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THERMAL TRANSITION DESIGN AND BEAM HEAT-LOAD ESTIMATION FOR THE COLDDIAG REFURBISHMENT*

H. J. Cha†, N. Glamann, A. Grau, D. Saez de Jauregui, A.-S. Müller
Karlsruhe Institute of Technology (KIT), Eggenstein-Leopoldshafen, Germany

Abstract

The COLDDIAG (cold vacuum chamber for beam heat load diagnostics) developed at Karlsruhe Institute of Technology has been modified for more studies at cryogenic temperatures different from the previous operations at 4 K in a cold bore and at 50 K in a thermal shield. The key components in this campaign are two thermal transitions connecting both ends of the bore at 50 K with the shield at the same or higher temperature. In this paper, we present design efforts for the compact transitions, allowed heat intakes to the cooling power margin and mechanical robustness in the cryogenic environment. A manufacture scheme for the transition and its peripheral is also given. In addition, the beam heat loads in the refurbished COLDDIAG are estimated in terms of the accelerator beam parameters.

INTRODUCTION

Despite remarkable development of synchrotron light sources with superconducting insertion devices, beam heat loads in a cold-bore vacuum chamber are still a critical subject to resolve, because the heat loads can be so high that the stable operation of a superconducting device becomes impossible. Several reports have also shown considerable discrepancy between theoretical results of the beam heat loads and the measured ones [1-3]. For deeper understanding, the COLDDIAG (cold vacuum chamber for beam heat load diagnostics) has been developed at Karlsruhe Institute of Technology (KIT) and successfully performed the beam heat-load studies at the Diamond Light Source (DLS) storage ring [4-6]. The COLDDIAG has been being refurbished for more investigation with different cryogenic temperatures at the other accelerator facilities.

In this study, we focus on the design of a thermal transition which is a key component bridging between a cold bore at 50 K and a thermal shield at the same or higher temperature (80 K) for this campaign. It should be noted that the operation temperature of beam screens at the future circular collider for hadron beams (FCC-hh) is approximately 50 K. Our aim is to develop a thermally efficient and mechanically stable transition with a simple structure. For this purpose, total heat intakes and thermal budgets in the COLDDIAG with the two new transitions are calculated. Simulation results on mechanical stress and thermal contraction in the cryogenic environment are presented. Manufacture processes of the transition and its nearby components are also introduced. Finally, feasible installation of the refurbished COLDDIAG at the accelerator facilities is discussed with the estimation of beam power losses depending on a geometrical step and resistive wall heating (RWH).

CONCEPTUAL DESIGN OF A NEW THERMAL TRANSITION

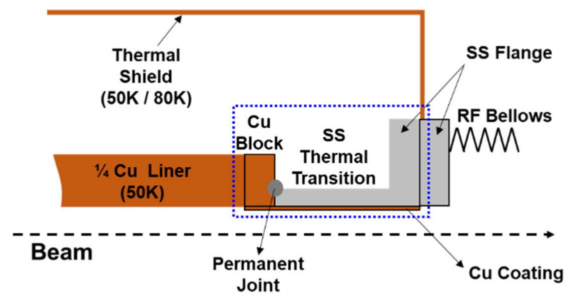

Figure 1: Thermal transition assembly in the cryostat.

Figure 1 shows a quarter schematic of the transition assembly with nearby components in the COLDDIAG. The other parts are symmetrical to a beam axis and a vertical axis in the middle of the cold bore (liner), respectively. The blue-dotted rectangle indicates the components newly manufactured and then installed. We consider two different operations of the refurbished COLDDIAG. The first scenario (Scenario-1) is that both the liner and the thermal shield have the same temperature of 50 K. In this case, the heat intake by thermal conduction between the shield and the liner vanishes due to no temperature difference. Thus, it is possible to increase the thickness of the transition to a rigid level. For the same reason, the heat intake by thermal radiation is also zero.

The second one (Scenario-2) is with the liner at 50 K and the shield at 80 K, respectively. Due to the presence of an insulation vacuum in the cryostat, the heat intake by convection is negligible. As the transition material, stainless steel (SS) was chosen for mechanical stability and ease of fabrication. The thickness of the transition was determined to 5 mm with considering both the conductive heat intake in Scenario-2 (~6.5 W each) and the permanent joint with the oxygen-free high conductivity (OFHC) copper (Cu) block. A thin Cu-layer deposition on the inner surfaces of the transition and neighbors was considered to avoid the increasing image current. The thickness of the layer was decided to 5 μm for low heat intake (~1 W in Scenario-2), which is also thicker than the skin depth of 3 μm at an RF frequency of 500 MHz. The beam power losses from a step (geometrical impedance) formed by the Cu layer with the

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† hyuk.cha@kit.edu

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adjacent component are expected to be less than 1 W from the beam heat-load calculation. Table 1 represents each thermal budget for the two operation scenarios using the existing cryocooler (model: SRDK-415D-F50H, manufacturer: Sumitomo Heavy Industries, Ltd.) with adding a heater to its 2nd (cold) stage working from ~4 K to 18 K.

Table 1: Thermal Budgets of Two Operation Modes taking into account the First Stage (1st) and the Second One (2nd) of the Cryocooler with Temperature Range (T), Total Heat Intake (Q), Cooling Power (P_c), and Cooling Power Margin (P_m)

Operation	**T (K)**	**Q (W)**	**P_c (W)**	**P_m (W)**
Scenario-1	300 - 50	44	40 (1st)	28
	50 - 50	0	32 (2nd)	
Scenario-2	300 - 80	44	62 (1st)	18
	80 - 50	13	32 (2nd)	19

SIMULATION RESULTS

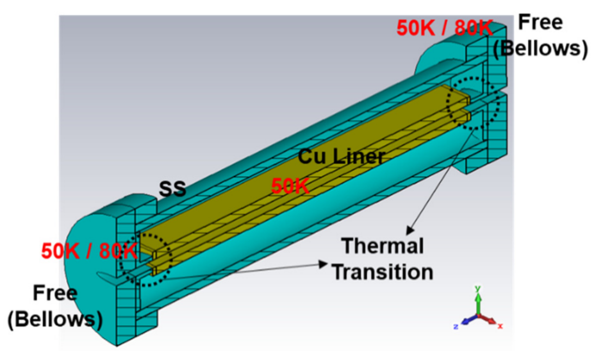

Figure 2: A schematic of the liner and its peripheral components for thermal and mechanical simulations.

In order to estimate mechanical stresses and displacements in the thermal transition and the nearby components at the cryogenic temperatures, the CST Studio Suite® Multiphysics Solver was utilized. The thermal simulation results were imported for the mechanical analyses. Figure 2 shows a schematic of the liner and its peripheral components including the transitions. All components except for the Cu liner and blocks are composed of SS. The 5-µm-thick Cu layer was not considered in the simulations. The boundary condition is free at both end flanges connected to each bellows. From the thermal analyses with Scenario-1, the temperature of 50 K is maintained to be identical all over the components. In measurements, the heat flow will disappear after a thermal equilibrium. The mechanical simulation result in Fig. 3(a) indicates that the maximum Von Mises stress is approximately 36 MPa at the major-axis position of the transition with an elliptical structure, which is far from the yield strength of around 500 MPa for SS at 50 K. The yield strength at room temperature is also known to be 250 MPa for SS. Figure 3(b) represents the displacements in beam (z-) direction. Note that the displacements of the Cu and SS components in transverse positions are almost same. It means that the thermal contractions of the two material in z-direction is not so different. The expected maximum displacement is 1.3 mm, which is similar to the analytic calculation result of ~0.9 mm and can be compensated by the bellows. The maximum displacements in transverse (x- and y-) directions by thermal contraction were also calculated to be ~340 µm.

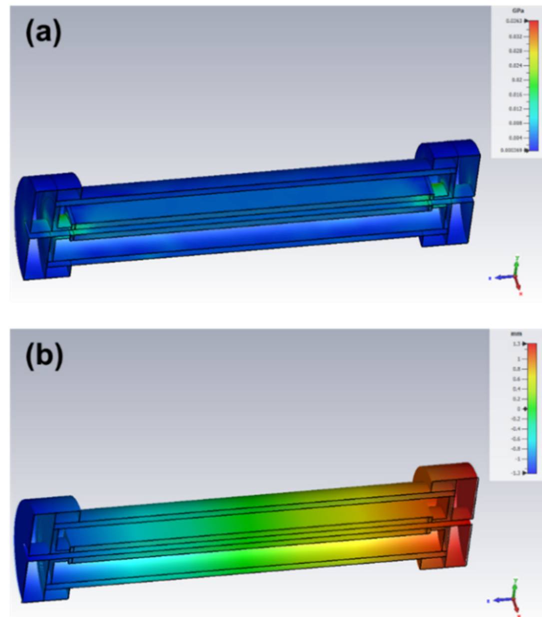

Figure 3: Distributions of (a) Von Mises stress and (b) displacement in z-direction with Scenario-1.

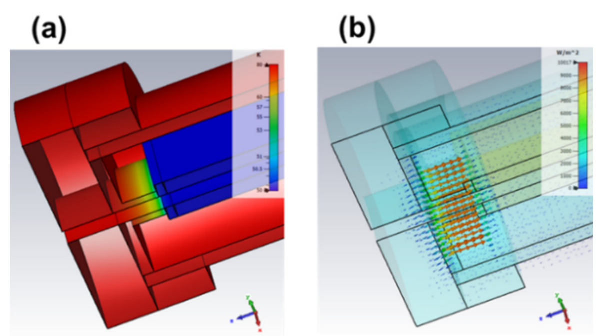

Figure 4: Distributions of (a) temperature and (b) heat flow density with Scenario-2.

The same analyses with Scenario 2 were also performed. As shown in Fig. 4(a), thermal gradients in the transition are foreseen, which originate from temperature difference between the liner and the nearby flange. Figure 4(b) also represents the heat flow from 80 K to 50 K. The maximum mechanical stress is expected to be ~ 276 MPa, which is ~ 8 times higher than that in Scenario-1 but still under the yield strength. The stresses are located at a joint between the transition and the adjacent flange. The two will be machined as a single component for removing possible steps, which will also contribute to the stress mitigation. The yield strengths of the OFHC Cu are known to be 35 ~ 420 MPa at 50 K and 70 ~ 350 MPa at 300 K, depend-

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ing on the material property such as RRR (residual resistivity ratio). The maximum stresses in the Cu liner and blocks were estimated to be around 70 MPa at 50 K. However, mechanical problems for the Cu components have never been reported from previous experiments before the COLDDIAG refurbishment, where the RRR of the Cu ones was ~100. Each thermal contraction in beam direction and in transverse directions was 120 µm and 40 µm, respectively, which are much lower than those with Scenario-1 due to the shield temperature change from 50 K to 80 K.

A MANUFACTURE SCHEME

When the thermal transition is assembled with the nearby components, a step caused by a mechanical error and/or a misalignment should be minimized, which leads to a geometrical impedance by the wakefield of a passing beam. The analytic calculation indicated that a step size of 100 µm in the refurbished COLDDIAG was allowable for beam power losses of several watts with hadron beams at the large hadron collider (LHC) and the FCC-hh [7]. In the case of the DAFNE (Double Annular Φ Factory for Nice Experiments), the maximum power loss of several tens of watts with the same step size was expected due to the high beam current of ~1.5 A [8]. A 50-µm step size is acceptable with the DAFNE beams, considering the cooling power margin in Table 1. Therefore, we aim the step size of 50 µm in the transition assembly. For this reason, the transition and the adjacent components should be machined within a tolerance of ±10 µm.

Figure 5 shows manufacture processes for "a compact transition module". First, a single component of the SS transition and flange is machined to avoid the possible steps, as mentioned in the previous section. The Cu block is trimmed by a depth represented by two opposite black arrows around the ellipse for a convenient alignment with the single SS component. Then, the two components are contacted on the trimmed surface with a minimal mechanical error. Second, the contacted area becomes robust using a permanent joint method. Vacuum furnace brazing is a

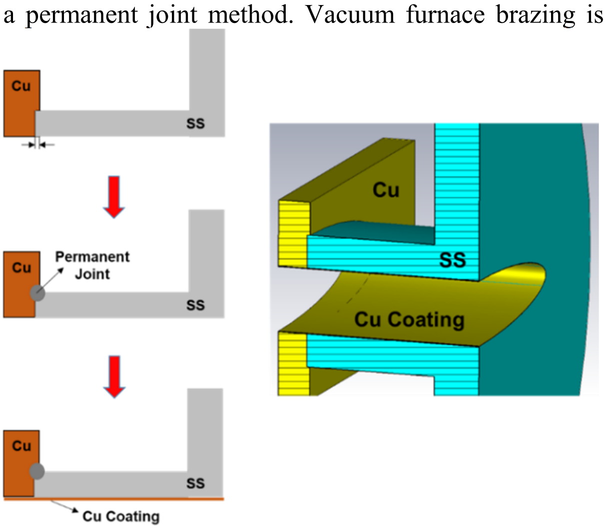

Figure 5: Manufacture processes for a compact thermal transition module.

candidate for the joint at the heterojunction between the SS and the Cu. Lastly, a Cu layer with the thickness of 5 µm is deposited on the inner surface of the ellipsoid with an electroplating technique. Fabrication of the compact transition module is ongoing.

BEAM HEAT-LOAD ESTIMATION

The refurbished COLDDIAG should be installed at the accelerator facilities for more beam heat-load investigations. As one of the feasibility studies, the heat loads by step size and RWH were calculated with the accelerator beam parameters. Figure 6 shows variations of the beam power loss with respect to beam current at the LHC. The power loss with a nominal beam current of 584 mA is estimated to be ~ 8.4 W at our target step size of 50 µm. When the RRR of the OFHC Cu is 100, the beam power loss by the RWH was less than 0.4 W at the same beam current. The operations with a beam current of 1 A will be proper at the DAFNE, considering the cooling power margin enough for the unknown power losses added to ~ 8 W at the 50-µm step size. The beam power loss by the RWH (RRR = 100) was also very low to be ~ 0.5 W with the same beam current at the DAFNE.

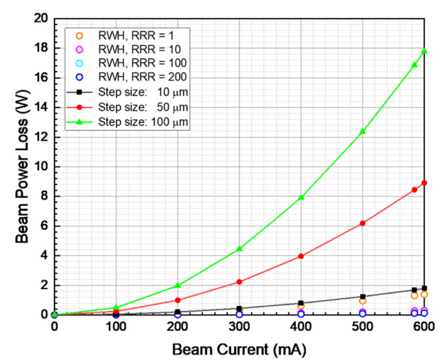

Figure 6: Variations of beam power loss with beam current for different step size and RRR at the LHC.

SUMMARY AND OUTLOOK

We have performed heat intake and thermal budget estimations and thermal and mechanical analyses for the COLDDIAG refurbishment. Two kinds of operations at different cryogenic temperatures are possible by exchanging the existing thermal transitions to newly designed ones. The compact transition module is being manufactured, where precise machining is required for minimizing the steps causing the beam heat load. The mechanical errors will be confirmed by three-dimensional shape measurements after fabrication. After installing the new transition module, the static heat load in the cryostat will be measured and compared to the heat intake estimation for reliable cooling power margin. Calibration of the temperature measured at the liner to the beam heat load using heaters is also planned. In addition, we have investigated the beam heat loads by possible steps and RWH with the LHC and DAFNE beam parameters. More feasibility studies at the facilities are in progress.

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