Cold Removal of Inner-Outer and Outer Inter-Coil Structure Components for ITER TF Coils

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Insulated inter-coil structure components are installed to ITER TF coils to fix the aliment of the coils. In the cases of Intermediate Outer Intercoil Structures (IOIS) and Outer Intercoil Structures (OIS), custom machined sleeves (CMSs) with Al_2O_3 coating are installed in the holes of TF coil structure. The IOIS/ OIS CMSs are possibly stacked in the IOIS/ OIS holes during their cold installation, and surface of their Al_2O_3 coating would thermally contact with the IOIS/ OIS holes tightly. Thus we propose a method to remove the CMS without damaging its insulation. In the method, the IOIS/ OIS CMSs are removed by cooling with liquid nitrogen (cold removal). The gaps of the IOIS/ OIS CMSs and holes ($\varDelta$) are influenced by contact thermal resistance between them (R_{ct}). Thus, in this study, we first numerically estimated the gap between the IOIS/ OIS CMSs and holes. Then, the cold removal was experimentally demonstrated with mock-ups of IOIS/ OIS holes and CMSs. In addition, an insulation test of the Al_2O_3 coating to confirm their soundness after the cold removal. It was numerically shown that $\varDelta$ became $> 57\,\mu m$, which was sufficiently large considering the manufacturing tolerance of IOIS/ OIS holes, even if R_{ct} is 0. The experimental result showed that IOIS/ OIS CMSs were successfully removed from the IOIS/ OIS holes. Moreover, the insulation test demonstrated that the cold removal did not influence on the insulation resistance of the IOIS/ OIS CMSs.

Keywords: ITER, toroidal filed coil, superconducting magnet, fusion magnet, inter-coil structure component

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1. Introduction

The 18 Toroidal Field (TF) coils generate a large magnetic field to confine a plasma in the ITER [1]. Since large electromagnetic forces are applied on the TF coils during a plasma operation, inter-coil structures as mechanical supports of TF coils are installed between adjacent TF coils [1–4]. Figure 1 illustrates four types of the intercoil structures; 1) Inner Intercoil Structures (IIS), 2) Inner Legs Intercoil Structures (ILIS), 3) Intermediate Outer Intercoil Structures (IOIS), and 4) Outer Intercoil Structures (OIS). During the plasma operation, magnetic field variation might lead to the large eddy current in the TF coil structure resulting in unacceptable heating for cooling of the superconducting magnets. Thus, in the IOIS and OIS, custom machined sleeves (CMSs) were insulated with Al_2O_3 for the intercoil insulation. Notably, Al_2O_3 was chosen as the insulation material because of its good insulation resistance and manufacturability [4]. As shown in the Fig. 2, IOIS/ OIS CMSs have cylindrical structure, and they are installed into the holes of the TF coil structure (IOIS/ OIS holes) by cooling with liquid nitrogen (cold fitting). Since the gap between the inner diameters of IOIS/ OIS holes and outer diameters of the IOIS/OIS CMSs is small, the CMSs are possibly stuck during the cold fitting.

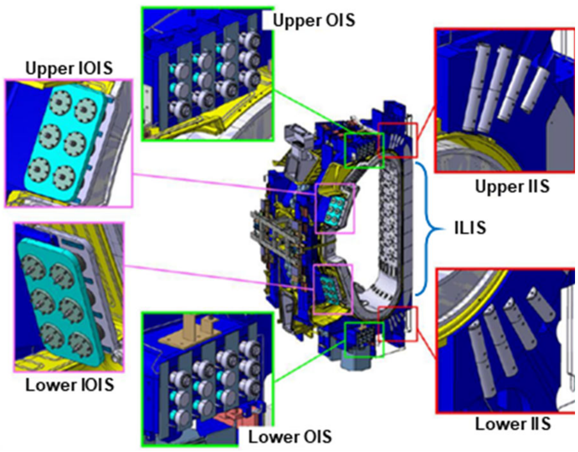

Fig. 1 Inter-coil structures for the ITER TF coils.

In this case, the CMSs must be removed without any damage on the fragile Al_2O_3 coating for their re-installation. To address this issue, we propose to remove the CMSs by cooling them with liquid nitrogen (cold removal). However, the CMSs possibly would not be sufficiently cooled for their removal due to thermal conduction from the IOIS/ OIS holes to the CMSs. The thermal conduction might be influenced by cooling condition and contact thermal resistance between IOIS/ OIS holes and CMSs. Thus, their in-

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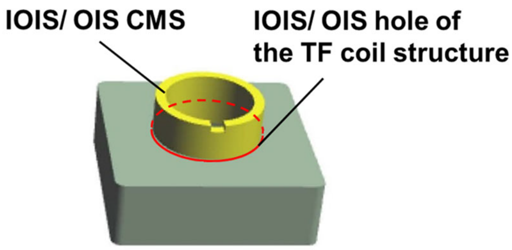

Fig. 2 IOIS/ OIS CMSs and holes of the TF coil structure.

fluence on the removability of the IOIS/ OIS CMSs should be investigated. In addition, it is desirable the removed IOIS/ OIS CMSs can be reused even after several cold insertion and removal. However, the thermal shock by liquid nitrogen (77 K) may degrade the insulation resistance of Al_2O_3. Many researches show the sufficient insulation resistance of Al_2O_3 for high voltage application at ∼ 77 K without thermal cycles [5–8]. On the other hand, the degradation of insulation resistance of Al_2O_3 by repeated thermal shocks has been reported [9]. Thus, the insulation resistance of the IOIS/ OIS CMSs after several thermal shocks also should be confirmed.

In this paper, we first numerically study the temperature distribution IOIS/ OIS CMSs during the cooling, and the feasibility of cold removal. Then, the cold removal was experimentally demonstrated with mockups of the IOIS/ OIS CMSs and holes. The insulation resistance of the IOIS/ OIS CMSs was measured after the experimental demonstration and several thermal shocks. Section 2 presents the numerical analysis. Section 3 presents the demonstrative experiment and insulation test with mockups, followed by a conclusion in Sec. 4.

2. Numerical Analysis on the Feasibility of Cold Removal

2.1 Analytical model and conditions

A thermal-mechanical coupling analysis was conducted to confirm the feasibility of the proposed method. In this calculation, the gap between the IOIS/ OIS CMSs and holes was calculated. The manufacturing tolerances of the outer diameter of IOIS/ OIS CMSs are 0.057 mm and 0.040 mm. Thus, it can be said that the cold removal is "feasible" if the gap between the IOIS/ OIS CMSs and holes become more than these values. Figure 3 illustrates the two-dimensional analytical model of the IOIS/ OIS holes and CMSs. Notably, q_z and q_r are the heat fluxes in the z and r directions, respectively. It was assumed that the IOIS/ OIS CMSs were stuck at 75% of the depth of IOIS/ OIS holes. Axial symmetricity was considered in the model. The analysis was conducted with a commercial finite element analysis code, Ansys Mechanical 2019 [10]. Figure 3 also shows the boundary conditions. For thermal analysis, natural convection (q_n) is considered on the top

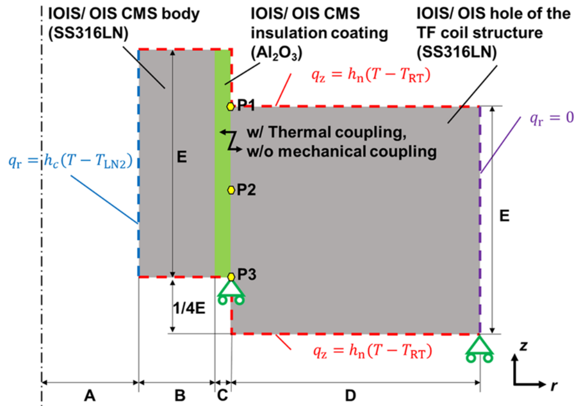

Fig. 3 Analytical model of the IOIS/ OIS CMSs and holes.

Table 1 Dimensions of analytical model.

Index in Fig. 3	Dimension	
	IOIS	OIS
A	145 mm	65 mm
B	15 mm	15 mm
C	0.4 mm	0.4 mm
D	215 mm	470 mm
E	200 mm	78 mm

and bottom surface by the following equation.

$$q_n = h_n (T - T_{RT}), \quad (1)$$

where h_n and T_{RT} are heat transfer coefficient of natural convection in air [11] and room temperature (= 293 K), respectively. h_n for the cases of IOIS and OIS are 7.6 W/m^2K and 9.6 W/m^2K, respectively. Convection cooling by the liquid nitrogen (q_c) is considered on the inner surface of the CMSs by the following equation.

$$q_c = h_c (T - T_{LN2}), \quad (2)$$

where h_c and T_{LN2} are heat transfer coefficient at the cooling with liquid nitrogen and temperature of liquid nitrogen (= 77 K). The initial temperature is set to 293 K for whole region. For mechanical analysis, displacement in the z direction is fixed at the corners of IOIS/ OIS CMSs and holes. Table 1 shows the dimensions of analytical models. Size of the analytical model is smaller than the actual TF coil case. However, a preliminary analysis confirmed that the size effect had a negligible impact on the simulation results.

Contact thermal resistance (R_{ct}) and h_c were considered as influential parameters on the efficiency of CMS cooling. The concerns are that low R_{ct} promotes the heat conduction to IOIS/ OIS holes and low h_c prevent the IOIS/ OIS CMSs from cooling. h_c is in the range of 10^3 - 10^4 W/m^2K with pool boiling when the superheat is 10 - 250 K [12]. R_{ct} and h_c are set to be 0 m^2K/W and

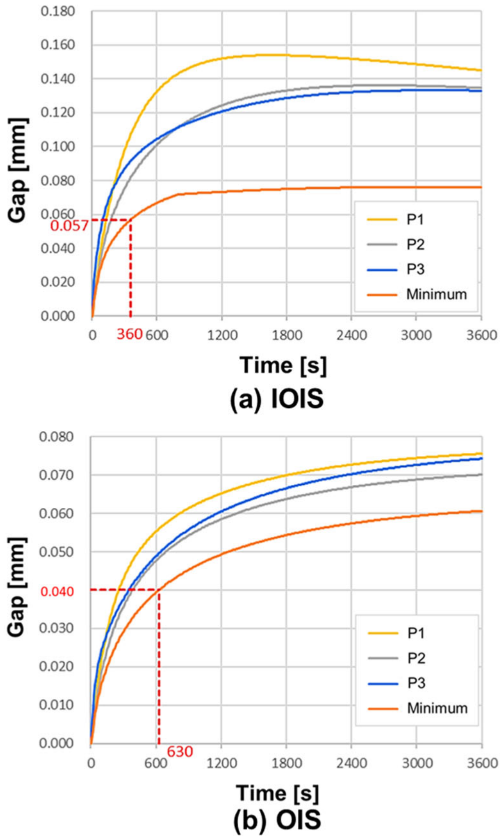

Fig. 4 Time evolution of the gap (a) between the IOIS CMS and hole, and (b) between the OIS CMS and hole.

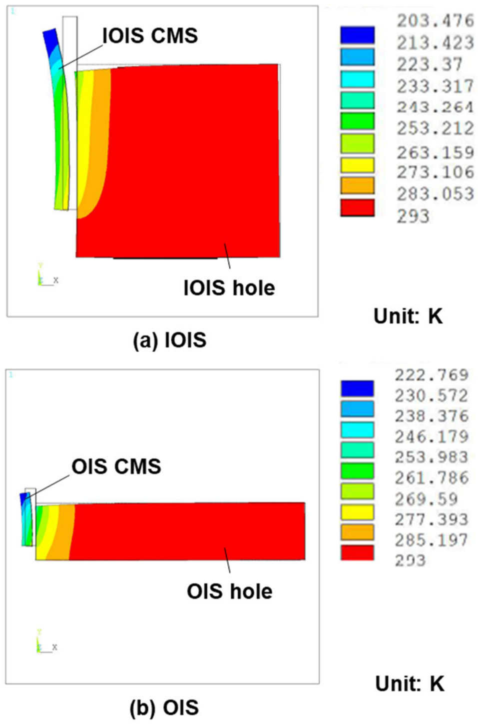

Fig. 5 Deformation and temperature of (a) the IOIS CMS and hole at 360 s, and (b) the OIS CMS and holes at 630 s.

10^2 W/m^{2}K, respectively. This corresponds to the situation where the IOIS/ OIS CMS and hole are fully thermally coupled, and the cooling efficiency on the IOIS/ OIS CMS surface is deteriorating to one tenth of 10^3 W/m^{2}K. This can be considered as conservative condition because the difference in thermal shrinkage of IOIS/ OIS CMS and hole would become less, and thermal shrinkage of IOIS/ OIS CMS would also become less. There is no mechanical coupling between the IOIS/ OIS CMS and hole, while they are thermally coupled even if the gap exists.

Young modulus of SS316 and Al_2O_3 are 193 GPa and 380 GPa, respectively. Poisson's ratios of SS316 and Al_2O_3 are 0.3 and 0.23, respectively. Temperature dependence of the linear thermal expansion, thermal conductivity, and heat capacity of the SS316 and Al_2O_3 are referred from [5, 13–15].

2.2 Simulation results

Figure 4 shows the transient gap between the IOIS/ OIS CMSs and holes. The yellow, gray, and blue lines indicate the gaps at points P1, P2, and P3 (see Fig. 3), respectively. The minimum gap is also plotted as orange. The gap varies at different points in the IOIS/ OIS CMSs. This is due to the temperature distribution in the IOIS/ OIS CMSs as shown in the Fig. 5. The upper region kept at ~77 K shows more gap. In the case of the IOIS, P1 and P2 show the extrema in the plots. This indicates that the thermal shrinkage of the IOIS CMS is almost saturated, and then the IOIS hole continues to be shrank. The cooling on the surface of the IOIS/ OIS holes will stop once the IOIS/OIS CMSs and holes are detached. Then, the gap will increase until the temperature field in the IOIS/ OIS CMS becomes steady state. Thus, the extrema would not be seen in the real case. The gaps between IOIS CMS–hole and OIS CMS–hole reach 0.040 mm and 0.057 mm at 360 s and 630 s, respectively. This result indicates the cold removal can be completed with realistic cooling time, and these times can be used as criterion of cooling time. In addition, the maximum temperatures on the IOIS/ OIS CMS outer surface are 273 K and 262 K, respectively. These temperatures also can be used to judge the removability of the IOIS/ OIS CMS.

3. Experimental Trial on the Cold Removal

The simulation results in the Sec. 2 indicates the IOIS/ OIS CMSs can be removed by the cold removal. However, it is difficult to simulate the distribution of heat transfer coefficient of liquid nitrogen on the surface of the CMS, and the uncertainty in the thermal conduction/ gap between the IOIS/ OIS holes and CMS remains. Thus, we performed the experimental trial to confirm the removability of the CMSs at actual cooling condition. The insulation resistance of the CMSs was also tested after the cold removal and several thermal shocks.

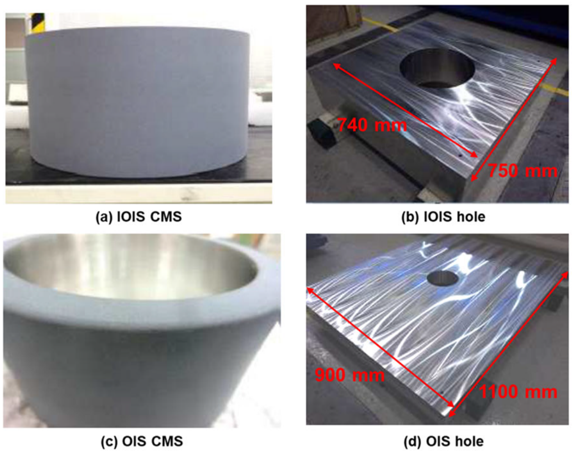

Fig. 6 Mockups of the IOIS/ OIS CMS and holes.

Table 2 Dimensions of manufactured mockups.

Mockups	Inner diameter	Outer diameter
IOIS CMS	290.04	320.050
IOIS hole	319.94	-
OIS CMS	129.92	160.038
OIS hole	159.98	-

3.1 Cold removal test

Figure 6 shows the mockups of the IOIS/OIS CMSs. The mockups are made of SS316LN and they have 300 µm of Al_2O_3 coating, as insulator, on the outer surface. Table 2 shows the dimensions of manufactured mockups. Figure 7 shows the procedure of cold removal test; i) a lid was attached on the bottom surface of the IOIS/ OIS CMSs with silicone sealant and they were pre-cooled for cold fitting, ii) IOIS/ OIS CMSs were inserted to IOIS/ OIS holes by cold fitting with liquid nitrogen, iii) the mock ups were kept until their temperature increased to room temperature, iv) liquid nitrogen was poured in the holes of IOIS/ OIS CMSs and they were kept for 900 s which was longer than the cooling time estimated in the numerical analysis, v) IOIS/ OIS CMSs were removed with support jig and hydraulic jack. During the cold removal test, temperature on the surface of IOIS/ OIS CMSs at P4 in the Fig. 3 was monitored with a thermometer.

As a result, we could remove both the IOIS/ OIS CMSs as expected in the numerical analysis. Thus, validity of the numerical analysis assuming sufficiently small R_{ct} and h_c as a conservative analysis was verified. In addition, no damage due to thermal shock and handling was found after the cold removal. The surface temperature of the IOIS/ OIS CMS was 199.65 K and 192.65 K, respectively. The surface temperature of the IOIS CMS was less than the saturated temperature in the numerical analysis. This would be because the thermal coupling of the IOIS CMS and hole disappeared after the gap occurred as mentioned in the Sec. 2. Thus, validity of the result of the numerical analysis as conservative analysis was verified. According to the results of numerical analysis and experiment, the feasibility of the cold removal was demonstrated.

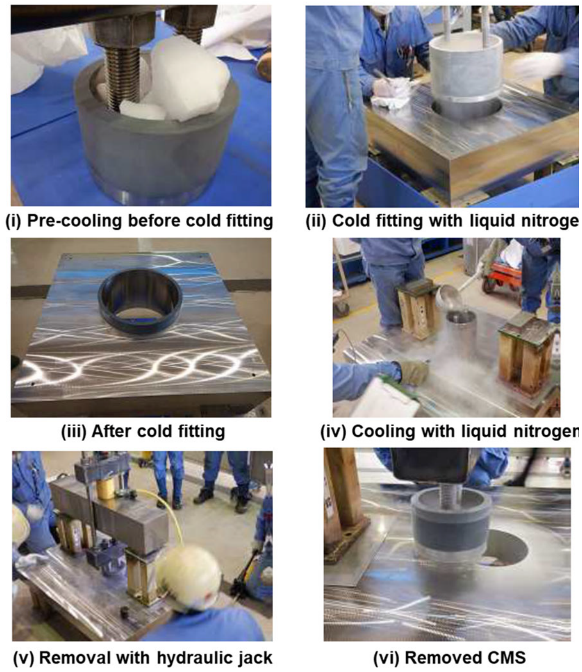

Fig. 7 Procedure of the mockup test.

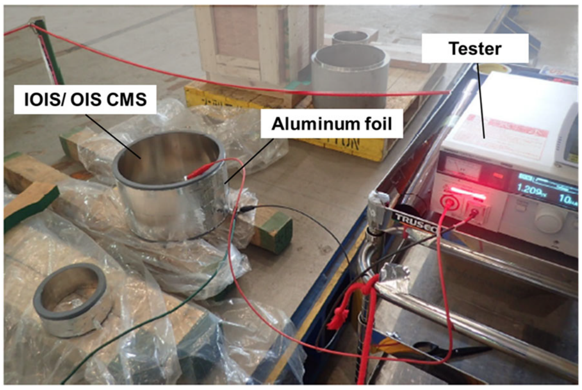

Fig. 8 Insulation test setups.

3.2 Insulation test

After the cold removal of the IOIS/ OIS CMSs, it would be desirable to reuse the IOIS/ OIS CMSs. The thermal shock might cause the damage of the fragile Al_2O_3 coating, thus the insulation resistance of the coating was confirmed after the cold removal (insulation test). Figure 8 shows the setup for the insulation test. The Al_2O_3 coating surface of the IOIS/ OIS CMSs were wrapped with aluminum foil, and the voltage was applied between the aluminum foil and inner surface of the CMSs. The insulation test was conducted with 2 steps; 1) 0.23 MΩ was confirmed with DC 500 V, and 2) the insulation resistance

Table 3 Results of the insulation test for IOIS CMS.

Cycle	Leak current	Insulation resistance	Humidity
1	12 μA	100 MΩ	41.1%
2	12 μA	100 MΩ	51.4%
3	143 μA	8 MΩ	81.6%
4	8 μA	150 MΩ	36.6%
5	9 μA	133 MΩ	53.6%

Table 4 Results of the insulation test for OIS CMS.

Cycle	Leak current	Insulation resistance	Humidity
1	3 μA	400 MΩ	40.9%
2	3 μA	400 MΩ	51.4%
3	11 μA	109 MΩ	81.0%
4	3 μA	400 MΩ	37.0%
5	3 μA	400 MΩ	53.4%

was confirmed up to DC 1.2 kV. Notably, the requirement of the insulation of CMSs are considered to ∼150 V. A hipot tester TOS5301, Kikusui Electronics Corp., was used for the measurement of insulation resistance. In addition, considering the risk of several times of thermal shock, we conducted the insulation test after up to four thermal cycles between 77 K and room temperature. In the additional thermal cycles, CMS are cooled by immersion in liquid nitrogen for 10 mins, and they were kept for > 36 h until they were dried.

Both IOIS/ OIS CMS passed the step1 with DC 500 V, and no break down was observed in the step 2. Tables 3 and 4 show the results of insulation tests at DC 1.2 kV. Cycle 1 indicates the one after the CMS removal test, and cycles 2 - 5 indicate the additional thermal cycles. Leak current in cycle 3 shows larger value than the others. This would be because the higher humidity. The insulation resistance did not significantly change through all the tests. Thus, the Al_2O_3 coating can keep its insulation resistance even after several trials of cold insertion and removal. These results of the insulation test would be useful information not only the ITER assembly work, but also the general cryogenic applications using ceramic insulation material. The configuration of IOIS/ OIS holes was considered vertical in this study, and we will see the inclined configuration in the real case. Although this study takes into account the ideal case in some sense, such as, vertical configuration of the IOIS/ OIS holes, all the results will be important information to discuss the improvement or further ideas.

4. Conclusion

In this paper, a cold removal technique for the IOIS/ OIS CMSs for ITER assembly is proposed, and its feasibility was numerically and experimentally investigated. The highlights are as follows:

- The numerical simulation indicates that the CMSs can be removed by cooling with liquid nitrogen even if the thermal contact resistance and heat transfer coefficient are small (0 m^2K/W and 10^2 W/m^2K, respectively).
- The experimental trial on cold removal demonstrated the feasibility of the cold removal technique as expected in the numerical analysis. The insulation check was also done after the cold removal trial. The results showed that the CMS after up to four thermal cycles withstood the 1.2 kV without breakdown, and it satisfied the ITER requirements.

The cold removal method would be important for the ITER assembly activity considering the risk of process failure. Moreover, the insulation characteristics shown in this paper will be helpful information to ensure the Al_2O_3 coating insulation for not only the ITER and fusion device but also for the cryogenic applications.

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