13th Int. Particle Acc. Conf. IPAC2022, Bangkok, Thailand JACoW Publishing
ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-THPOST027

FABRICATION OF ROBUST THERMAL TRANSITION MODULES AND FIRST CRYOGENIC EXPERIMENT WITH THE REFURBISHED COLDDIAG*

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Abstract

Two sets of thermal transition modules as a key component for the COLDDIAG (cold vacuum chamber for beam heat load diagnostics) refurbishment were manufactured, based on the previous design study. The modules are installed in the existing COLDDIAG cryostat and tested with an operating temperature of approximately 50 K at both a cold bore and a thermal shield. This cool-down experiment is a preliminary investigation aiming at beam heat-load studies at the FCC-hh where the beam screens will be operated at almost the same temperature. In this contribution, we report the fabrication processes of the mechanically robust transition modules and the first thermal measurement results with the refurbished COLDDIAG in a cryogenic environment. The static heat load in the refurbished cryostat remains unchanged, compared to that in the former one (4-K cold bore and 50-K shield with thin transitions), despite the increase in the transition thickness. It originates from the identical temperature at the cold bore and the shield, which can theoretically allow the heat intakes by thermal conduction and radiation between them to vanish.

INTRODUCTION

At Karlsruhe Institute of Technology (KIT), the COLDDIAG (cold vacuum chamber for beam heat load diagnostics) was developed to mainly measure the beam heat loads in a cold-bore vacuum chamber, based on calibration methods with highly accurate temperature sensors [1-5]. It has been refurbished for more beam heat-load studies with different cryogenic temperatures and beam parameters [6]. Two thermal transitions between a cold bore (liner) and a thermal radiation shield are key components for the stable operation of the COLDDIAG. The former transitions for the liner at 4 K and the thermal shield at 50 K should have been as thin as possible to decrease the heat intake by conduction with considering the cooling power of a cryocooler. As a result, the transition with a thickness of several ten microns has been destroyed due to reasons related to its thermal contraction under an ultrahigh vacuum (UHV) [7].

The purpose of this investigation is to check out the mechanical robustness of new transitions for the stable operation and the possibility of practical applications with the refurbished COLDDIAG at the accelerator facilities. In this paper, we introduce the fabrication processes of a thermal transition module with a simple structure based on the previous design [6]. Especially, we consider the identical temperature at both the liner and the shield, which can increase the transition thickness to a mechanically rigid level (theoretically, infinity) from the following equation:

$$H = kA\frac{dT}{dx} \tag{1}$$

where H is a conductive heat intake, k a thermal conductivity, A a cross-sectional area of the thermal transition, dT a temperature difference between the liner and the shield, and dx a length of the transition [8]. A target temperature is 50 K for a preliminary beam heat-load study on beam screens of the future circular collider for hadron beams (FCC-hh), which is also reachable with the existing cryocooler used for the COLDDIAG [9]. The installation of the newly manufactured transition modules in the cryostat and the first cool-down testing with the refurbished COLDDIAG are described in the next section, which can evaluate the thermal and mechanical stabilities of the transitions. Finally, the beam power losses depending on possible beam heat-load sources in the COLDDIAG with the FCC-hh beams are estimated and the work is concluded with a summary and outlook.

FABRICATION OF THERMAL TRANSITION MODULES

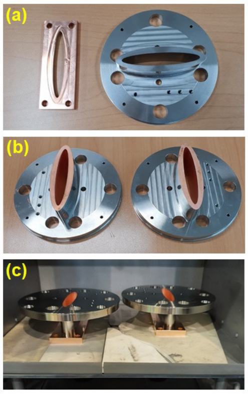

Figure 1: Fabrication processes of two thermal transition modules. (a) Machining of a Cu block and an SS component for a single transition module, (b) deposition of each thin Cu layer inside the SS components, and (c) formation of each permanent joint in a vacuum furnace.

The fabrication of a thermal transition module is based on the design parameters and the manufacturing scheme [6]. Firstly, as shown in Fig 1(a), the machining of an oxygen-free

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* This work is supported by the BMBF project 05H18VKRB1 HIRING (Federal Ministry of Education and Research).
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high conductivity (OFHC) copper (Cu) block and a stainless steel (SS) component, which includes a 5-mm-thick transition and a flange, for a single transition module was performed with a wire cutting equipment. The Cu block and the SS component will be connected to the Cu liner and the thermal shield, respectively, operating at the same temperature of 50 K. The inner surfaces of their elliptical cylinder shapes were polished with diamond powders. The next process is the formation of a thin Cu layer inside the SS component, as shown in Fig. 1(b). It can dramatically decrease the image current from resistive wall heating (RWH) by beams in the SS. The Cu was deposited on the surface by conventional electroplating in a bath. Its thickness is estimated to be approximately 10 μm by reducing the deposition time (but keeping the electric current) for a structurally simple test specimen with a thickness of 20 μm, measured with an optical instrument. The thickness in the original plan was 5 μm, which was doubled for better uniformity without partial absence in the Cu layer. This also does not result in the increase of heat intake in the transition due to the operation of the liner and the shield at the same temperature. Finally, a permanent joint at the contact location of the Cu block and the SS component was formed for mechanical robustness, as shown in Fig 1(c). The brazing, especially reliable at the heterojunction, with an alloy of silver (Ag) and Cu in a vacuum furnace was done at a temperature of 785 °C under a pressure of 3.2×10^{-7} Torr for 2.5 hours. The permanent joint with the transition thick enough (5 mm) is believed to guarantee the mechanical stability of the transition module against the thermal contraction under the UHV in an accelerator beam line. It was also predicted by thermal and mechanical simulations [6]. After sufficient cooling, a final machining process considering a thermal deformation (shrinkage in a length) in the brazing was added and then the transition module was cleaned with an alkaline liquid and the following distilled water. A difference when comparing to the original fabrication scheme is that the thin Cu coating was done before the brazing. For an efficient coating, an etching process with some liquid acid is required to eliminate natural oxide on the inner surface of the SS component. If the Cu coating is done after the brazing, the chemical for etching reacts with the brazing alloy, which can lead to damage and/or leaks in the transition module. This is why the process order was reversed.

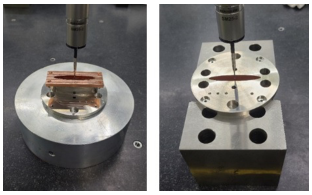

Figure 2: Accurate measurements for key dimensions of the transition modules.

High mechanical accuracy of the transition modules is the only way for a combination with existing components in the cryostat. For this reason, the major dimensions of the two modules were measured with a coordinate measuring machine (CMM), as shown in Fig. 2. The critical dimensions such as the elliptical spaces for beams and the hole-to-hole distances for installation matched up with those in the design stage where the minimum target tolerance was ±10 μm.

INSTALLATION AND ACCEPTANCE TESTING

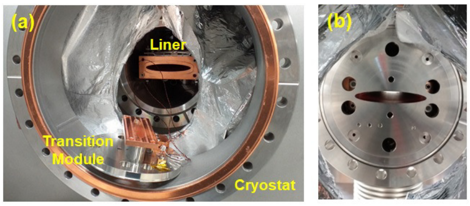

Figure 3: (a) Before and (b) after an assembly of the transition module with the liner in the cryostat.

The two thermal transition modules were installed in the existing COLDDIAG. The Cu block of a module could be connected to the liner using two SS guides fixed to the liner in one diagonal direction and two bolts through the holes in the SS flange of the module in the other diagonal one (Fig. 3). In order to monitor the temperature changes at the transitions, each temperature sensor (Pt100) was attached to both flanges.

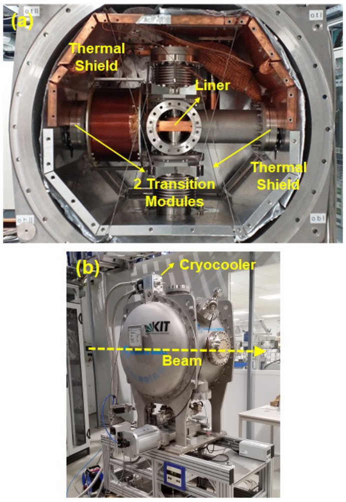

Figure 4: (a) Cryostat inside and (b) the refurbished COLDDIAG with a cryocooler.

Figure 4 shows photographs of the refurbished COLDDIAG. Each transition module was assembled to both ends of the Cu liner which has the respective 8 temperature sensors (Cernox 1050-SD) on its top and bottom to measure the beam heat loads. The cryocooler (two-stage Gifford-McMahon type, model: SRDK-415D-F50H, manufacturer: Sumitomo Heavy Industries, Ltd.) for the previous experiments with 4-K liner and 50-K shield was used again for the refurbished COLDDIAG. The 1^{st} stage of the cryocooler, working from ~30 K to 110 K, was connected to the Cu thermal shield which enabled the transition modules and the liner to be cooled and finally reach 50 K for the FCC-hh application. A Cu strap from the shield was also connected to the liner for achieving the same temperature with more efficient cooling. The 2^{nd} stage working from ~3 K to 18 K for the liner at 4 K was isolated in the cryostat. The original COLDDIAG had two warm sections (liners) at both ends of the cryostat in a beam direction for mutual comparison in experiments with beams, which were excluded from this campaign as an acceptance test.

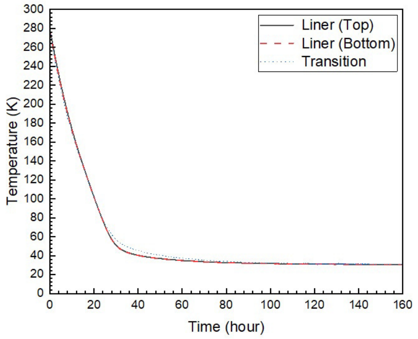

Figure 5: Temperature measurement results with time at the liner and the thermal transition, respectively.

The cool down was begun at a vacuum pressure of ~3 $\times 10^{-5}$ mbar by a combination of a turbo molecular pump (TMP) and a scroll one with an additional diaphragm one in another port. Figure 5 shows the measurement results of temperature depending on time, where the curve for the transition was calibrated by those for the liner owing to the used different kinds of sensors. After a thermal equilibrium, the average temperature at the liner is coincident with that at the transition modules, which leads to the absence of conductive heat intakes in the transitions. The reachable minimum base temperature was ~31 K, which was almost the same as that for the 1^{st} stage in a cold head capacity map of the cryocooler [10]. In order to measure the beam heat loads on the FCC-hh beam screen, it is possible to increase the temperature to 50 K using a heater at the 1^{st} stage. The static heat load in the cryostat is expected to be equal to that before refurbishment, even though the transition thickness was increased to 5 mm by a factor of ~25 to 100 [4, 6]. The vacuum pressure was much more dropped by the cryopumping with the cool down and maintained at ~2 $\times 10^{-8}$ mbar at 31 K. The stable operation of the COLDDIAG for about 2 weeks also represents the mechanical robustness of the new transition modules.

The COLDDIAG should be operated with cooling powers enough for a variety of beam heat loads such as a geometrical impedance and an RWH. For this purpose, it is considered applying each heater to the 1^{st} and 2^{nd} stages to make the same and higher temperature at the thermal shield and the liner, respectively, as the second operation scenario. In this case, each stage can have more cooling power allowing for the beam heat loads. For example, when the temperature of the 1^{st} stage arrives at 50 K, the cooling power increases from no margin at the base temperature of 31 K to 40 W, as shown in the capacity map. Furthermore, if the 2^{nd} stage is heated to 50 K, the cooling power will have an additional margin of ~32 W [11]. Such operations with a variable temperature are also intended for accelerators working at cryogenic temperatures different from 50 K.

BEAM HEAT-LOAD ESTIMATION

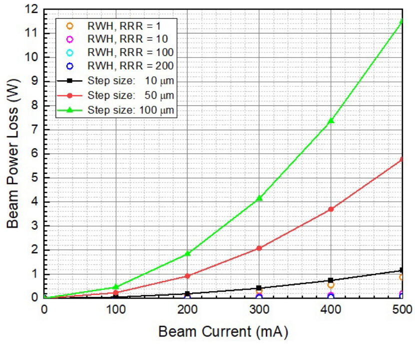

Figure 6: Variations of a beam power loss with a beam current for different step sizes and RRR's in the liner with the FCC-hh beams.

The COLDDIAG has been characterized to investigate the beam heat loads at 50-K cold bore. In particular, the FCC-hh is a candidate for a feasibility study with the refurbished COLDDIAG. The beam heat loads by a geometric step and RWH were analytically calculated with the beam parameters [9]. The variations of the beam power loss with respect to a beam current are shown in Fig. 6. The power loss at a nominal beam current of 500 mA is estimated to be less than 6 W at our target step size of 50 µm [6]. If the cold-bore liner is replaced by a Cu cylinder having a diameter of 27 mm, which is similar to that of a beam screen at the FCC-hh, the estimated beam heat load is ~3.7 W at the step size. When the RRR (residual resistivity ratio) of the OFHC Cu is higher than 100, the beam power loss by the RWH is negligible at the same beam current (~84 mW at RRR = 100).

SUMMARY AND OUTLOOK

We have refurbished the COLDDIAG with mechanically robust thermal transitions. It could be realized from the theoretical zero-conductive heat intake in the transition due to an identical temperature at the cold bore and the thermal shield. The temperature was set to 50 K for investigating beam heat loads on the FCC-hh beam screen. For this purpose, the experiments for calibration of a temperature above 50 K measured at the liner with heaters to a beam heat load are planned. The COLDDIAG operation at different cryogenic temperatures can be also considered because it is possible to substitute the existing liner with a vacuum chamber used at accelerator facilities. We hope that the COLDDIAG could be utilized with various vacuum chambers, operation temperatures, and beam parameters to more deeply understand the beam heat-load mechanism.

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