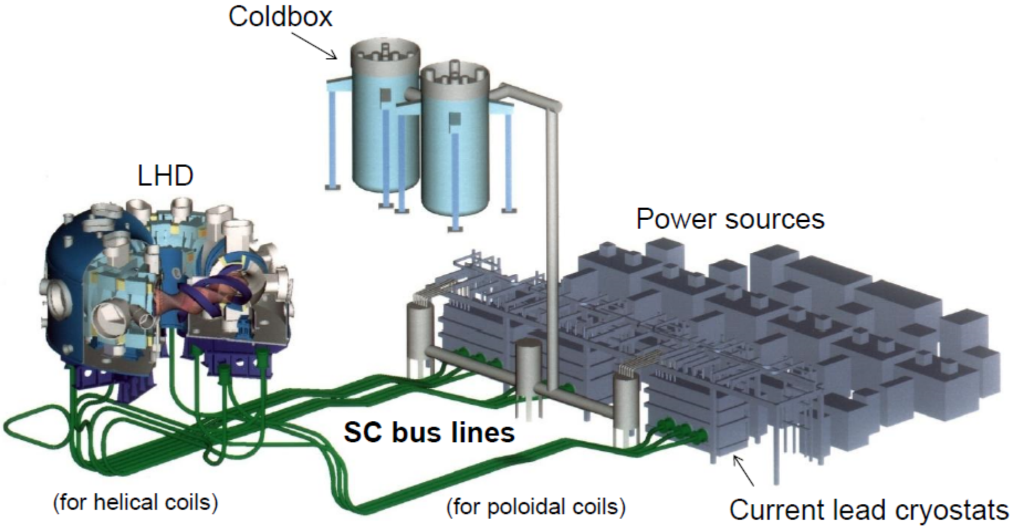

Figure 1. Current feeder system for the LHD.

2. Superconducting bus lines for LHD

2.1. Description of superconducting bus lines

The LHD has nine flexible superconducting bus lines, which are the average length of 55 m. The six bus lines are for helical coils, while three for poloidal coils. The superconducting bus lines consist of a pair of aluminum stabilized NbTi/Cu compacted stranded cable insulated electrically and coaxial five corrugated stainless steel tubes with vacuum insulation as shown in figure 2. The nominal current is 32 kA for the Phase II operations in the LHD project [1, 10] and the withstand voltage is 5 kV in 77 K gas helium [6].

The bus lines are designed to have excellent stability and safety, exceeding those of the superconducting magnets. That is the reason why the conductors, which are fully stabilized at the nominal current, are applied to the bus lines. The bus lines are also designed to be low heat leak, which is 3.0 W/m for the thermal shield and 0.3 W/m for the returned liquid helium [6]. Furthermore, the bus lines were installed with many corners and bends in order to avoid the direct shine through of neutrons, as shown in figure 1.

2.2. Operation of superconducting bus lines

Figure 3 shows an operational method of the current feeder system for the LHD. In the steady state, the liquid helium from the coldbox of the LHD cryogenic system is supplied into the first corrugated tube of the bus lines after subcooled to 4.4 K through a heat exchanger in the subcooler tank, flows to the LHD cryostat in the bus lines and then is returned into the tank through the second corrugated tube. A part of liquid helium in the tank is utilized as a coolant of current leads. The mass flow rate of the supplied helium is controlled by inlet valves of the bus lines. The nominal mass flow rate of each bus line is 12 g/s while the nominal supply and return pressure are 147 kPa and 115 kPa, respectively. In the subcooler tank, the pressure is regulated to approximately 120 kPa by an outlet valve of the tank and the liquid helium level is kept to be 60 % by a heater in the tank. Typical measured profiles are shown in figure 4. The stable operation has been achieved during coil excitations for the LHD plasma experiments. On the other hand, the mass flow rates of the current leads are controlled by the outlet valves of the leads. In addition, the stable liquid helium levels of the current leads are obtained with back siphonage by opening the communication valve VX [7].

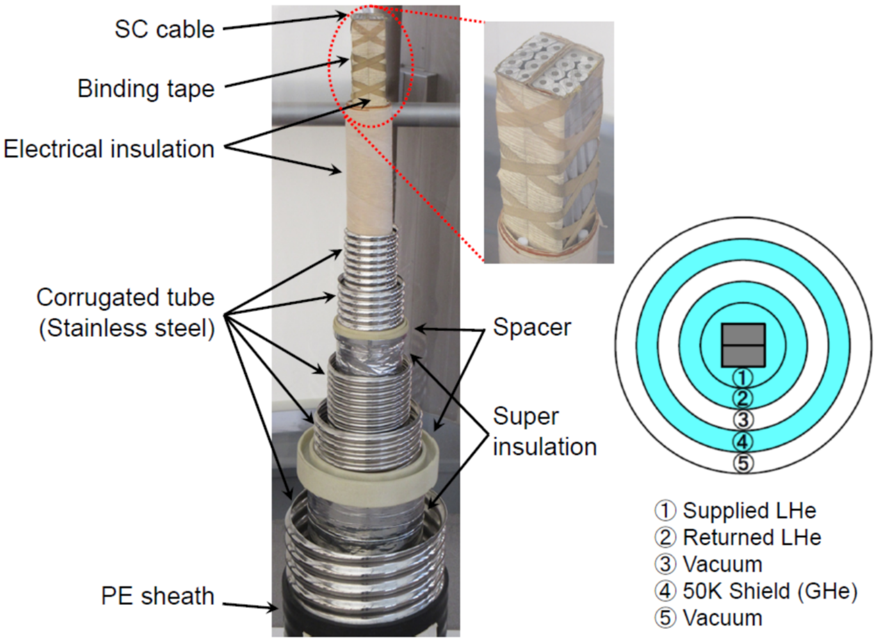

Figure 2. Structure of superconducting bus line.

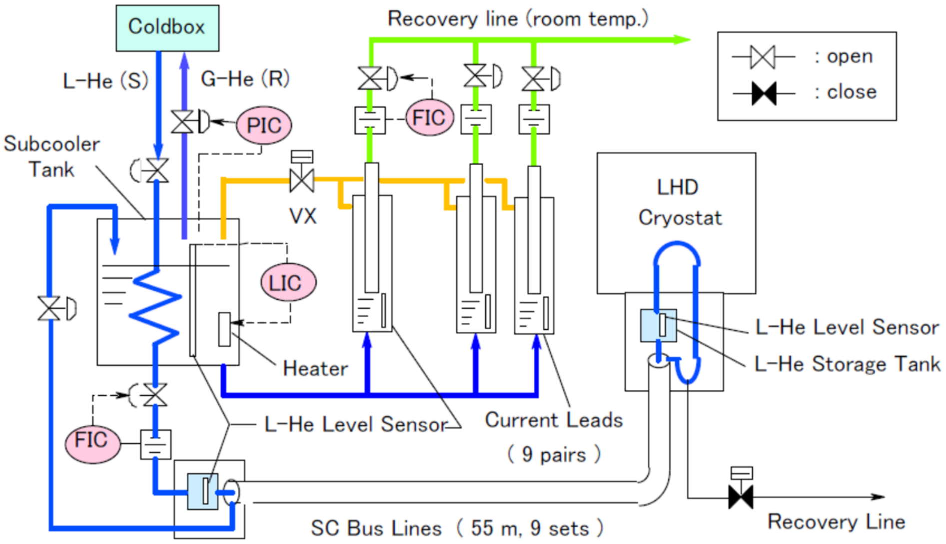

Figure 3. Operational method of current feeder system for the LHD, where FIC, PIC and LIC indicate flow, pressure and level control, respectively.

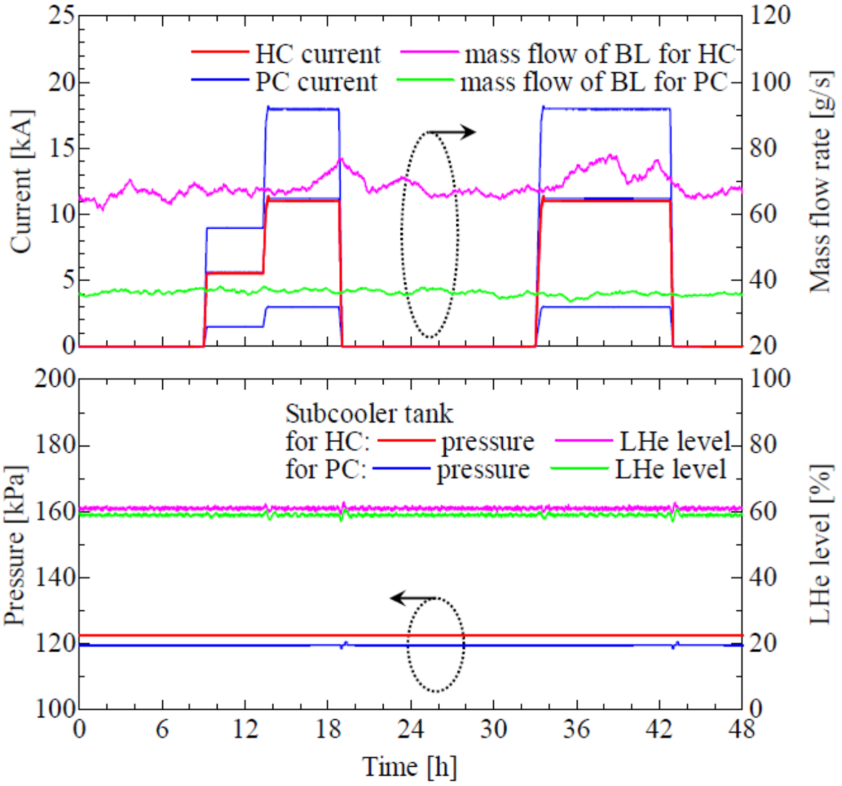

Figure 4. Typical measured profiles of bus lines during coil excitations for the LHD plasma experiment. Coil current and mass flow rate of bus lines appear in upper figure, pressure and liquid helium level in subcooler tank in lower figure. BL means bus line, HC helical coil and PC poloidal coil in the figures.

3. Reliable long-term operation

3.1. Operational history

In March 1998, the first experimental campaign of the LHD was started and the bus lines were energized for the first time with both the helical coils and the poloidal coils [1]. The superconducting bus lines have since been stably operated in the steady state cooling by using the above operational method during twenty plasma experimental campaigns for 22 years. The maximum current that the bus lines have ever experienced in various plasma experiments is 20.6 kA, about two third of the nominal current. That is because the operating current is limited to approximately 90 % of the maximum current of 23.5 kA in the Phase I due to a partial normal transition observed in a helical coil [9]. The operational history of the bus lines for each experimental campaign is summarized in figure 5. The total operational time of the steady state cooling is 57,943 hours while the total energization time is 11,304 hours. The bus lines have also experienced twenty thermal cycles. The reliable operation of the superconducting bus lines has been demonstrated during the plasma experimental campaigns without normal transition and any other serious failure thanks to appropriate maintenance between experimental campaigns. Especially, the nineteenth experimental campaign was the longest one where the deuterium experiment was launched, but it was carried out without trouble.

3.2. Heat leak

Generally, it is important to keep the heat leak for the superconducting device low in order to minimize the cooling power of the helium refrigerator. If the heat leak for the bus lines increases, it is considered that the cause is mainly degradation of vacuum of thermal insulation layers and contact between outer and inner tubes due to displacement or deformation by repetitive thermal cycles. In the bus lines, the thermal insulation layers have been evacuated by using a vacuum pump for about one month every maintenance period and good vacuum condition have been maintained. While, comparing X-ray photographs of a bent portion of the bus lines between in 2005 and in 2018, it was confirmed that the relative position between the outer tube and the inner tube has not changed as shown in figure 6. Besides, when the heat leak for the bus lines during the eighteenth experimental campaign was estimated, the averaged heat leak for the entire 50 K shield was 2.65 W/m and that for the entire returned liquid helium line 0.36 W/m. Consequently, it was confirmed that the heat leak was almost the same as that in the beginning of the operation [9].

3.3. *Preventive maintenance*

Not only periodical self-inspections in accordance with the High Pressure Gas Safety Act but also regular inspections and adjustments of instrumentations and control equipment, which are control valves, pressure and differential pressure transmitters, temperature and level indicators, heaters, electro-pneumatic converters, quench detectors and so on, have been conducted every maintenance period for stable and safe operations. Furthermore, appropriate preventive maintenance has been performed in addition to those. In 2014, it was observed that the outermost corrugated tubes of the bus lines started to be deformed plastically to a kink as shown in figure 7. Because the plastic deformation might become more intense and there was the risk of developing a crack and additional heat load in the future, the eleven kinked portions were repaired with resin and glass fiber to be on the safe side. After the buckled PE sheath was cut away, the bus lines was bent in opposite direction without overstress to expand the waves on the surface of the outermost corrugated tubes. The expanded waves were hardened with resin and glass fiber to hold the status and then the repaired portions were covered with PE sheet for protection. It is thought that the repair work has stopped deteriorating the present condition further. In addition, all seal-off valves and ON/OFF valves were replaced and all quench detectors were updated as preventive maintenance.

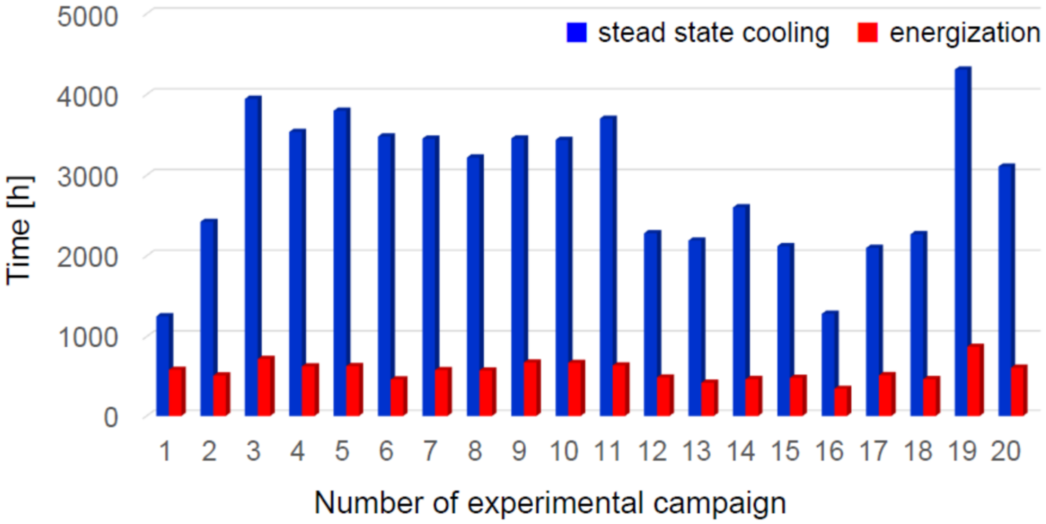

Figure 5. Operational history of the bus lines.

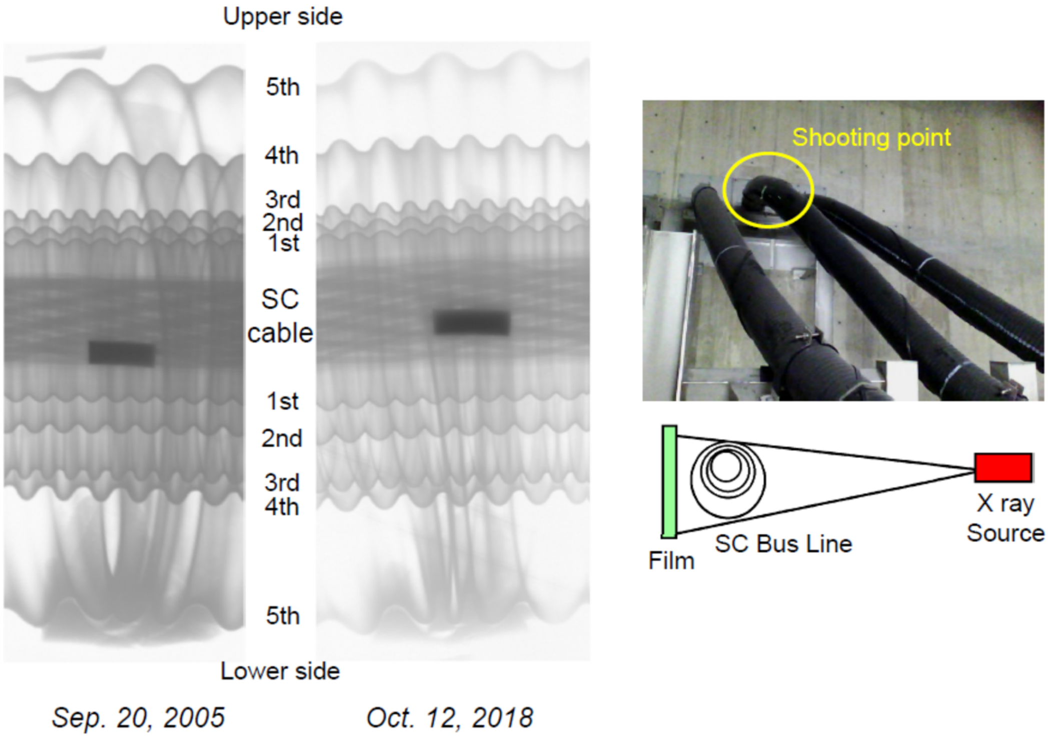

Figure 6. X-ray photograph of a bent portion in the steady state operation at 4.4 K.

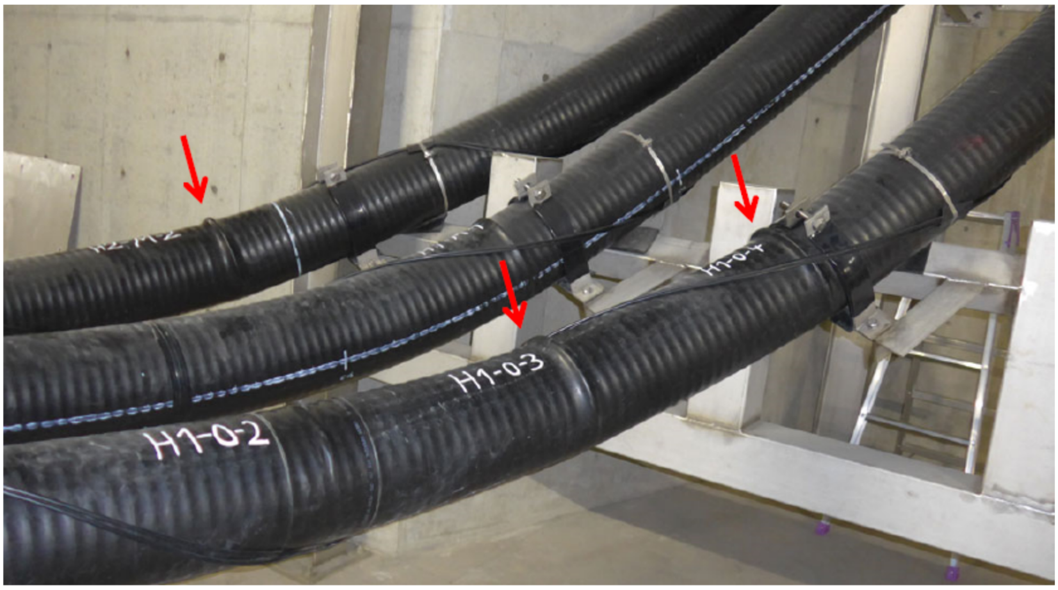

Figure 7. Photograph of three kinked portions of the bus lines for the helical coils.

4. Conclusion

During twenty plasma experimental campaigns after the construction of the LHD, the superconducting bus lines have been stably and reliably operated without normal transition and any other serious failure thanks to both adequate operational method by using optimal automatic control and various appropriate maintenance between the experimental campaigns. The total time of the steady state cooling has been achieved 57,943 hours, including the total energization time of 11,304 hours. In particular, the bus lines had no trouble in the nineteenth experimental campaign, although it was the longest experimental campaign and the first deuterium experiment was launched. Since no increase of the heat leak have been observed over the whole steady state cooling and also the kinked portions were repaired, it is expected that the bus lines keep almost the same condition as that in the beginning of the operation.

Acknowledgements

This work was performed with the support of the NIFS budget, ULAA705. The authors would like to appreciate the great help of operating staffs for the LHD cryogenic system and thank Fuji Electric Co., Ltd. for periodic inspections and repairs. This paper is dedicated to the late S Yamada.

References

[1] Iiyoshi A et al. 1999 *Nucl. Fusion* **39** p 1245
[2] Motojima O et al. 2002 *J. Plasma Fusion Res.* **5** p 22
[3] Wu S and the EAST Team 2007 *Fusion Eng. Des.* **82** p 463
[4] Kizu K, Murakami H, Natsume K, Tsuchiya K, Koide Y, Yoshida K, Obana T, Hamaguchi S and Takahata K 2015 *Fusion Eng. Des.* **98-99** p 1094
[5] Yoshida K, Takahashi Y, Isono T and Mitchell N 2005 *Fusion Eng. Des.* **75-79** p 241
[6] Uede T, Yamada S, Mito T, Hiue H, Itoh I and Motojima O 2001 *IEEE Trans. Appl. Supercond.* **11** p 2563
[7] Yamada S et al. 1998 *Proc. ICEC17* p 443
[8] Yamada S et al. 2002 *IEEE Trans. Appl. Supercond.* **12** p 1328
[9] Yamada S et al. 2000 *Adv. Cryog. Eng.* **45** p 1525
[10] Yamada S et al. 1996 *IEEE Trans. Magn.* **32** p 2422