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# COPPER BRAID HEAT CONDUCTORS FOR SIRIUS CRYOGENIC X-RAY OPTICS

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*Abstract*

The low emittance and high photon flux beam present at the 4th-generation Sirius synchrotron light source beamlines result in high energy densities and high heat loads at some specific X-ray optics such as monochromators and white beam mirrors. This challenges the design of such systems since the introduction of thermal stresses may lead to optical surface deformation and beam degradation. Thus, to keep the systems within acceptable deformations some of the optical elements are cryogenically cooled. However, this poses the requirements of decoupling the thermal sinks (cryostats) from the optics and the mechanisms to maintain their desired degrees of freedom for alignment and dynamic operation. In this context we present the development of low-stiffness copper-braid-based heat conductors, summarizing the motivation and main aspects regarding their fabrication and application at the beamlines.


## INTRODUCTION

For high heat-loads monocrystalline silicon optics at Sirius beamlines, one of the standard design concepts for beam-load deformation suppression is the use of liquid nitrogen ($LN_2$) cryostats for cooling the elements down to near 125K, where their coefficient of thermal expansion is virtually zero and deformations due to thermal gradients are minimized [1]. In this context, low-stiffness copper braids are widely used to thermally couple the optics to the cryostats while limiting the mechanical coupling between them, such that external vibration disturbances are avoided and kinematic is preserved. Even though commercial solutions for cryogenic, ultra-high vacuum (UHV) compatible copper braids exist worldwide, the high costs, long lead time and customization limitations stimulated the development of an in-house solution with local partners. For special applications, either because of complex geometry or heat extraction capacity, smaller braided modules can be soldered into larger systems using low temperature fillers.

## COPPER BRAID MANUFACTURE

The basic manufacturing process consists in cold forging (ambient temperature), or *pressing*, copper ropes inside bulky copper terminals. The copper ropes are usually made from cold-drawn thin wires stranded together to form a small braid with the diameter in the millimeter range. This results in an all-copper, weld free braid system with solid ends that can be machined for different geometries. As there is no metallurgical joint between the wires themselves and the end-blocks, the heat must be carried across multiple contact interfaces, making the correct design of these interfaces a point of attention. Furthermore, the copper thermal conduction at low temperatures has a strong correlation with its electrical conductivity [2] and is heavily affected by impurities as oxygen and sulphur, leading to the correct material selection [3].

### *Commercial and 1st-Generation In-House Braids*

An initial effort of in-house development of copper braids for mirrors and monochromators was made between the years of 2017 and 2019. The first systems were designed by the LNLS team and manufactures by a local partner (Barbanera Qualità) and consisted of pressing multiple braids of 2.5mm in diameter inside electrical-discharge-machined (EDM) cavities in the electrolytic copper end-blocks. The braids were made of 588 40 AWG stranded electrolytic-tough-pitch (ETP) copper wires by the national manufacturer Indel LTDA. The pressing was performed with a 100-ton hydraulic press in an open-die fashion, i.e. without any mold. The compaction criteria were visual, with the pressing process being stopped when there were no visible gaps between the wires and the block. The large end-blocks were then machined, and the entire braid system gold plated to reduce radiation heat transfer.

Despite the good geometry and low-stiffness results, they presented much lower thermal conductivity when compared to commercial systems that were already in use. In fact, some of the braided systems had a tested performance as low as 57% of the theoretical calculated thermal conductivity (CATERETÊ beamline M2 braid). Initial investigations performed via microscopy, after cutting both a commercial braid and an in-house one (Fig. 1), highlighted the potential culprit, namely: the poor wire compaction inside the end blocks. It was found that the cross section of the first one had an average void density of 4.2%, whereas the problematic one had 24.1% (ImageJ). Also, the wires were much less deformed, leading to limited contact area between them due to insufficient pressing forces. This resulted in a poor thermal coupling among both the wires themselves and the end-blocks.

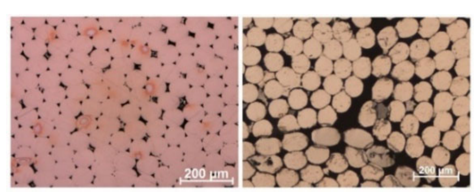


Figure 1: Micrographies of the commercial (left) and the 1st-generation in-house (right) solutions from section-cut of the braids inside the end-blocks.

The hypotheses for the bad pressing consisted of a combination of insufficient hydraulic pressing forces and excessively large and stiff end-blocks, resulting in low plastic

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deformation. These results led to new efforts being made towards improving the manufacturing process, focusing on better compaction and deformation of the wires.

### *2nd-Generation In-House Braids*

To reduce the end-block stiffness for better pressing, we abandoned the concept of starting from the large copper blocks for subsequent machining. Instead, those terminations were standardized as 1x1x1/4" (LxWxH) for systems with a single row of 9 of the same 2.5mm ETP braids, and 1x2x1/4" for the single-row 18-braid ones. In this manner, most of the termination internal volume was comprised by the wires. After the pressing, the blocks were fine machined to remove the extra material (approx. 1 mm) and for hole drilling. Also, the blocks were manufactured out of completely annealed OFHC copper, increasing the load transfer to the wires due to their low yield strength. The pressing strategy and load were varied aiming the lowest void density among wires.

### *Open Versus Closed Die Pressing*

Initial tests with the new 9 braids, 1x1" geometry was performed without any die and a pressing load of 30 Ton (456 MPa). While already achieving a better pressing performance, as compared to the 1st-generation systems, the open fashion resulted in an anisotropic wire load distributions and highly deformed end-block, making it difficult to machine the final form. Also, the load could not be further increased without breaking the blocks.

To better distribute the pressing loads to the wires and blocks, a U-shaped, 2-part die was machined out of high-speed steel (HSS) with the exact final geometry of the desired end-blocks. Then, new tests were performed with the same load. The void densities achieved were 6.6 and 6.8% for the open and closed die, respectively.

### *Pressing Load*

A new U-shaped HSS closed die was made to admit the larger 1x2", 18-braid system. The pressing was then redone with the same 456 MPa compression load (60 tons scaled total force), reaching a slight higher void density of 8.2%. Following this, an even higher load of 570 MPa (75 tons total force) was used to press another 18-braid system. This time, the final average void density was of only 1.7% and was considered enough as it was already better than the well performing commercial braids (4.2%) (see Fig. 2).

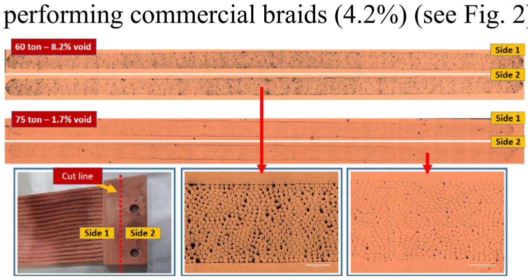


Figure 2: Closed die pressing with different loads.

### *Conditioning for UHV*

To remove contaminants introduced during manufacturing for the UHV application compatibility, the systems were sonicated with: IC115 + deionized (DI) water solution (1:4, volume); then, pure DI water; and, finally, pure isopropanol, 30 minutes each. After that, cleansing was made in a sulphuric acid and hydrogen peroxide (1:1, volume) bath, aka. *Piranha* solution, for approximately 2 minutes, followed by DI water rinse and isopropanol sonication for 15 minutes. The braids were, then, vacuum backed at 120°C for 24h, and stored in vacuum until assembled or gold platted. Residual gas analyses (RGA) were performed with a Stanford SRS RGA200 up to 200 Da in a ~1e-6 mbar vacuum, with no specific contaminants detected. Indeed, some systems are currently working at < 5e-10 mbar. In the cases of gold platting, the braids were still re-cleaned with the same IC115/DI water solution, followed by isopropanol sonication for 30 minutes and the same baking procedure.

## THERMAL CONDUCTION TESTS

To validate the thermal conductivity of the braids, a dedicated setup was developed (Fig. 3). It consisted of an aluminium machined bar coupled to a Janis ST400 $LN_2$ cryostat, to which one of the end-blocks of the braids was coupled. 2k Ohm IST resistive temperature detectors (RTD) were attached to both braid end-blocks and read by a NI cRIO 9226 card. Thin film Kapton heaters were attached to the other extremity and driven by a Keithley controller. Indium foil was used in all interfaces. The entire system was kept under high vacuum (< 1e-6 mbar).

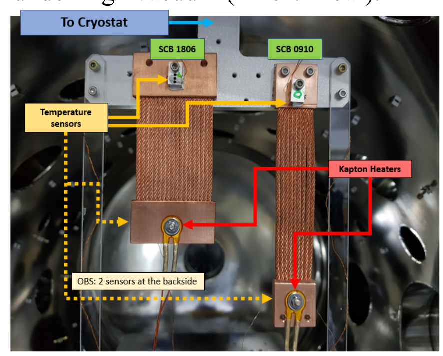


Figure 3: In-vacuum cryogenic thermal test setup.

After cooling, the temperature offset of both terminations caused by the radiation heat transfer was normalized and power was delivered to the heaters in controlled steps. The thermal conductivity was then calculated by the simple division of the total power delivered to the heaters by the temperature difference of both end-blocks, with corrections for cable losses and radiation heat transfer. Some of the results are shown at Table 1. For all tests, the determined conduction efficiency varied between 82 and 91% of the theoretical values.

Table 1: Thermal Conduction Test Results

| Braid ID | Braid n# | Length (mm) | Mean Temp. (K) | Power (W) | Conductivity (W/K) |
|---|---|---|---|---|---|
| **SCB1806** | 18 | 60 | 111.4 | 5.55 | 0.314 |
| **SCB1806** | 18 | 60 | 131.0 | 9.78 | 0.293 |
| **SCB0910** | 9 | 100 | 111.0 | 2.35 | 0.101 |
| **SCB0910** | 9 | 100 | 139.6 | 5.25 | 0.094 |

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## SOLDERING AND BRAZING

A common fashion for thermally coupling solid bodies consists in layering a soft, good conductor interface material and compressing it with a static load. Due to the need for UHV compatibility and cryogenic properties, annealed indium foil (0.2 mm, Goodfellow) is usually employed between the conduction blocks, mirrors, and cryostats at Sirius. An acceptable thermal conductivity value for this solution currently used in many Sirius thermal models is 3 kW/m$^2$K, based on [4]. Nevertheless, since the new developed braids end-block geometries are standardized, they often must be coupled to intermediary parts to form the thermal links, but any new interface may lead to a loss in thermal efficiency. To improve the interface conductivity in relation to the pressed indium, soldering and brazing tests were performed in vacuum (<1e-5 mbar) with multiple fillers (Table 2).

Table 2: Brazing and Soldering Tests

| Filler Material | Filler Thickness (mm) | Temp. (°C) | Time (min) | Category |
|---|---|---|---|---|
| **Palcusil 10** | 0,1 | 885 | 5 | Brazing |
| **Cusil** | 0,1 | 780 | 5 | Brazing |
| **Sn100C** | 0,3 | 227 | 30 | Soldering |
| **Sn100CV** | 0,3 | 227 | 30 | Soldering |
| **Indium** | 0,5 | 157 | 30 | Soldering |

Figure 4 shows the micrographies for the several cases. Despite both Cusil and Palcusil resulted in thinner, metallurgically bonded interfaces, the high temperatures employed during the process caused an undesired adhesion of the copper wires among themselves by diffusion bonding, as well as strong annealing. This led to a completely loss of flexibility in the braids, as the wires could no longer slip among themselves, invalidating the application. Thus, new efforts for low temperature bonding (soldering) using tin based fillers, namely, Sn100C and Sn100CV, and pure indium were made.

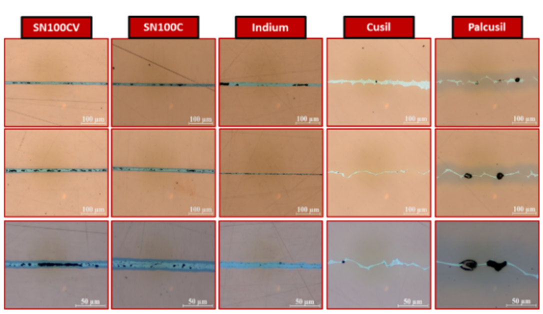


Figure 4: Different brazing and soldering interfaces between copper end-blocks.

Although the Sn100C and Sn100CV fillers resulted in even, reproducible interfaces, it was later found that both alloys contained a considerable amount of phosphorus (0.73 and 0.68% w.t. respectively, measured by inductively coupled plasma mass spectrometry), being unsuitable for vacuum applications near optical surfaces. Therefore, the pure indium soldering method was chosen, having an expected conductivity near 400 kW/m$^2$K [5].

## BEAMLINE SYSTEMS

The CARNAÚBA beamline M1 mirror along with an associated diffraction beam diagnostic is currently the cryogenic system relying on copper braids with the highest power load at Sirius [6]. Indeed, the total power in the commissioning phase of the storage ring is approximately 77 W [7], but it should reach 100 W in the near future.

To solve the needed cooling requirements, while preserving the optics alignment and motion, a set of 12x 18-rope braids were used to couple a cryostat-cooled copper block to the optics interface sets (Fig. 5). All copper surfaces were gold plated to reduce radiation heat exchange. Solid indium foil was used as interface material in all cases but will be indium-soldered soon. The system has been proven fully functional during the beamline commissioning.

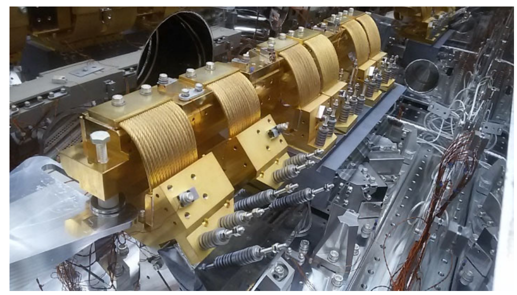

Figure 5: Braided system at the CARNAÚBA beamline M1 mirror and diagnostic system.

Also, both the M2 mirror and SSA (secondary source aperture [8]) at CARNAÚBA use the same developed braids, but have already indium-soldered interfaces, as they were used as experimental systems, having the best performance so far. Other systems, as the CARNAÚBA 4CM monochromator [9] and IPÊ M4 and M5 mirrors, also use these braids, and many others are on the way.

## CONCLUSION

A manufacturing process for fabricating weld-free, low-cost, high-efficiency flexible copper braids for cryogenic applications was developed in-house with the help of a local partner. The main challenge of achieving a high compaction at the braids solid blocks was solved with: a closed die pressing process, optimized end-block geometries, and copper annealing for lower yield strength, resulting in a void density as low as 1.7% when cold pressed with 570 MPa. Both the vacuum and thermal performances were tested with successful results, with systems working down to < 5e-10 mbar and conduction efficiency between 82 and 91% of the theoretical values. Large optical systems currently use the developed systems at Sirius up to 100 W.

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