§6. Estimation of AC Losses of LHD Helical Coils from Enthalpy Increase of Subcooled Helium

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Helical coils of LHD are pool-cooled superconducting magnets. Liquid helium is supplied from ten positions at the bottom of the two helical coils through two inlet-headers, and it is taken out from ten top positions to an outlet tank, as shown in Fig.1. Longitudinal cooling channels inside the coils are arranged at the higher side of each layer and both corners of the top cover of the case. In order to improve the cryogenic stability, an additional heat exchanger with two-stage cold compressors was installed at the inlet of the helical coils. When the bath temperature of the heat exchanger is 3.0 K and the mass flow is 50 g/s, the outlet temperatures of the coil have been successfully lowered to 3.8 K from 4.4 K of the saturated temperature. The level of liquid helium in the outlet tank is controlled by tape heaters on the outlet pipes.

When the cryogen is subcooled, heat inputs can be estimated from the enthalpy increase between the coil inlet and the outlet. The positions of the thermo-sensors are shown in Fig. 1. The pressure of the outlet tank was controlled at 0.110 to 0.112 MPa. In steady condition, the mass flow can be estimated from the outlet temperature and the heater power to control the liquid level in the outlet tank. The steady heat load of HC is about 100 W, as shown in Table 1, when the outlet temperature is about 3.8 K. The steady heat inputs seem to be slightly less at the higher temperature of the coil.

Temperature rises at the coil outlet in charging by three kinds of ramp rates are shown in Fig. 2. AC losses are divided into joule losses and hysteresis losses. The former is in proportion to a ramp rate when it is sufficiently slow, and the latter is independent of it. In addition, the former is independent of the temperature at lower than about 10 K, because the conductivity of the materials is constant. In this case, the joule losses consist of coupling losses of the conductors and eddy current losses of the coil-cases. The time constant of overall coupling currents in the conductor had been measured.[1] Eddy current losses of the coil-cases can be estimated by their mutual inductance to the helical coil. Hysteresis losses can be derived by subtracting the calculated joule losses from the measured losses, as shown in Table 2. The evaluated hysteresis losses are reasonable, because they are independent of the ramp rate except for the case of 14 A/s, in which heat inputs from the supports would increase by their temperature rise.

The critical current density of the superconductor in subcooled helium is estimated at 1.5×10^{10} A/m^2 at zero field by using Kim model to fit the data in Table 2. The current density at saturated temperature of 4.4 K is estimated 0.9 to 1.0×10^{10} A/m^2 from the measurement of residual magnetic field[2]. Since the hysteresis loss is in proportion to the current density, the loss in subcooled helium is about 1.5 times as high as that in saturated helium.

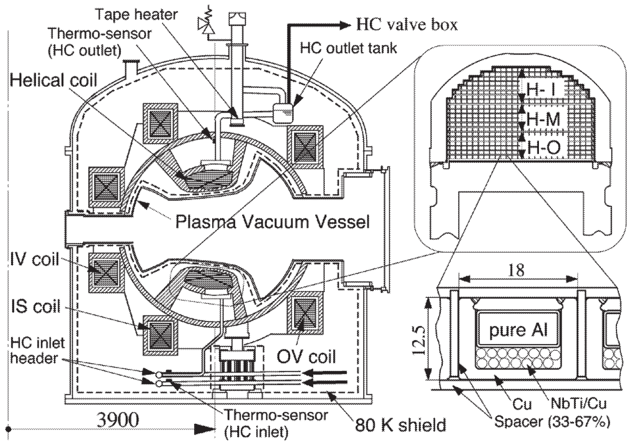

Fig. 1. Cross-section of the LHD cryostat and the helical coils.

Table 1. Steady heat inputs to the LHD helical coils. The data are averaged from 8:30 to 9:00.

HC temperature (K) Inlet	Outlet	Heater power (W)	Mass flow (g/s)	Heat input (W)	Date
3.480	4.036	966	45.0	94.0	'06.11.14
3.477	4.007	1028	47.5	93.8	'06.11.15
3.201	3.839	1049	47.0	98.2	'06.11.16
3.192	3.809	1130	50.4	100.5	'06.11.28
3.191	3.797	1168	51.9	101.4	'06.12.19

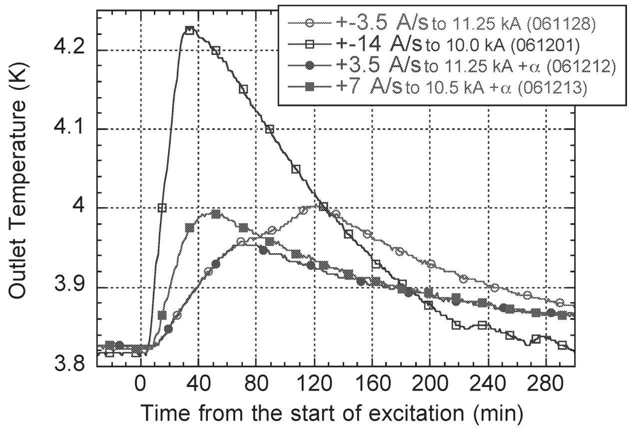

Fig. 2. Temperature rises at the outlet of helical coil by excitation, where the inlet temperature and the mass flow were 3.2 K and 50 g/s, respectively.

Table 2. Coupling and hysteresis losses of helical coils for various ramp rates of the currents, [unit: kJ]

Ramp rate	Total (measured)	Joule (calculated)	Hysteresis
+-14 A/s to 10.0 kA	837.8	(494)	(343.8)
+7 A/s to 10.5 kA +α(*1)	286.7	137.6	149.1
+3.5 A/s to 11.25 kA +α(*2)	221.8	73.3	148.5
+-3.5 A/s to 11.25 kA	447.0	146	301

(*1) +1.4 A/s to equivalent 11.1 kA
(*2) +0.7 A/s to equivalent 11.5 kA

Reference

1) Yanagi, N. et al., Fusion Eng. Des. **41** (1998) 241.
2) Imagawa, S. et al., IEEE Trans. Appl. Supercond. **15** (2005) 1419.