Material Characterisation and Preliminary Mechanical Design for the HL-LHC Shielded Beam Screens Operating at Cryogenic Temperatures

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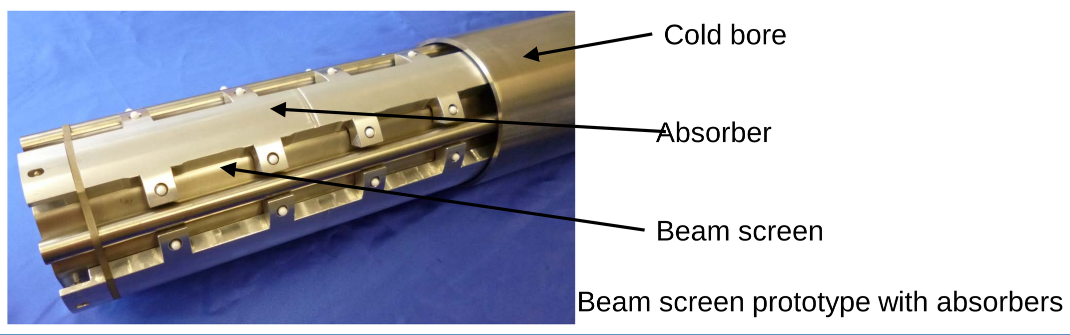
M2PoB

Abstract

In the HL-LHC, the intense flow of debris from beam collisions will be shielded by blocks of Inermet® 180, a sintered tungsten-based composite material with around 3.5 wt% of nickel and 1.5 wt% of copper. The blocks will be assembled on the beam screen, which operates in the range 40-60 K, and inserted in the beam pipe (cold bore) of superconducting magnets operating at 1.9 K.The overall thermal and mechanical performance depends strongly on the electrical, thermal, magnetic and mechanical properties of the selected W alloy for which no data are available for cryogenic temperatures. Thus, a dedicated study has been conducted to evaluate such properties and finally assess the efficiency and reliability of the system.

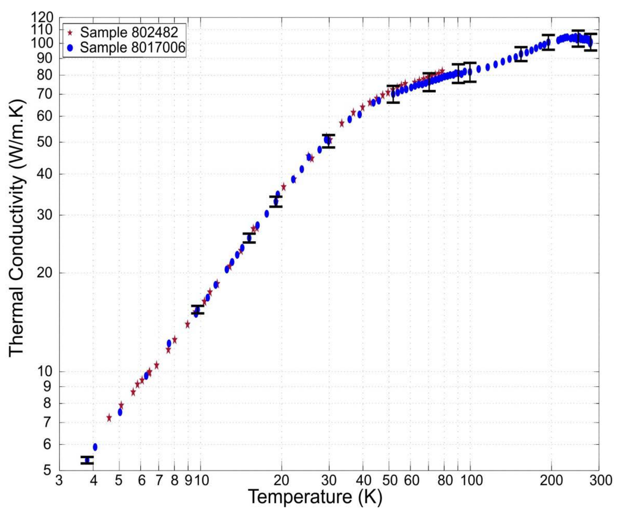


Beam screen prototype with absorbers

Inermet® 180 properties

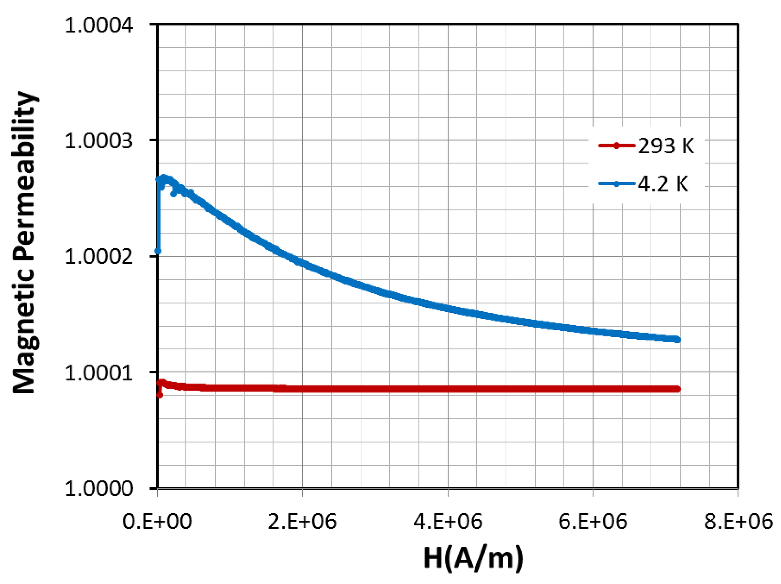
The Inermet® 180 is a sintered tungsten-based material with around 3.5 wt% of nickel and 1.5 wt% of copper. Tungsten has a high atomic number and is therefore suitable for absorber application. For the HL-LHC project, this tungsten alloy has been chosen for the absorbers to be used in the beam vacuum chamber of superconducting magnets operating at 1.9 K.

Thermal conductivity



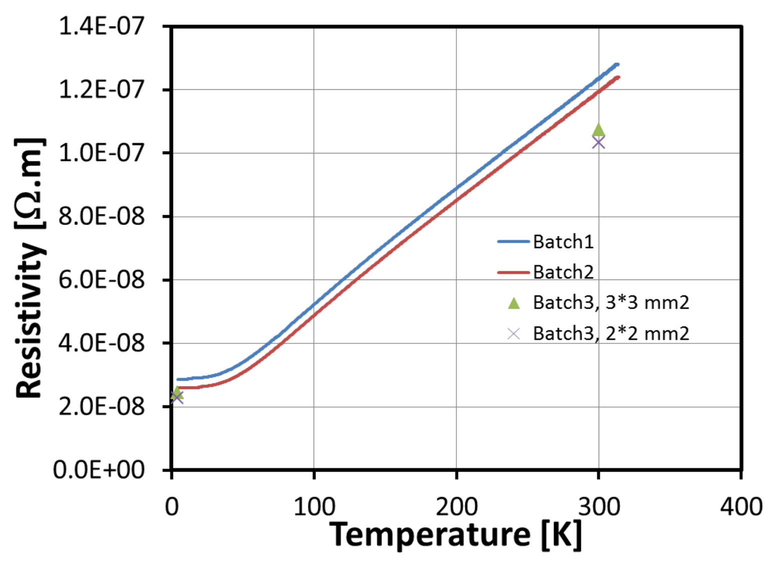
Thermal conductivity as a function of temperature. The conductivity of one sample (802482) has been measured up to 70 K, while for the other (8017006) the temperature range has been extended up to room temperature.

Magnetic permeability



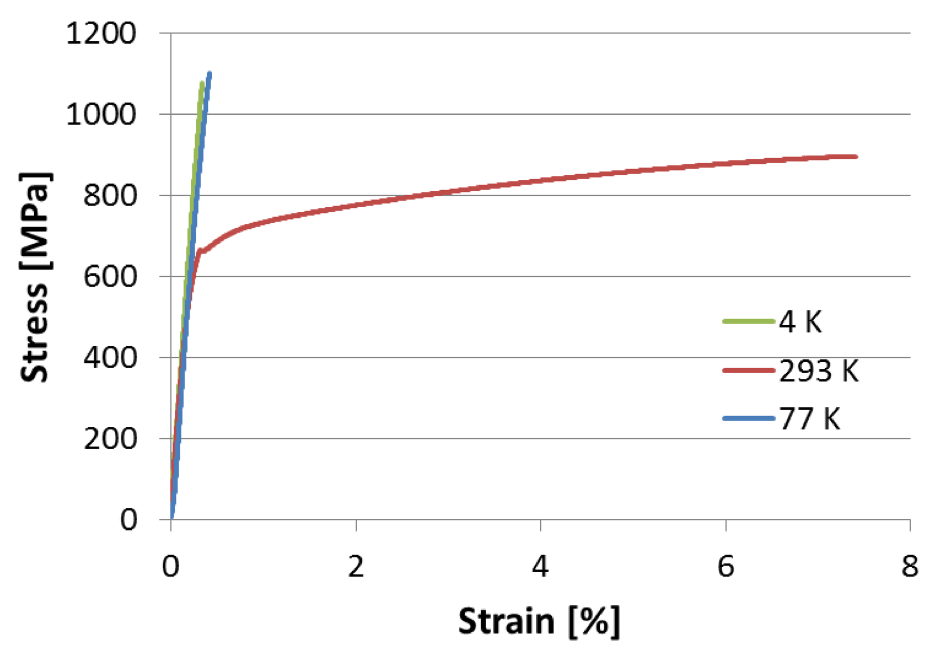
Typical magnetic permeability as a function of magnetic field. Values at room temperature and 4.2K.

Electrical resistivity



Electrical resistivity as a function of temperature. Batch 1 corresponds to reference 8017006 and Batch 2 to reference 802482, compare Table 2. The sample dimensions of Batch 1 and 2 have been 2 mm x 2 mm x 73 mm

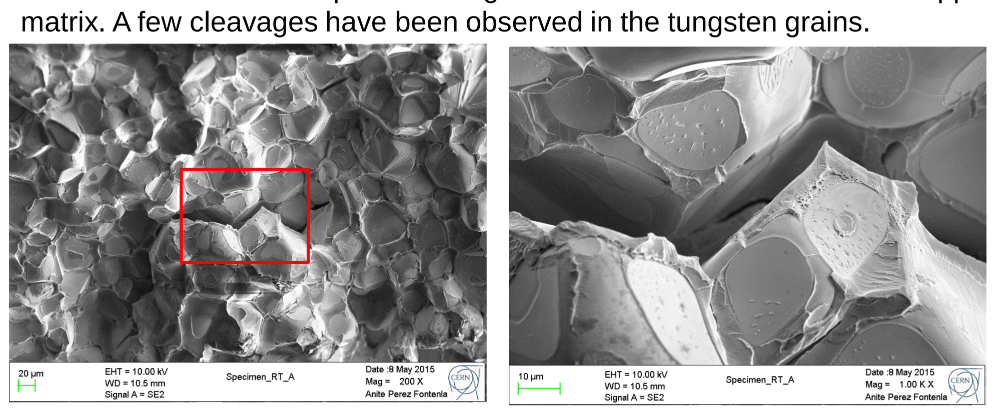
Tensile tests



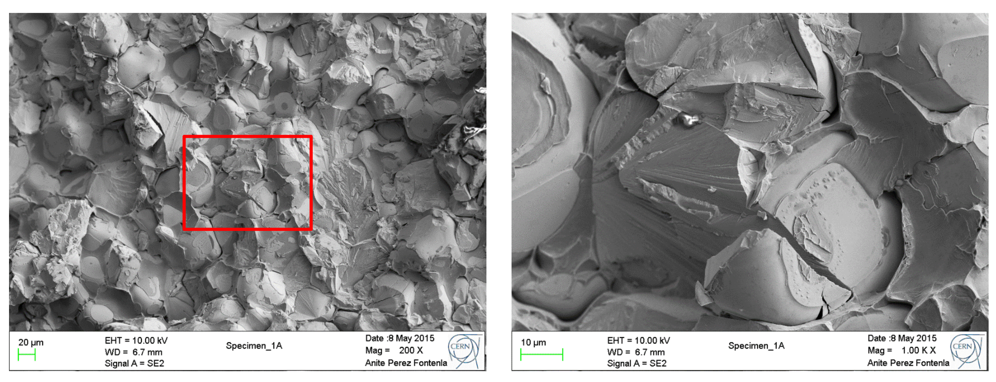
Typical tensile curves of Inermet® 180 at 4.2 K, 77 K and room temperature

Temperature	Number of specimens	Young modulus		Yield strength		Ultimate strength		Deformation to rupture	
		[GPa]		[MPa]		[MPa]		[%]	
[K]		$\bar{x}$	σ_x	$\bar{x}$	σ_x	$\bar{x}$	σ_x	$\bar{x}$	σ_x
293	3	330	11	696	18	944	2	9.2	1.1
77	3	320	40	-	-	1155	52	0.45	0.03
4.2	4	324	40	-	-	1048	53	0.34	0.03

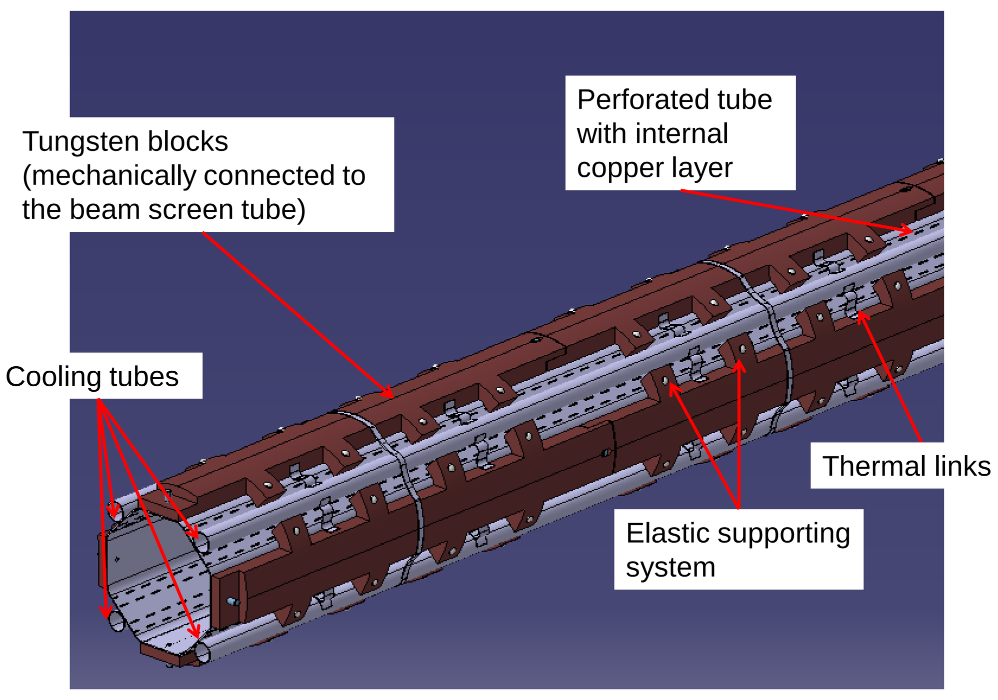
An intergranular facture is observed on specimens tested at room temperature. Some microvoids and quasi-cleavage surfaces are noticed in the copper-nickel matrix. A few cleavages have been observed in the tungsten grains.



Examination of the fracture surfaces on specimens tested at 77 K revealed a transgranular brittle fracture dominated by cleavage in the tungsten grains. A debounding between them and the matrix is noticed as well.



Mechanical design and behaviour of the beam screen during a magnet quench



Assembly of the beam screen

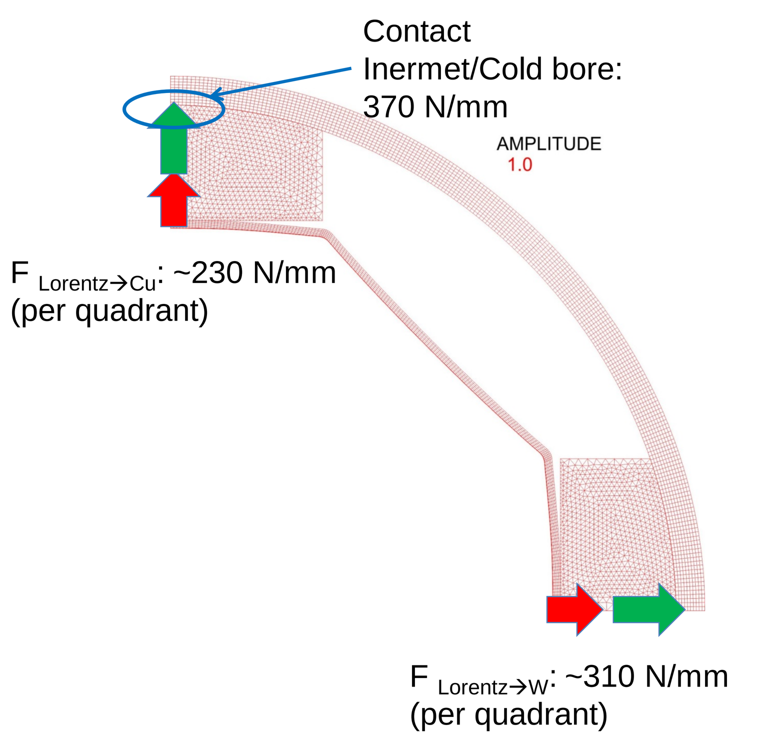
→ Magnetic forces, developed in the copper layer and tungsten absorbers during the quench, are absorbed by the cold bore.
→ Deformation and stress field are driven by the initial gap between the tungsten blocks and the cold bore
→ Maximum stresses are around 840 MPa and 650 MPa in the beam screen and the cold bore, respectively

Lorentz forces induced by the Foucault currents during a quench:

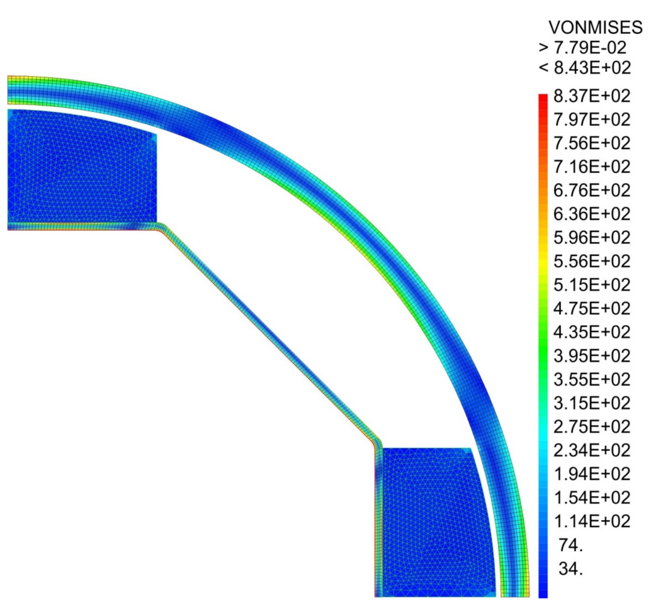
$$f \propto \frac{G.\dot{G}.r^3}{\rho}$$

Magnetic gradient — Specific force — Electrical resistivity

Forces and deformation



Stress field

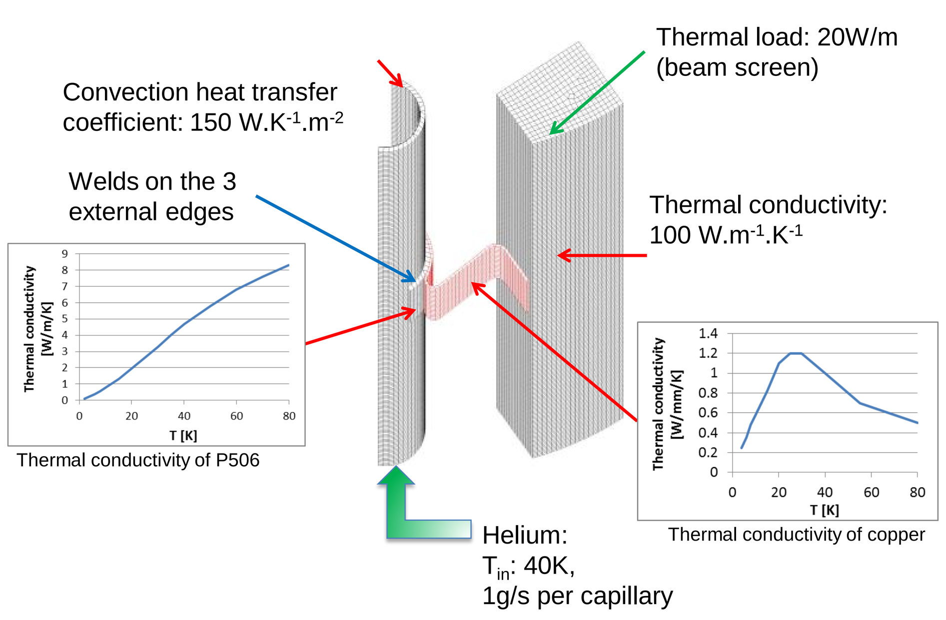


Typical Von Mises stress field in the beam screen and cold bore during a magnet quench

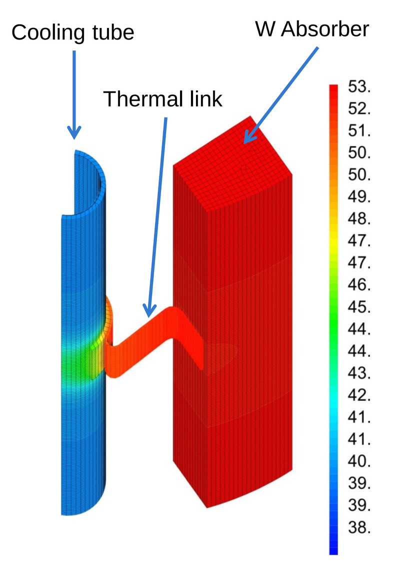
Thermal study of the beam screen

The heat transfer is assured by thermal links in copper installed between the tungsten absorbers and the cooling tubes.

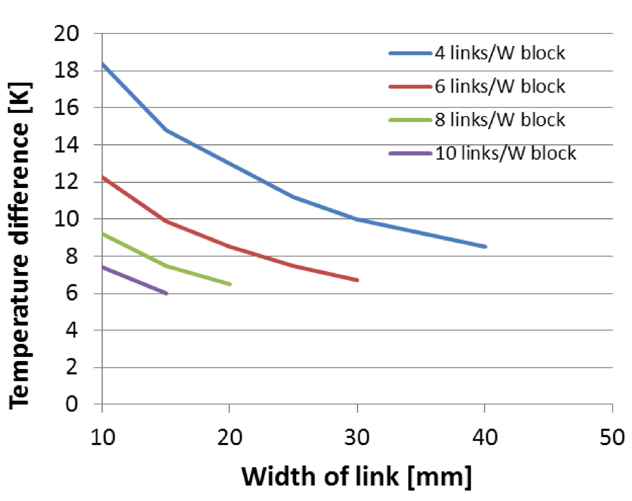
Model



Temperature distribution



Temperature field

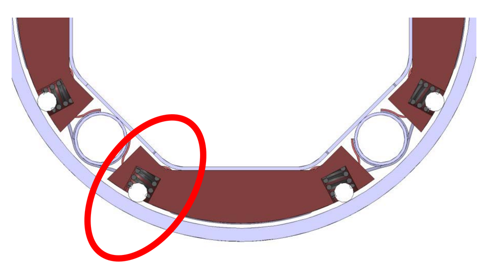


Influence of width and number of thermal links

Supporting system and heat leaks to the cold mass

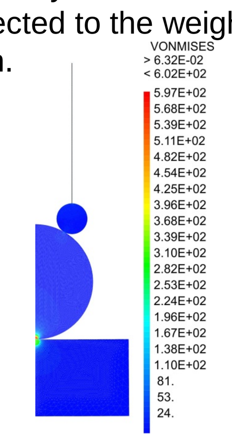
The beam screen is supported in the cold bore tube. The specific weight is up to around 50 kg.m^{-1} for the Q1. The supporting system has to fulfil:

- low thermal conductivity (heat inleak to the cold bore <0.5 W/m),
- good mechanical reliability,
- good tribological properties under vacuum and cryogenic temperatures.

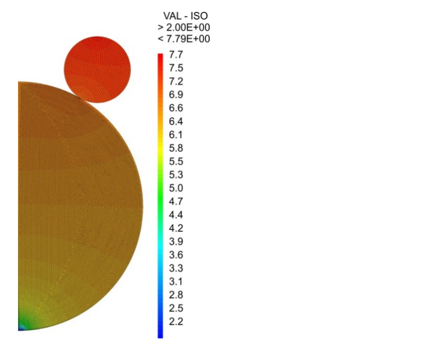


A solution based on zirconium oxide balls supported by elastic springs made of titanium alloy, grade 5, located in the Inermet® 180 absorbers is retained.

Mechanical analysis of the supporting system subjected to the weight of the beam screen.



- Local stress field
- Contact area between the components



Heat transfer evaluation from the warm beam screen to the cold bore

Conclusion and Perspectives

The tungsten-based composite, Inermet® 180 has been chosen for the absorbers of the final focusing HL-LHC superconducting magnets. Mechanical, thermal, magnetic and electrical properties of this material have been measured at cryogenic temperatures. From mechanical point of view, a brittle behavior is observed at 77 K. Inermet® 180 has also a very low thermal expansion coefficient. The magnetic susceptibility is in the order of 10^{-4} in the temperature range of 40-60 K, and the material is therefore suitable in high magnetic field environment. Thermal conductivity and electrical resistivity have been measured at cryogenic temperatures as well.
The thermal behavior of the HL-LHC beam screen has been assessed. The number and geometry of the copper thermal links, used to transfer the heat load from the absorbers and the cooling tube, are being optimized and a validation test of the thermal performance is foreseen on a short prototype.

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