§2. Lessons Learned from the Eighteen-Year Operation of the LHD Poloidal Coils Made from CIC Conductors

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The poloidal coils were first energized with the helical coils on March 27, 1998. Since that time, the coils have experienced 50,000 h of steady cooling, 10,000 h of excitation operation, and eighteen thermal cycles. The subsequent experience gained from eighteen years of operation has also provided further useful information regarding preventive design and maintenance of peripheral equipment and long-term changes in electromagnetic and hydraulic characteristics.

The operation of the superconducting magnet system must always remain stable. However, a malfunction of peripheral equipment can stop continuous operation. Even the poloidal coil system has experienced events that have interrupted plasma experiments due to the malfunction of a quench detection system and an insulating break used in cryogenic piping.

The quench detection system forces the coils into fast discharge to protect the conductors from excessive temperature increase. However, fast discharge involves the risk of electrical breakdown in the coil. Therefore, needless discharge due to malfunction should be avoided. Table I lists the history of malfunctions experienced by the quench detection system for the poloidal coils. The system can send out signals that demand fast (a time constant of 30 s) or slow (300 s) discharges, which correspond to the detected burst voltage duration. The criterion for burst duration was set to 1 s and 3 s for the slow and the fast discharges, respectively. The detection delay of 3 s for the fast discharge is the upper permissible value determined by a temperature rise during a quench, which is limited to 250 K. Fortunately, fast discharge has never occurred during excitation. In 2004, the system malfunctioned frequently and synchronously with the neutral beam injection (NBI) pulse during conditioning. A malfunction was considered to be a high voltage input exceeding a threshold level for detecting an instrument fault (for example, 11 V), and the surge from the NBI exceeded this value. First, using an additional timer circuit, we were able to exclude burst noise with a duration of less than 3 s. In addition, external wiring for remote operation was removed to eliminate the noise sources. The slow discharges in 2005 and 2008 were caused by the coupling current, which is an intrinsic property of a composite superconductor, during magnetic axis swing experiments. The voltage exceeded the quench detection (0.2 V) threshold for almost 1 s. Theoretical and experimental analyses then indicate that the voltage lasts for less than 1.5 s, even though the voltage pulse reaches 2 V. Therefore, the criterion was changed from 1 s to 1.5 s. Thanks to various measures introduced, there have been no malfunctions since 2010.

The poloidal coil system has 120 insulating breaks made of fiber-reinforced plastic (FRP). During the sixteenth cool-down of the coils in 2012, one of the breaks suddenly leaked helium, which was caused by the cracking of a plastic adhesive material between the FPR and the stainless-steel pipes. The break was temporarily repaired after warm-up at that time, and then all of the breaks were replaced with new improved breaks with larger adhesive area after the experimental campaign. The broken break had been cycled at a range of room temperature to 77 K ten times for quality assurance before installation on LHD. Thus, it is unlikely that only the thermal stress caused the cracking. Further investigation is needed to clarify the age degradation and the creep behavior of plastic adhesive materials.

The long-term monitoring of the electromagnetic and hydraulic characteristics of the coils has also been performed. For example, AC losses were monitored by measuring the inlet and outlet temperatures of coolant during the discharge of the coils after daily plasma experiments. Even though the AC losses slightly decreased during the first three years, the losses have remained unchanged in the fifteen years since. The initial change was probably caused by a decrease in an inter-strand coupling loss due to electrical contacts between strands. Electromagnetic forces during excitations may move the strands and then remove the contacts with large contact area, produced by plastic deformation of the strand surface during the cabling and jacketing processes.

Table I History of malfunctions of the quench detection system for the LHD poloidal coils

#	Event	Excitation	Cause	Year
1	Slow discharge	ON	False operation of timer circuit	2002
2	Failure signal (frequently)	OFF	Surge voltage from NBI conditioning	2004
3	Fast discharge (frequently)	OFF	Surge voltage from NBI conditioning	2004
4	Slow discharge	ON	Unknown	2004
5	Fast discharge	OFF	Unknown	2005
6	Slow discharge	ON	Magnetic axis swing	2005
7	Slow discharge	ON	Age degradation of potentiometer	2008
8	Slow discharge (3 times)	ON	Magnetic axis swing	2008
9	Failure signal	OFF	Lightning surge	2009