# DESIGN AND FABRICATION OF SUPERFLUID HELIUM HEAT EXCHANGER TUBES FOR THE LHC SUPERCONDUCTING MAGNETS

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*Abstract*

The dipole and quadrupole cold masses of the LHC machine require about 1 700 heat exchanger tubes (HET). In operation the HET carries a two-phase flow of superfluid helium at sub-atmospheric pressure. The HET consists of an oxygen-free, seamless copper tube equipped with stainless steel ends. After an evaluation of different alternatives, a design based on the technologies of vacuum brazing and electron beam welding has been adopted. Presence of these multiple technologies at CERN and synergies with the cleaning, handling and transport of other 15-metre components for LHC, motivated CERN to undertake this series fabrication on site. The raw copper tubes are procured in industry, presenting challenging issues of geometric precision. Organisation of the HET fabrication includes cryomeasurements to validate cleaning procedures, characterisation of welding procedures, design and experimental verification of buckling pressure, quality control during series production. The series fabrication of these long, multi-technological components is proceeding successfully, respecting the project's tight budgetary and planning constraints.

## INTRODUCTION

The dipole and quadrupole superconducting magnets of the LHC machine operate in pressurised helium II at 1.9 K and about 0.13 MPa. The heat generated in the cold mass, typically 0.3 – 0.7 $W \cdot m^{-1}$ at 1.9 K, is transported by conduction to a heat exchanger tube (HET) running inside the magnet cold masses. Inside the tube, a flow of saturated helium II absorbs the heat by vaporisation of the liquid.

The thermal impedance is largely dominated by the Kapitza resistance across the interfaces between the tube and the superfluid: this depends strongly on the quality of the surface, and particularly its cleaning.

About 1 700 heat exchanger tubes (HET) are required. CERN is responsible to supply all major components to the Cold Mass Assemblers. The supply of the HET was the last to be organised, hence time pressure was an important consideration.

## DESIGN

The mechanical design of the HET structure is based on conditions of cold mass quench: external radial pressure 2.6 MPa, internal vacuum and temperature 1.9 K. The thermal design of the HET is based on the optimization of both radial and longitudinal heat transfer capacity.

These factors led to a basic design of the HET as a seamless, round oxygen-free Cu-OF copper tube, outer diameter 58 mm and wall thickness 2.15 mm. The refined copper grade UNS C10200 in the ¼-hard temper status (H01) - typically 21 % cold work - was selected having at $20^0$C:

- yield strength: 200 MPa $\leq R_{p0.2} \leq$ 280 MPa
- ultimate tensile strength: 260 MPa $\leq R_m \leq$ 320 MPa
- elongation: A5 $\geq$ 20%
- thermal conductivity: 400 $W \cdot m^{-1} \cdot K^{-1}$ (estimated to be 200 $W \cdot m^{-1} \cdot K^{-1}$ at 1.9 K).

The typical HET length for dipoles is 15 m. For easier integration by welding in the magnet assembly, the HET requires austenitic stainless steel ends.

All joints are to be leak tight – the maximum allowable leak rate is $1 \cdot 10^{-10}$ $Pa \cdot m^3 \cdot s^{-1}$ - any restriction of the inside diameter in the area of the joints is forbidden and welding projections on the inside of the tube are forbidden.

Many manufacturing techniques have been tried for the copper to stainless steel joint in the development phase: induction brazing, electromagnetic forming, direct electron beam welding of copper to stainless steel, friction welding and TIG welding with high-nickel alloy as filler metal. Many of these proved unacceptable because they annealed an excessive portion of the copper tube, thereby degrading its mechanical strength.

The assembly solution adopted for series construction uses proven techniques available on CERN site. A bi-metallic junction between the stainless steel end and a short copper ring was obtained by vacuum brazing, then a copper to copper junction between the short copper ring and the main copper tube was obtained by electron beam welding, see Fig. 1.

Figure 1: Heat Exchanger Tube – different end versions

## FABRICATION

Once the design requirements were detailed in a Technical Specification [1], CERN tendered for the fabrication, both in Industry and internally in its technical services. For reasons of economy – including synergy between HET and other long components of the LHC machine – the fabrication was organised internally at CERN.

The OF copper tubes are procured industrially and are produced by hot extrusion followed by cold drawing: the small wall thickness represents an important manufacturing challenge. Significant experience on geometric tolerances in large series precision production has been gained, specifically for diameter, circularity, thickness, eccentricity and straightness. In order to achieve the required precision, more cold work than specified was required.

The copper tubes are delivered at CERN to a dedicated area of 25 m x 10 m set up for handling long components, see Fig. 2, equipped specifically for this project with a 3 - axes milling machine and an electron beam welding equipment.

The tubes are machined to length with a perpendicular cut and sharp edges: they are also milled internally over a length of 10 mm to obtain a constant wall thickness around 360°. This joint preparation is recommended for high quality electron beam welding reproducible in conditions of series fabrication.

### *Chemical cleaning*

The machined tubes are transported internally between CERN sites to a dedicated installation for cleaning. Cleaning of lengths up to 16 m exceeds the normal industrial capacities available, hence CERN decided to expand its existing facilities for the LHC project.

The cleaning installation has three tanks and a drying tunnel, each with dimensions 17 m x 1 m x 0.6 m. Using the appropriate solutions, this allows cleaning to UHV standards.

The HET tubes, treated in batches of ten, are mounted on supports that keep them separate. They are first hand wiped externally with an adequate solvent to remove black residues of drawing grease. Cleaning is done in four steps. The batch is immersed in an alkaline detergent solution at 50ºC for at least 80 minutes. Ultrasonic agitation is provided by emitters moving longitudinally at 0.4 $m \cdot min^{-1}$. The detergent solution tank is equipped with a filtering circulation system that allows a flow of ~11 $m^3 \cdot h^{-1}$ over 10 µm filter.

The batch is moved to a second tank for rinsing with tap water by immersion. This preserves the quality of the demineralised water for a longer time.

The final rinsing is done by immersion in a third tank of demineralised water (>1 MΩ·cm) to remove residue salts. This tank is equipped with a filtering circulation system connected to a demineralised water recovering system that allows a flow of 8 $m^3 \cdot h^{-1}$ over 10 µm filter.

Drying is in ambient, still air, but there is the possibility to place the tubes inside a drier, with 600 $m^3 \cdot h^{-1}$ of filtered air for two hours.

Surface conditions and cleanliness requirements have been checked experimentally with cryomeasurements: a Kapitza conductance of the order of 1 200 $W \cdot K^{-4} \cdot m^{-2}$ has been verified [2].

The same installation is also used for cleaning other long components of the LHC project: beam screens, vacuum chambers for the interconnection cryostats and the long straight sections, and experimental vacuum chambers.

### *Vacuum brazing of bi-metallic junctions*

The stainless steel ends are in AISI 316L, machined from a seamless tube. The 316L used was checked for ferrite content and against the risk of creation of the fragile sigma - phase.

The ends are cleaned, then nickel plated with 1-2 µm in a Wood bath at 50ºC. The excess nickel outside the brazing surface is chemically removed, and finally precision mechanically stripped to limit the wetted area.

The copper ring material is Cu-OFE - grade UNS C10100: experience shows that the lower oxygen content results in increased wetting and better brazing performance. These pieces are also cleaned and finally passivated in a solution of chromic acid.

Vacuum brazing is performed in batches of 100 junctions in an all-metal vacuum furnace, diameter 650 mm, height 1 750 mm, having 3 levels and a vacuum pressure below $1 \cdot 10^{-5}$ mbar. The junctions are brazed with their axis being vertical. The brazing material is 0.75 mm wire, alloy B-Ag68CuPd-807/810 according to ISO 3677. The heating rate is 300°C$\cdot h^{-1}$ up to 795°C, dwell time 2 h, increased at 100°C$\cdot h^{-1}$ up to 825°C dwell time 6 min. Cooling is under vacuum with heating cut off.

After brazing, each junction is visually controlled to check that the braze material has completely wetted the joint and is therefore visible at both its ends.

Figure 2: dedicated area for HET assembly at CERN

### *Electron beam welding*

The equipment used is a 7.5 kW/150 kV generator with a 1 $m^3$ chamber extended with a 16 m - Ø150 mm sleeve composed of 5 segments. A single HET is completely inserted in vacuum, supported inside the sleeve by roller bearings, with pumping time below 5 min.

Welding is performed inside the 1 $m^3$ chamber, gun vertically down, working distance 175 mm. The tube end is driven by a CNC chuck. The joint is positioned accurately and clamped using an internal expansible mandrel. This also plays an important role as a thermal sink, protecting the brazed area from an excessive increase in temperature.

Tacking is not normally done, except for some special quadrupole HET where angular deformations can be critical. Typical welding parameters are 60 kV and 50 mA (i.e. 3 kW), speed 16.7 $mm \cdot s^{-1}$.

Tubes are welded in batches of 10, first all at one end, then at the other end. Special support jigs have been devised to handle the long tubes safely and economically.

Experience showed that deviation from straightness of the raw copper tubes was sometimes a problem, as it impeded a smooth rotation of the tube during welding.

## TESTS

### *Qualification tests*

Both the vacuum brazing and electron beam welding procedures have been fully qualified, according to EN 13134 and ISO 15614-11 respectively.

The qualification tests include a helium leak test on the complete joint (bi-metallic joint and weld), radiography, metallographic analysis, hardness tests to determine the extent of the heat-affected-zone, and transversal tensile tests. The acceptance criteria include full weld penetration with smooth head and root and no inner projections, defect level B "stringent" category according to ISO 13919-1 with excess weld metal limited to 0.3 mm and an excess penetration limited to 0.2 mm internally.

Tensile tests show fracture occurring in the heat affected zone of the electron beam weld on the annealed OFE side.

Radiography and metallographic analysis show highly compact brazed and welded joints, without cracks or porosities.

Additionally, two full-scale tubes were used for destructive buckling tests, with external pressure applied hydraulically. At 6 MPa (60 bar), room temperature, the tubes did not show any trace of permanent deformation and successfully passed the required helium leak test. The limit buckling pressure was determined to be 11 MPa, see Fig. 3.

Figure 3: full-scale destructive test, buckling mode

The structure was modelled by Finite Element Analysis, including effects of plasticity, defects of circularity and co-axiality: the first buckling mode was estimated at 12 MPa.

### *Series production tests*

All raw copper tubes are visually inspected for straightness and surface appearance.

All finished tubes are dimensionally controlled for length and visual control of the welds. 10% of production was checked by radiography and leak-tightness. The interpretation of radiographs was sometimes ambiguous, possibly because of the large copper grain size.

Experience with assembly of the HET inside the cold masses was very positive. There was some feedback concerning defects in straightness that were corrected by increasing the tacking prior to welding.

## PLANNING AND LOGISTICS

The overall production consists of 1 700 HET in 13 different versions: dipole HET length 15.3 m, and quadrupole HET with lengths between 5.5 m and 9.8 m.

The production is spread over 2 years at a rate of 70 HET and 140 brazed bi-metallic joints per month, for an approximate overall workload of 5 man-years.

Full traceability is ensured by uniquely identifying and engraving all bi-metallic joints and assembled HET. A pneumatic, round tip engraving tool is used, compatible with nuclear applications.

Packing of the assembled HET uses the same wooden boxes used for the delivery of the raw copper tubes, with each tube individually supported by spacers. The tube ends are closed by plastic caps, protecting the inner volume against dust.

Transport to Cold Mass Assemblers is often combined with cold bore tubes insulated at CERN, allowing to achieve simpler and more economical logistics.

## CONCLUSIONS

After over one year of production at CERN, over 1 000 HET have been produced. Quality is conforming to specification, production costs and schedule according to plan.

While this special production was ongoing, the regular CERN-wide technical support in vacuum brazing and electron beam welding was ensured in parallel. The HET project represents a successful example of insourcing. Significant economies have indeed been obtained.

## REFERENCES

[1] Technical Specification for the Supply of Oxygen-Free Copper Heat-Exchanger Tubes for the LHC Magnets, LHC-QHB-CI-0001, April 2002

[2] D. Camacho, S. Chevassus, C. Policella, J.M. Rieubland, G. Vandoni, R. van Weelderen, Thermal Characterization of the HeII LHC Heat Exchanger Tube, 17th International Cryogenic Engineering Conference ICEC 17, Bournemouth, UK, July 1998.