Material characterisation and preliminary mechanical design for the HL-LHC shielded beam screens operating at cryogenic temperatures.

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Abstract. The High Luminosity LHC project (HL-LHC) aims at increasing the luminosity (rate of collisions) in the Large Hadron Collider (LHC) experiments by a factor of 10 beyond the original design value (from 300 to 3000 fb⁻¹). It relies on new superconducting magnets, installed close to the interaction points, equipped with new beam screen. This component has to ensure the vacuum performance together with shielding the cold mass from physics debris and screening the cold bore cryogenic system from beam induced heating. The beam screen operates in the range 40-60 K whereas the magnet cold bore temperature is 1.9 K. A tungsten-based material is used to absorb the energy of particles. In this paper, measurements of the mechanical and physical properties of such tungsten material are shown at room and cryogenic temperature. In addition, the design and the thermal mechanical behaviour of the beam screen assembly are presented also. They include the heat transfer from the tungsten absorbers to the cooling pipes and the supporting system that has to minimise the heat inleak into the cold mass. The behaviour during a magnet quench is also presented.

1. Introduction
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 [1], which operates in the range 40-60 K, and inserted in the beam pipe (cold bore) of superconducting magnets operating at 1.9 K (figure 1). 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 at cryogenic temperatures. Thus, a dedicated study has been conducted to evaluate such properties and finally assess the efficiency and reliability of the system.

![Figure 1. Beam screen prototype with absorbers.](image-url)
2. Properties of the Inermet® 180 tungsten alloy at cryogenic temperatures

The material used to measure the different properties has been supplied by Plansee, France, according to their specifications. Different batches have been used. The size of the tungsten grains has been measured to around 50-60 µm.

2.1. Mechanical properties

Tensile tests have been carried out on flat machined, dog bone shaped, 2 mm thick samples. They have been performed at room temperature, 77 K and 4.2 K. Samples have been designed according to ISO 6892-1:2009 with a cross section of the active part of 2 mm x 4 mm, fillet radius of 20 mm and a straight length of 62 mm. The displacements are controlled with a strain rate of $10^{-4}$ s$^{-1}$. The results (average and standard deviation) of the tensile tests are reported in table 1.

| Temperature [K] | Number of specimens | Young modulus [GPa] | Yield strength [MPa] | Ultimate strength [MPa] | Deformation to rupture [%] |
|----------------|---------------------|---------------------|----------------------|-------------------------|----------------------------|
| 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                |

Contrary to W-N-Fe alloys that have been deeply studied in the literature, only a few data are available for the W-Ni-Cu materials [2-4]. The tensile strength and the fracture elongation, measured at room temperature, are significantly higher than the values given by the supplier (685 MPa and 3%, respectively) and found in the literature: 660 MPa and 3% in [2], 631 MPa and 0.6% in [4]. The measured values are comparable with reference [3]. The mechanical properties of the Inermet depend on the strain rate at room temperature [4] and the grain size as well. The scattering at cryogenic temperature is rather high. Results should be refined with additional measurements.

The fracture faces of tensile tests done at room temperature and 77 K are shown in figures 2 and 3, respectively. An intergranular fracture 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.

![Intergranular fracture](image1)

![Quasi brittle fracture of the matrix](image2)

**Figure 2.** Intergranular fracture surface after tensile test at room temperature.

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 the grains and the matrix is noticed as well.

![Quasi brittle fracture of the matrix](image3)
a) Transgranular brittle fracture.  

b) Cleavage in the tungsten grains and debounding of the matrix.

**Figure 3.** Transgranular fracture surface after tensile test at 77 K.

To determine the thermal contraction of the samples a calibrated dilatometer made out of Pyrex® has been used, which allows the immersion of the mounted sample in cryogenic liquids. The dilatometer is of the compensation type measuring the differential contraction of the sample at the respective liquid temperature of nitrogen and helium at atmospheric pressure saturation condition. Table 2 shows the results of the measurement carried out at room temperature as reference using two specimens precisely machined to 8 mm by 8 mm cross section and a length of 50 mm. To guarantee the mechanical contact to the dilatometer a conical (specimen side) to spherical shape contact is applied. Great care is taken to ensure proper fitting of the sample by measuring the reproducibility on 10 sample mountings.

**Table 2.** Results of the thermal contraction measurements.

| Temperature [K] | Batch reference | Expansion Δl/l [%] | Deviation Δ(Δl/l) [%] |
|-----------------|-----------------|--------------------|------------------------|
| 293             | 1               | 0                  | ± 0.0001               |
| 78              | 1               | - 0.086            | ± 0.003                |
| 4.2             | 1               | - 0.096            | ± 0.007                |
| 293             | 2               | 0                  | ± 0.0005               |
| 78              | 2               | - 0.087            | ± 0.005                |
| 4.2             | 2               | - 0.095            | ± 0.008                |

2.2. **Electrical resistivity**

Depending on the purity, the electrical resistivity of tungsten varies a few orders of magnitude at cryogenic temperature [5]. The electrical resistivity of the Inermet® 180 has been measured between 4.2 and 300 K. Different batches have been tested to assess possible scattering during the manufacturing. The samples have been machined from sintered blocks. Two different geometries have been considered to evaluate the impact of the machining and the local surface modifications. The measurements are given in figure 4. No significant influence of the batch nor of the sample geometry has been observed at cryogenic temperatures.
2.3. Magnetic permeability

The magnetic permeability has been measured at University of Zaragoza using a vibrating sample magnetometer. Three different samples, 8 mm x 4 mm x 2 mm each, have been extracted by electro discharge machining at different position from a machined tungsten piece and have been tested. The measurements have been carried out between 4 K and 300 K with a magnetic field, H, up to 90 kOe (7162 kA.m⁻¹). The magnetic permeability curves are given as a function of the temperature and the magnetic field in figures 5 and 6, respectively. Magnetic permeability is less than 1.0003 at all measured fields and temperatures. No significant deviation has been observed between these three specimens. The magnetic susceptibility is in the order of 10⁻⁴ in the temperature range of 40-60 K. This is more than one order of magnitude lower than the magnetic susceptibility of the specific high-Mn austenitic stainless steel used for the beam screen wall.

2.4. Thermal conductivity

The absolute measurement method was used to determine thermal conductivity, $\lambda$, as

$$\lambda = \frac{\dot{Q} \cdot L}{A \cdot \Delta T}$$

(1)
where $\dot{Q}$ denotes the heat flow. $L$ and $A$ stands for the length and the cross section of the sample, respectively. $\Delta T$ is the temperature difference along the sample length. The measurement has been carried out between 3.8 K and 280 K on two 8 mm x 8 mm x 50 mm samples. Samples identical to those used for the thermal contraction measurement have been used to determine the thermal conductivity. An active length of 30 mm has been chosen for the measurement of the temperature difference. Figure 7 shows the measured thermal conductivity as a function of temperature for both specimens. No significant deviation has been observed between the two samples. The relative measurement error was estimated as maximum error considering errors in the measurement of the applied heat load $Q$, the sample length, the sample cross section and the recorded temperature difference along the sample length by equation (2).

$$\frac{\Delta \lambda}{\lambda} = \left| \frac{\partial \lambda}{\partial Q} \Delta \dot{Q} \right| + \left| \frac{\partial \lambda}{\partial L} \Delta L \right| + \left| \frac{\partial \lambda}{\partial A} \Delta A \right| + \left| \frac{\partial \lambda}{\partial T} \Delta T \right|$$

The calculated relative measurement error varies from about 2.5% to 6.5% depending on the temperature range of measurements. The respective error bars for the thermal conductivity values are exemplarily shown in figure 7. The error for the absolute temperature is related to the uncertainty of the used calibrated temperature sensor of ±8 mK at 4.2 K and ±120 mK at room temperature.

![Figure 7. Graph of the thermal conductivity as a function of temperature. The conductivity of one sample, batch 2, has been measured up to 70 K, while for the other (batch 1) the temperature range has been extended up to room temperature.](image)

3. Thermal mechanical behaviour of the High-Luminosity LHC beam screen with shielding

3.1. Mechanical behaviour during a magnet quench

The fast decay of the magnetic field leads to the development of Foucault currents that induce Lorentz forces, especially in high electrical conductivity material such as copper. The phenomenon is governed by the Maxwell-Faraday equation. For a quadrupole magnetic field, characterized by a magnetic gradient $G$, the specific Lorentz forces ‘$f$’ for long and symmetrical geometries are given by the equation (3):

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

(3)
\( \rho \) denotes the electrical resistivity and \( r \) the radial coordinate. The behaviour of the assembly is driven by the 80 \( \mu \)m thick copper layer and the tungsten alloy absorbers; their electrical resistivities have been assumed to be \( 1.9 \times 10^{-10} \Omega \cdot \text{m} \) and \( 3.10^{-8} \Omega \cdot \text{m} \) (section 2.2), respectively. The analysis does not take into account the magneto-resistance and is therefore conservative. The specific resultants of the Lorentz forces, per quadrant, are around 230 N.mm\(^{-1}\) and 310 N.mm\(^{-1}\) for the copper layer and tungsten absorbers, respectively. The beam screen assembly has been designed to be rather elastic and therefore, during a magnet quench, the tungsten absorbers go in contact with the 4 mm thick cold bore, which can withstand the high magnetic forces (figure 8). The contact force between the tungsten and the cold bore is around 370 N.mm\(^{-1}\). The maximum Von Mises stress in the cold bore is around 650 MPa (figure 9) which is below the yield strength (860 MPa). The maximum stress in the beam screen wall is around 840 MPa, whereas the yield stress is around 1150 MPa [6]. This value is driven by the initial gap between the tungsten and the cold bore.

![Figure 8](image8.png) Deformation of the beam screen during a magnet quench.  
![Figure 9](image9.png) Von Mises stress field in the beam screen and cold bore during a magnet quench.

### 3.2. Heat transfer from the tungsten absorber to the cooling tube

The heat deposited on the tungsten absorbers is transferred by thermal links to the cooling tubes, in which a helium flow is imposed. The specific thermal load for the whole beam screen is 20 W.m\(^{-1}\). A thermal analysis has been carried out based on the model presented figure 10.

The thermal conductivities for the copper, stainless steel and the tungsten alloy have been considered temperature dependent. It is assumed that the copper thermal link is perfectly bounded to the tungsten absorbed and to the stainless steel strip used as the interface with the cooling tube. This interface is welded to the cooling tube on three edges. The heat transfer by convection, between the helium and the cooling tube, has been estimated by several empirical formulae. A conservative value of 150 W.kg\(^{-1}\).m\(^{-1}\) has been assumed. A helium flow rate of 1g.s\(^{-1}\) per cooling tube is considered. The inlet helium temperature is 40 K.

The typical temperature profile is shown in figure 11. The temperature difference between the cooling gas and the tungsten blocs is around 13 K. The helium temperature gradient, along the cooling tube, is 0.5 K.m\(^{-1}\). The number of thermal links or their width can be increased to improve the thermal performance (figure 12).
3.3. Heat leaks to the cold bore through the supporting system

The beam screen is supported in the cold bore tube. The linear weight is about 50 kg.m⁻¹. The supporting system has to fulfil:

- low thermal conductivity (heat inleak to the cold bore should be lower than 0.5 W.m⁻¹),
- good mechanical reliability,
- good tribological properties under vacuum and at cryogenic temperatures.

Different technical solutions have studied in two steps. The first one consists in a mechanical analysis of the supporting system subjected to the weight of the beam screen. This leads to the estimation of the local stress field and to the determination of the contact area between the components of the supporting system. Then, given the contact area, a thermal analysis is carried out to evaluate the heat transferred from the warm beam screen to the cold bore. The beam screen and the absorbers temperature is conservatively assumed to be 55 K, whereas a temperature of 1.9 K is considered for the cold bore. The thermal conductivity is temperature dependent.

Presently, a solution based on zirconium oxide balls supported by elastic springs made of titanium alloy, grade 5, located in the Inermet absorbers is retained (figure 13). In normal condition, the heat
inleak is transferred through the spring and the ceramic ball. Both have a relatively low thermal conductivity coefficient. During a quench, the elastic springs are compressed and the ball comes inside the absorbers. Therefore the high Lorentz forces, which develop in the beam screen wall and in the tungsten blocks, are transferred uniformly to the cold bore.

![Cryogenic Beam Screens for High-Energy Particle Accelerators](image)

**Figure 13.** Supporting system of the HL-LHC beam screens with shielding.

High stress field develops between the ball and the cold bore, in which local plasticity occurs. The maximum of the principle stresses in the sphere reaches around 900 MPa and 80 MPa in compression and tension, respectively. The heat leak to the cold mass through the supporting system is estimated to be between 50 mW.m⁻¹ in the best case, i.e. contact of the absorber and the spring only at its extremity, to 400 mW.m⁻¹ in the worst case, i.e. contact of the absorber and the first spring spire.

4. Conclusion

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 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 to the cooling tube, are being optimized and a validation test of the thermal performance is foreseen on a short prototype.

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