Measurement of Flexible Cooling Link Conductance for X-Ray Monochromator Applications

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Abstract:
The thermal performance of copper (Cu) flexible cooling links was measured at cryogenic temperatures. The aim was to characterise what was commonly in use at The Diamond Light Source Ltd (DLS), in order to select the best option for the In-house Double Crystal Monochromator (DCM). A stack of annealed, 50 μm thick, copper foils was found to be superior to the crimped braid assemblies typically used, in terms of flexibility and conduction efficiency. At 100 K, the crimped braid and foil stack exhibited conduction efficiencies of 54% and 95% respectively. A production method has been developed and the thermal links have been successfully utilised on the I09 and I23 DCMs at DLS, to conductively cool the 2nd crystal via the 1st crystal liquid nitrogen (LN_2) manifold.

1-Introduction
Synchrotron facilities such as The Diamond Light Source Ltd are designed to produce intense beams of light for scientific investigation. High power densities generated by insertion devices, necessitate the use of cryogenic cooling for DCM optics. Many DCMs at DLS and around the world use Cu braid as a thermal link. They are used to thermally stabilise assemblies via a connection to a water manifold and to cool crystals indirectly from a LN_2 manifold. Cu braid has the benefit of relative mechanical isolation while maintaining a thermal contact.

1.1-Motivation for Study

Many instruments such as DCMs operate successfully at DLS using crimped braid assemblies for thermal links; however there is room for improvement. The thermal conductance of the DCM 2nd crystal cooling braid assemblies, define two main operational parameters; 2nd crystal temperature and thermal stabilisation time. The first MX beamlines built at DLS, observe a mechanical stabilisation time when the shutter is opened, of 30-45 minutes. During this period the 2nd crystal pitch must be driven to compensate for the drift. The 2nd crystal thermal stabilisation time correlates to the mechanical effects, suggesting an improvement in the cooling efficiency would reduce the equilibration time.

The results and conclusions of this study could be applied to the existing as well as future monochromators. A better knowledge of the thermal performance of the braid links will aid future design processes.

1.2-Thermal Properties of Cu Joints

The standard method used to connect braid is to crimp Cu lugs onto each end (See Figure 1). These blocks are then bolted on to the cooling manifold and the part to be cooled. It is difficult to braise the joint because it tends to wick up the braid. The crimp method creates four interfaces, all of which will have a thermal contact conductance (TCC). The effective thermal conductivity is a combination of the interface effects and the bulk properties. The thermal conductivity of OFHC Cu over a wide temperature range is readily available [1]. A number of studies have measured the TCC across Cu-Cu joints over a range of interface loads and over a range of temperatures (Ref Table 1). The main problem with applying these values is wide spread in published data. The TCC depends upon a number of variables; Surface roughness, Surface contamination e.g. oxidation, Interface force not pressure (for high loads with Cu-Cu Joints), Interface area (low loads, when using interstitial materials e.g. Indium foil)

Table 1: Published Thermal Contact Conductance (TCC) of Cu-Cu Joints

Temperature (K)	Area (cm^2)	Force (N)	Conductivity ($Wm^{-2}K^{-1}$)	Conductance (WK^{-1})	Ref
77	0.79	226/886	2050/8400	0.572/2.34	[2]
326/355	3.5	9993	70000/190000	24.5/66.5	[2]
110/300	1.3	504	1680/3770	0.2184/0.490	[2]
50/100	-	500	-	0.08/0.1	[1]
100/300	0.012	485	1500/3000	0.019/0.037	[3]
80	-	150	-	0.060 (Ra 3.2)	[4]
80	-	150	-	0.113 (Ra 0.2)	[4]

2-Conductance Estimations for Cu-Cu Joints

A simple numerical model of the DCM installed on the DLS beamline I18 was created. The cooling circuit from the LN_2 manifold to the 2nd Si crystal, was modelled to estimate the Cu-Cu interface conductance. The measured temperature rise when the shutter was opened, along with the estimated absorbed heat-load on the 2nd crystal, leads to an average interface conductance of approximately 0.4 W/K. When compared with the published values (See Table 1), this suggests either the interface force for the braid is ~500 N or that the interface is compromised by another factor such as flatness, contamination or surface finish. A typical tight M4 bolt force measured with a loadcell, was found to be in the 1000 – 1500 N range. There are two M4 bolts securing most of the braid lugs. The published test samples mostly have a tighter surface finish tolerance, than the typical Ra 3.2 µm specified on the DLS components. So the numerical spreadsheet model appears to give a conductance value which is at least consistent with published data.

3-Thermal Conductance Measurement Test Rig

A test rig was built to measure four thermal links simultaneously. An image of the assembly is given in Figure 1 and a schematic is given in Figure 2.

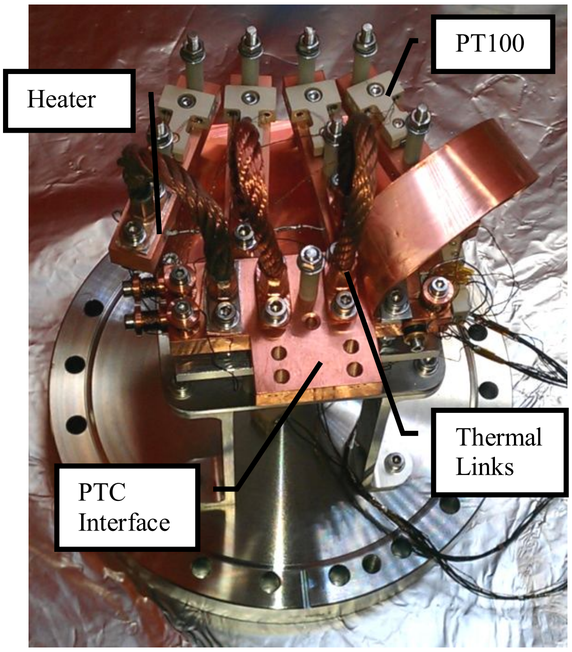

Figure 1: Test Rig assembled with three braid links and one foil stack

The apparatus was designed to measure the temperature drop across the thermal links for a given common supplied heatload. The thermal isolation was provided by G10 tubes for the four Cu mount blocks and three glass balls for the common Cu plate, which interfaced to the pulse tube cryo-cooler. PT100 temperature sensors were pushed into contact with the Cu blocks using a film of Apiezon grease to ensure a good thermal contact. The PT100 temperature sensors were read by a Lakeshore controller and recorded by the standard EPICS PV archiver. A manual power supply was used for the sample heaters which were wired in series. The Lakeshore controller was used to drive the common plate heater in closed loop.

The conductance is defined as = ΔPower x ΔTemperature^{-1}. Changes in power and temperature were used rather than absolute values in the calculation to cancel out systematic errors.

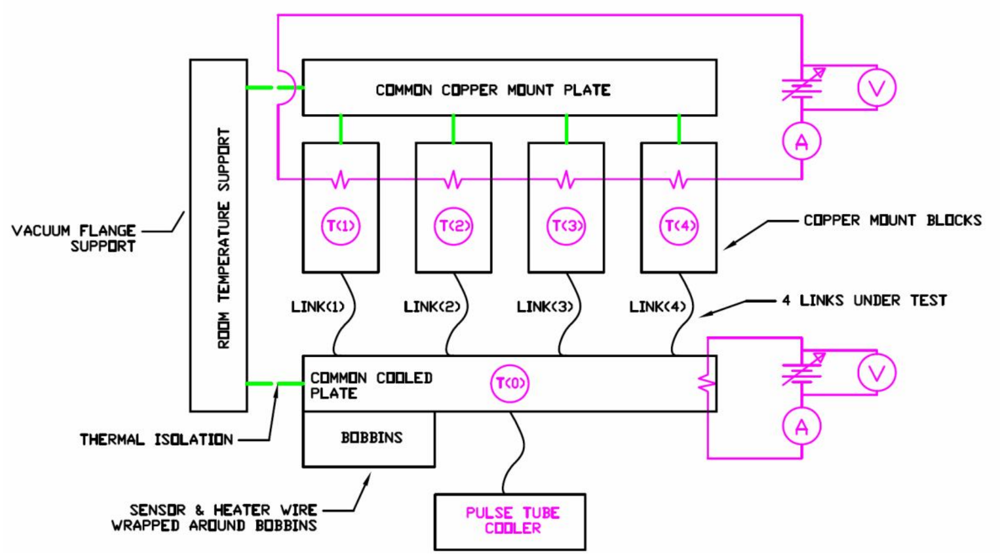

Figure 2: Diagram of the electrical and thermal connections of the test rig

4-Experimental Results & Discussion

The first test performed with the test rig was with four nominally identical braid assemblies. Although there was a variation in measured conductance of ± 8% there was no correlation between location and conductance of the test samples.

The results presented are for four thermal links. The four samples were: 1) A crimped braid assembly with an Indium layer at the bolted interface and a solder potted crimped interface 2) A crimped braid assembly with grease at the bolted interface 3) A standard plain Cu crimped braid assembly 4) A stack of 12, 150 mm long by 25 mm wide, 50 μm thick OFHC foils. The OFHC braid used had a solid cross section area of 16 mm^2 and an exposed length of 100mm. The foil stack had an exposed length of 125 mm and a cross sectional area of 15 mm^2.

To achieve the lowest test temperatures, initially only the sample mount block heaters were used.

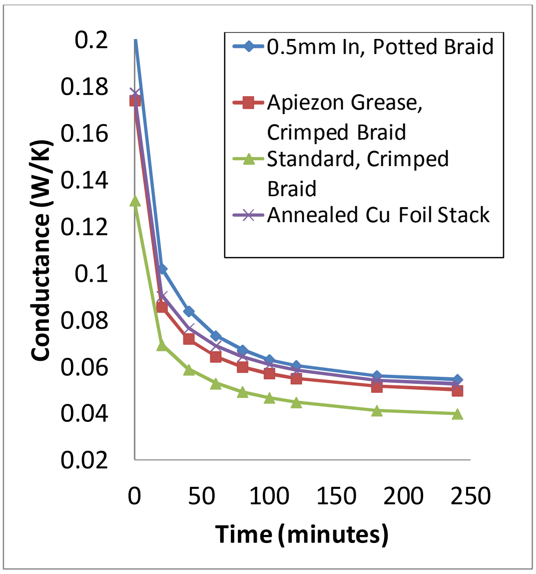

Figure 3: Thermal Conductance measurement stabilisation, from application of sample heatload with a final common cooled plate temperature of 90 K.

It is clear from Figure 3, that the commonly used plain crimped braid gives the poorest thermal performance. The Apiezon vacuum grease increases the contact area by filling the voids within the bolted joint. Despite the vacuum grease having a relatively low bulk thermal conductivity, the enlarged effective contact area increases the TCC. This conductance improvement suggests that either the flatness or surface finish of the mating parts could be improved. The higher conductance of the solder potted sample might suggest that there is room for improvement at the crimped interface as well. The thermal efficiency i.e. the ratio of measured to calculated conductance (using only bulk conduction, no interfaces) for the four samples was; 75%, 68%, 54% and 95% as numbered above. A preliminary study using a non-annealed, folded and hence stiff Cu foil stack, gave very poor results. Both foil samples had the oxide removed. A 10% Acetic acid dip was used for the folded sample [4]. The vacuum annealing process decomposed the oxide in the presented sample. This comparison suggests that the superior foil performance presented here, is due to the compliance of the foil and its ability to conform to the mating part.

In this operation the temperature of the common plate increased with input power and took hours to stabilise. A long term drift in temperature and hence calculated conductance was observed. The likely cause was the influence of the ambient temperature variation through the thermal isolation conduction and radiation.

4.1-Closed-loop Common Cooled Plate Temperature Tests

The 2nd test mode was to hold the common cooled plate at a constant temperature by driving the heater in closed loop with the T(0) PT100. The data presented also used an increased sample input power from 0.2 W in Figure 3, to 2.4 W in Figure 4, in order to raise it above the thermal leakage through conduction (~0.2 W through G10 tubes and wires) and radiation (~0.05 W Black Body Radiation). This mode successfully improved the measurement repeatability but the increased heatload raised the required common plate temperature up to 226 K. The measurements follow the same trend as shown in the previous section; however due to parasitic heat sources and electrical resistance the measured conductance is an over estimate. The data presented in Figure 4 have been corrected for:

- Thermal conduction through the G10 supports and electrical wires which varies linearly with temperature
- Black Body Radiation from the vessel walls and surrounding structure
- Electrical resistance of the heater wires which acts as a resistor in series with the heaters
- PT100 systematic error caused by a resistance offset

The measured conductance values post error correction were: Solder potted braid 0.050 W/K, greased joint braid 0.045 W/K, standard braid 0.042 W/K and foil stack 0.050 W/K.

There were other sources of error such as; the measurement of the physical dimensions, the thermal conductivity, material specification and the temperature gradient within the Cu blocks between the PT100 and the test sample interfaces.

No error bars have been drawn because the size is difficult to estimate.

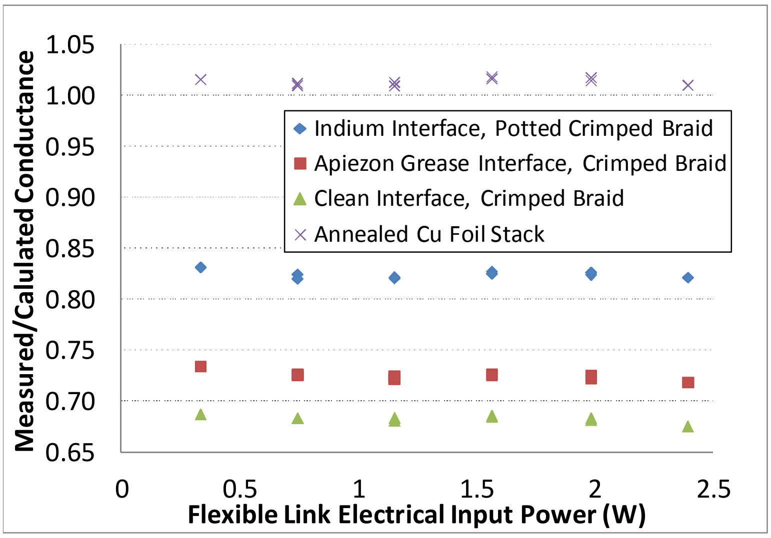

Figure 4: Thermal link efficiency (Measured Conductance/Calculated Bulk Conductance)

5-Conclusion

The 100 mm long crimped braid assembly commonly used at DLS, has a thermal conductance of 0.04 W/K in the 100 to 260 K temperature range. This can be improved by potting with solder but this stiffens the braid and is variable. The foil stack tested with a similar cross section to the braid, and being 25% longer with higher flexibility, has an improved conductance of 0.05W/K and achieves near theoretical conductance of the solid copper involved.

The foil thermal links have been successfully utilised on the I09 & I23 DCMs at DLS, to conductively cool the 2nd crystal via the 1st crystal providing equivalent cooling but superior mechanical isolation to the original braid assemblies.

To measure more accurate conductance values in the future, the PT100s should be calibrated, radiation shielding should be added and the G10 thermal isolation should be improved.

References

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