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PRODUCTION AND VALIDATION OF THE RF COOLING DAMPER FOR THE LHC INJECTION KICKERS*

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Abstract

Fast single-turn injection kicker systems deflect incoming beam onto the orbit of the LHC. The higher intensities of High Luminosity (HL) LHC beams are predicted to cause the ferrite yokes of the LHC injection kicker magnets (MKI), in their current configuration, to heat up to their Curie temperature. Studies to reduce the beam induced heating have been carried out over the past years and resulted in a design featuring a water-cooled RF damper. A significant portion of the beam induced power has been relocated from the yoke to a ferrite in the RF damper. The ferrite damper is cooled via a copper sleeve, brazed to the ferrite, surrounded by a set of water pipes. The manufacturing of this RF damper system is challenging since different materials are brazed together to form a complex and fragile assembly, optimized for heat transfer, and installed in an ultra-high vacuum environment. This paper outlines fabrication methods and their reproducibility, compares the results of measurements of the thermal interface between the ferrite and copper sleeve, and concludes on the challenges of assuring a production technique that results in a reliable and suitable thermal interface.

INTRODUCTION

The LHC is equipped with two injection kicker systems (MKIs) to deflect incoming beam onto the LHC orbits [1]. The yoke of the MKI magnets is ferrite [2, 3], which is a lossy material: hence, the electromagnetic fields of circulating high intensity beam result in significant heating. If the ferrites reach their Curie temperature of ≥125°C [4, 5], they will temporarily lose their magnetic properties [2] which would result in a mis-kick of injected beam. To reduce the beam induced heating, screen conductors are placed in slots of an alumina tube inserted into the magnet's aperture, providing sufficient beam shielding up to and including LHC run III [6]. However, for HL-LHC, the beam induced power deposition in the yoke had to be reduced further. Thus, the design features a water-cooled radio-frequency (RF) damper which relocates a significant portion of the beam induced power from the yoke to a ferrite cylinder in the RF damper [7, 8]. The RF Damper consists of a copper cylinder which encloses a 60 mm long, cylinder of CMD10 ferrite [7, 8]. The copper cylinder is equipped with an outside water-cooling circuit to cool the ferrite [7, 9, 10]. The assembly, located outside of the magnet's aperture, is brazed to a stainless-steel tube, and mounted on the alumina tube (Fig. 1).

A design study for the RF Damper was presented in [9, 10] where the manufacture of a prototype was described. The principal requirements for joining the copper and ferrite cylinders were: (a) a good thermal contact between these cylinders, (b) a low residual stress on the ferrite ring to avoid potential cracking, and (c) the use of a filling material which would not melt during magnet bake-outs to 300°C.

Following the study in [9, 10], two RF Damper assemblies were manufactured, verified to have good thermal contact [11] and installed in MKI Cool magnets. One of these MKI Cools was installed in the LHC during year end technical stops in 2022 [12] and 2023. Both have good operational performance [12]. However, during manufacturing of more RF Dampers, a poor contact with visual gaps between the copper and ferrite cylinders, and deformations of the copper cylinder, were observed: measurements showed insufficient thermal conduction between the copper and ferrite cylinders. Thus, a new campaign to investigate manufacturing techniques, for the RF Damper, was launched.

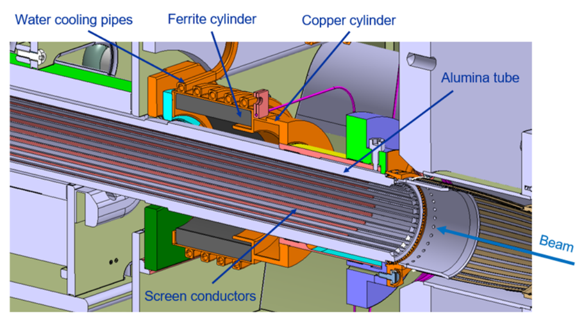

Figure 1: Cross-section of RF Damper assembly.

MATERIALS AND METHODS

The campaign consisted of several investigations: (1) brazing tests to understand how to control the process to achieve good thermal contact and ensure reproducibility; (2) repair of brazing for already manufactured RF Dampers with poor thermal contact; (3) test of cold shrinking the copper cylinder to the ferrite cylinder; (4) testing of a copper spray technique where a copper layer is directly applied on the ferrite cylinder.

Brazing Tests

As mentioned above, the brazing technique to join a ferrite ring to a copper OFE sleeve was already studied in [10]. At that time, the main issue for joining these two materials was the difference of the thermal expansion coefficients: copper has (17–20 × 10^{-6}/K [13]) and the ferrite ceramics (7–8 × 10^{-6}/K [14]). Therefore, metrology of the copper sleeve, to ensure perfect fitting with the ferrite, is needed and, the preparation of the joining surface of the ferrite is essential to provide sufficient wettability during the brazing process. The difference of thermal expansion of these two materials required a well-controlled setup and

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external constraint of the copper cylinder by molybdenum wire [10].

Preparation of test samples

Initially two test samples were brazed, following the procedure defined for the successfully manufactured RF Damper [9], to evaluate potential steps requiring better control. These test samples each consisted of two relatively short ferrite rings 4M2 or 4B3 [14] and a copper sleeve (Fig. 2). The difference between the samples was that one had six lateral grooves, each of 0.3 mm width, machined in its sleeve to allow better constraining with molybdenum wire and to allow potentially trapped air to escape.

To be able to achieve the correct dimensional fit of the copper sleeve, the external diameters of the ferrite rings were measured, and the sleeves' inner diameters were adjusted to have <0.1 mm gap. The copper wasn't annealed so no major deformation was expected during machining.

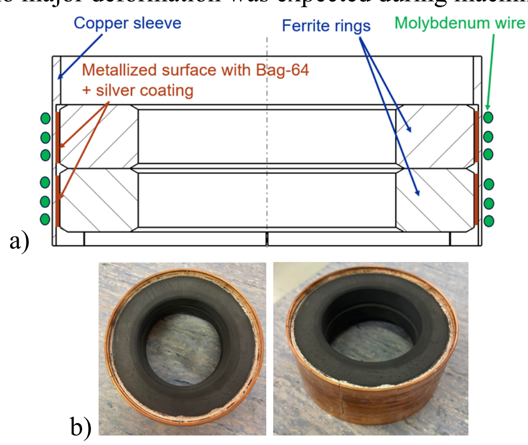

Figure 2: Test sample: a) Assembly, b) Brazed: sleeve without grooves (left) and with grooves (right).

Prior to applying the filling alloy AWS BAg-64 (melting point 779°C), heat treatment of ferrite is important, as it prevents undesirable peeling-off of the BAg-64 layer. The firing cycle is shown in [10]. The AWS BAg-64 alloy is then applied by brush on the ferrite ring. The brush application does not ensure a perfectly uniform surface layer and, additionally, the ferrite absorbs irregularly the BAg-64 alloy, dependent upon ferrite firing, which results in circularity defects of the layer. The BAg-64 is then dried, and the joining surface is silver plated (~15 µm). This silver-plating layer is very beneficial because it reacts, during brazing, with the copper sleeve to the eutectic phase and creates a liquid filler material [10]. According to ultrasound, it improved the joint contact to 90% from an initial 33% without silver plating. The 90% of joined contact had previously been shown to give a good thermal contact [11], hence 90% was considered as a minimum filling criterion.

Repair of brazed RF Damper

An investigation of a possible brazing repair, of the already manufactured RF Dampers, with poor joint contact, was carried out. Two approaches were chosen. The first RF Damper underwent additional brazing with a lower melting point (745°C) solder, INCUSIL®10 filling wire (63% Ag, 27% Cu and 10% In), placed at the interface: it was hoped that this would melt and fill empty spaces between copper and ferrite: remelting of the BAg-64 from initial brazing is undesirable. The second approach was to drill small lateral holes along the brazing area to allow any potentially trapped air to escape during the brazing. This brazing also used INCUSIL®10 filling wire.

Cold Shrinking

The cold shrinking assembly technique was considered to compare the thermal contact performance of a brazing-free joint. Metrology of a ferrite ring sample was carried out and the inner diameter of a copper sleeve was then machined to have a 20 µm interference after the assembly when considering thermal dilatation of both materials. The copper sleeve was heated up to 230°C and the ferrite ring, at room temperature, was inserted.

Copper Spray

A copper spray technique was considered as an alternative to brazing. This cold-spray additive manufacturing technology is based on thermomechanical deformation of particles accelerated by compressed gas in the spray nozzle and then deposited at high speed, of up to 1200 m/s, to the substrate [15, 16]. The expected porosity for copper cold-spray is about 0.1 – 1 % [16].

A full size CMD10 ferrite was used for the first trial to evaluate the uniformity of a copper sprayed layer, its ultra-high vacuum compatibility, ability to withstand thermal cycles up to 300°C without peeling off and thermal contact performance.

RESULTS

As mentioned above, the contact at the interface between ferrite and copper is crucial. Two methods of evaluating this were used to assess the thermal interface of the test samples. Firstly, ultrasound or X-ray tomography was performed of the interface. Secondly, thermal measurements were carried out according to the procedure described in [17] and the thermal contact conductance (TCC) was determined. According to [10], all measured TCC values along the joint should be ≥1000 $W/(m^2{\cdot}°C)$. If the TCC is lower than this limit the ferrite cylinder of the RF Damper could crack [10]. In addition, if beam induced power is not adequately removed from the ferrite of the RF damper, this could result in further heating of the MKI ferrite yoke [9], and eventually mis-kicking of the injected beam.

Brazing Tests

Figure 3 shows the ultrasound echo from the interface of the brazing of two test sample. A high amplitude (yellow and red) indicates a lack of filler metal, and a low amplitude (blue) represents presence of filler. The brazing coverage of joints was very poor and can be considered as unbrazed. The horizontal lines with slightly better contact represent the molybdenum wire constraining the full assembly during brazing (Fig. 2). The ultrasound of the brazed sample with grooves showed slightly better contact, mainly at the grooved area.

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The transient thermal test was carried out after soldering cooling pipes on to the copper sleeve (Fig. 4). The measured TCC values of the brazed test samples, with small ferrite rings, cannot be directly compared with the larger CMD10 ferrite cylinder, because of different geometries and potentially different ferrite properties, however the trend can be compared.

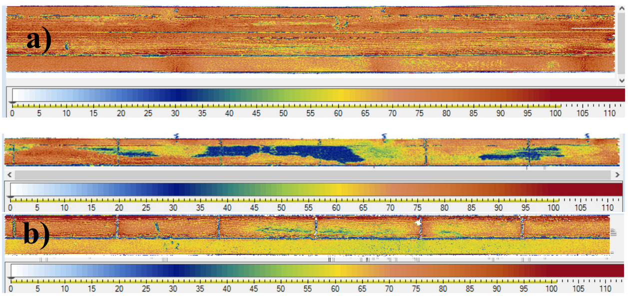

Figure 3: Mapping of ultrasound echo from brazing interface of the two test samples: a) Brazing without grooves in the copper sleeve. b) Brazing with lateral grooves of 0.3 mm in the copper sleeve.

Table 1 shows the TCC average of six measured points around the circumference of the test sample: all TCC values should be above 1000 $W/(m^2{\cdot}°C)$ [10]. The TCC of the brazed test sample without grooves was better than the 1000 $W/(m^2{\cdot}°C)$ limit: however, the test sample with grooves did not reach this value, despite a slightly better brazed filling according to the ultrasound mapping (Fig. 3).

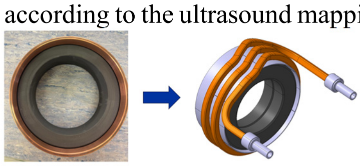

Figure 4: Soldering of copper water cooling circuit on to the test samples.

Table 1: Averaged Measured Value of TCC with Standard Deviations (std) for Brazed and Cold Shrink Samples

		TCC average $W/(m^2{\cdot}°C)$	TCC std $W/(m^2{\cdot}°C)$
Brazing	without grooves	1285	223
	with grooves	957	128
Cold shrinking		1848	386

Concerning the correlation between ultrasound mapping and TCC measurements, from what was observed, even a poor filling brazing joint can reach adequate TCC at the copper and ferrite interface. This suggests that 90% minimum filling criterion may be too restrictive for preliminary assessment of the suitability of an RF Damper. Nevertheless, the acceptance of an RF Damper is based upon the measurement of the TCC [17]. To further understand the poor brazed interface, the test samples will undergo metallographic cut and investigation.

Thermal measurements were also performed on the repaired RF Dampers from previous production and both assemblies had acceptable TCC, however for the second one, the ferrite cracked during the process.

Cold Shrinking

The evaluation of uniformity of copper and ferrite interface by ultrasound was not possible because no filling material is present. Thus, X-ray tomography with a Zeiss METROTOM 1500 CT scanner was conducted instead. One scan was performed with a voxel size of 53.01 µm (Fig. 5). At this resolution, no gaps were detected between the ferrite and copper sleeve. Due to the resolution used in the µCT analysis, it is not possible to determine whether smaller gaps are present at the interface.

Thermal measurements were performed, as for the brazed test samples. The average TCC of nine measured points around the circumference is compared in Table 1 with the brazed samples and it was approx. 50% higher than the brazed sample without grooves.

To further investigate the potential of the cold shrinking method, thermal cycles up to 300°C, which represent the magnet bake-out temperature, are ongoing. Subsequently the TCC will be remeasured to determine if there has been any degradation of the thermal interface. The cold shrinking will be tested also on the CMD10 full size ferrite cylinder.

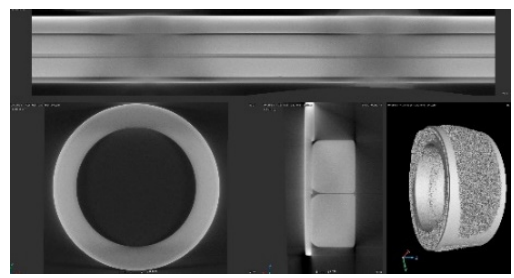

Figure 5: X-ray tomography scan with unrolled, top, cross-section and 3D view.

Copper Spray

No TCC measurement results are available yet for the copper sprayed full size ferrite cylinder.

CONCLUSION

Several tests and investigations were performed, not only to fully understand and to control the current brazing process but also to identify an alternative method to ensure production of a reliable and suitable thermal interface between the copper cylinder and ferrite of the RF Damper. This study showed that the ultrasound evaluation of the interface does not properly assess the efficacy of the thermal contact. Nevertheless, the acceptance of an RF Damper is based upon the measurement of the TCC. However, the ultrasound remains an important validation for the mechanical stability of the brazing. The cold shrinking and copper spray methods are showing high potential and further testing, and design work is planned.

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