In-house Industrial Production of the Superconducting Conductor for the 43 T Hybrid Magnet of LNCMI-Grenoble

P. Pugnat, T. Boujet, T. Disparti, P. Hanoux, C. Peroni, R. Pfister, M. Pissard, L. Ronayette, and J.M. Tudela

***Abstract*— The hybrid magnet being built at LNCMI-Grenoble is based on the combination of resistive inserts, made of Bitter and polyhelix coils, with a large bore superconducting outsert. It will produce in a first step, an overall continuous magnetic field of 43 T in a 34 mm warm bore aperture. The superconducting coil will provide a nominal magnetic field of 8.5 T in a 1.1 m cold bore diameter. It relies on the novel development of a Nb-Ti/Cu Rutherford Cable On Conduit Conductor (RCOCC) cooled down to 1.8 K by a bath of superfluid helium at atmospheric pressure. After a brief recall of the specificity of hybrid magnets, namely the strong electromechanical coupling between resistive and superconducting coils, the main requirements of the RCOCC for efficient and reliable magnet operation, are given. The test and validation phases prior to the industrial production of the RCOCC are reported, including the trial production of the ½ hard-drawn (H02 cold-worked) Cu-Ag0.05% hollow stabilizer in continuous lengths of 325 m. The novelty of the RCOCC development concerns the assembly and the induction soft-soldering of the Rutherford cable on the Cu-Ag hollow stabilizer allowing a strict control of the inter-strand contact resistance. Studies, developments and the integration of the industrial production line at LNCMI-Grenoble are presented together with the result of the production of all RCOCC unit lengths.**

***Index Terms*— Hybrid magnet, large bore superconducting magnet, Rutherford cable on conduit conductor, Nb-Ti/Cu, very high field magnet.**

I. Introduction

SINCE the pioneering work of Wood and Montgomery in 1965 at the Francis Bitter Laboratory [1], hybrid magnets are still the optimal solution for producing the highest continuous magnetic fields with limited electrical power consumption. They consist of a large-bore superconducting magnet surrounding a small-bore, high-power-density resistive insert. Hybrid magnets generate today fields well above those possible with a purely superconducting magnet and allow substantial savings in conductor volume and/or power consumption compared to purely resistive magnets. Currently, the highest continuous magnetic field produced is 45.2 T in 32 mm diameter at NHMFL in Tallahassee with 30 MW of electrical power [2]. A 40 T hybrid has recently put in operation in China [3]. Two other high field hybrid magnets are close to completion, one in Nijmegen [4] and the other at Grenoble [5]. Their realization remains a technological challenge mainly due to difficulties in building the large external superconducting coil that must survive not only quenches but also extreme electromechanical forces originating from its coupling to resistive insert during fault operation modes [6]. Low AC losses in the superconducting conductor as well as efficient cooling is also of prime for the superconducting coil outsert to prevent a quench in case of an insert trip.

The Grenoble hybrid magnet will produce in a first step a maximum field of 43 T in 34 mm diameter by pushing the resistive coils to their present limit whereas the superconducting outsert will be based on the most conservative and validated technology, *i.e.* Nb-Ti/Cu with pressurized superfluid He at 1.8 K, to produce 8.5-9 T in 1200 mm diameter. The main parameters of the large bore superconducting coil are given in Table I. One of the distinctive features of the Grenoble hybrid magnet is that the design anticipates the possibility of upgrading the maximum field produced up to 45-46 T benefiting from the ongoing upgrade of the LNCMI power installations from 24 MW to 30 MW [6]. This article focuses on the study, the development and the in-laboratory industrial assembly of the superconducting conductor of the outsert coil.

TABLE I
Main Parameters of the Superconducting Outsert Coil of the Grenoble Hybrid Magnet

Parameters	Values
Inner / outer diameter	1106 / 1920 mm
Height	1406 mm
Coil weight	16.3 tons
Nominal / ultimate current (for 8.5 / 9 T)	7115 / 7516 A
Inductance	3 H
Stored Energy (at 8.5 / 9 T)	76 / 84 MJ
Operating temperature	≤ 1.8 K

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II. The Rutherford Cable-on-Conduit Conductor

A. Conductor overview

The large bore superconducting outsert coil, with parameters given in Table I, is based on the development of the Rutherford Cable On Conduit Conductor (RCOCC) [7]. It is composed of a flat Rutherford cable soft-soldered on a Cu-Ag hollow stabilizer (Fig. 1). It must fulfill the following final key requirements:

- Cu-Ag stabilizer with a proof tensile stress $Rp_{0.2\%}$ *(4.2 K)* > 290 MPa, significantly larger than the maximum Von Mises stress of 203 MPa calculated for 9 T central magnetic field with finite element modeling [8],
- Low losses (RRR of the Cu-Ag stabilizer < 70, interstrand contact resistance > 0.1 μΩ) and dynamic stability,
- Internal cooling with enthalpy reservoir leading to cryostability,
- Significant margins in current and temperature (> 2 K at ultimate field of 9 T).

Fig. 1. Picture of the cross-section of the produced Rutherford cable on conduit conductor (RCOCC). The dimensions are 17.92 x 12.96 mm^2.

B. Production of the Nb-Ti/Cu flat Rutherford Cable

Bruker EAS GmbH has successfully produced about 13 km of flat Rutherford cable with 19 strands of 1.6 mm diameter. They were assembled around a stainless steel foil of 50 μm thickness to increase the cross contact resistance between strands. Most of the difficulties were encountered during the cabling process at Furukawa Co, Ltd to achieve a mechanically stable cable with dimensional tolerances of width and thickness of ±0.04 mm and ±0.03 mm, respectively (max/min of the whole production, *cf.* Table II).

TABLE II
As Built Main Parameters of The Rutherford Cable
(overall production)

Parameters	Values(Max/min)
Width[a]	15.28 ± 0.04 mm
Thickness[a,b]	3.06 ± 0.03 mm
Unit length (44 lengths in 14 cabling runs)	> 265 m
Twist pitch of the Rutherford cable (L_p)	140 ± 5 mm
Strand diameter	1.62 ± 0.02 mm
Strand coating thickness	3 μm of $SnAg_{5wt\%}$
RRR of the Cu after cabling	70-80
Strand Cu/Nb-Ti ratio	1.24 ± 0.06
Filament diameter / twist pitch	14 μm / 15 ± 1 mm
Number of filaments	6264
I_c of the cable at T = 1.9 K & B = 10 T[c]	> 20 610 A

[a]From online continuous measurements during the cabling process with a cable measuring machine (CMM). For cross-check, about 20 % of the cable production has been re-measured at CERN with a similar CMM.
[b]The conductor thickness measured at 20 MPa from the stacking of 5 conductors at the end of each cabling run is equal to 3.055 ± 0.015 mm.
[c]Deduced from measurements on strands and which is typically 2-3 % larger than the technical specification [7].

C. Production of the Cu-Ag Stabilizer

To prepare the industrial production of the hollow Cu-Ag stabilizer with tight geometrical tolerances and in unit length of 325 m, a specific R&D program was performed in collaboration with Aurubis Belgium. The hollow stabilizer is produced from a continuous extrusion forming (CONFORM) followed by cold drawing. Various full lengths of stabilizer of $CuAg_{0.03\text{-}0.05\%}$ with the proper geometry and various hardening levels were first produced and characterized in detail (Table III) including chemical analysis, $Rp_{0.2\%}$ measurements at 300 K and 4.2 K, grain size characterization from optical microscope, hardness and micro-hardness measurements as well as residual resistive ratio (*RRR*) between 300 K and 4.2 K. To fulfill the technical specification regarding the value of $Rp_{0,2\%}$, silver content of 0.05% was selected.

TABLE III
Results of Traction Tests Performed on 200 mm Long Sample of Cu-Ag Hollow Stabilizer

% Ag	Cold work (%)	Grain sizes (μm)	$Rp_{0.2}$*(MPa)* at 300 K	$Rp_{0.2}$*(MPa)* at 4.2 K
$CuAg_{0.032}$	15	52 ± 32	≥ 208	≥ 265
$CuAg_{0.052}$	22	31 ± 24	≥ 230	≥ 290

The addition of silver to the copper for the stabilizer has followed a twofold objective: *1)* No significant decrease of $Rp_{0,2\%}$ after thermal cycling reproducing the RCOCC soft-soldering (30 s at 230°C) as well as the typical impregnation processes of the superconducting coil (9 h at 140°C) and *2)* limitation of the average *RRR* value to 65.

Aurubis Belgium has successfully produced 4 + 44 lengths of Cu-Ag hollow stabilizer in 325 m unit lengths. The reception tests of all $CuAg_{0.05\%}$ stabilizer unit lengths were based on systematic dimensional measurements (Table IV) and leak test of the superfluid He channel (leak rate < 10^{-5} mbar l/s).

TABLE IV
As Built Main Parameters of The $Cu\text{-}Ag_{0.05\%}$ Hollow Stabilizer
(overall production)

Parameters	Values(Max/min)
Total width	18 ± 0.1 mm
Total height[a]	13.05 ± 0.1 mm
Height between the lips	15.4 ± 0.08 mm
Unit length (x 44)	325 m
Copper cross-section of the Cu-Ag stabilizer	≥ 157.4 mm^2
Cross-section of the cooling channel	≥ 28.3 mm^2
$Rp_{0,2\%}$ after soft-soldering (300 / 4.2 K)	> 230 / 290 MPa
RRR after soft-soldering	65 ± 5

[a]Including the height of the lips equal to 3.15 ± 0.05 mm. The excess with respect to the thickness of the Rutherford cable (*cf.* Table II) was plastically deformed for the crimping.

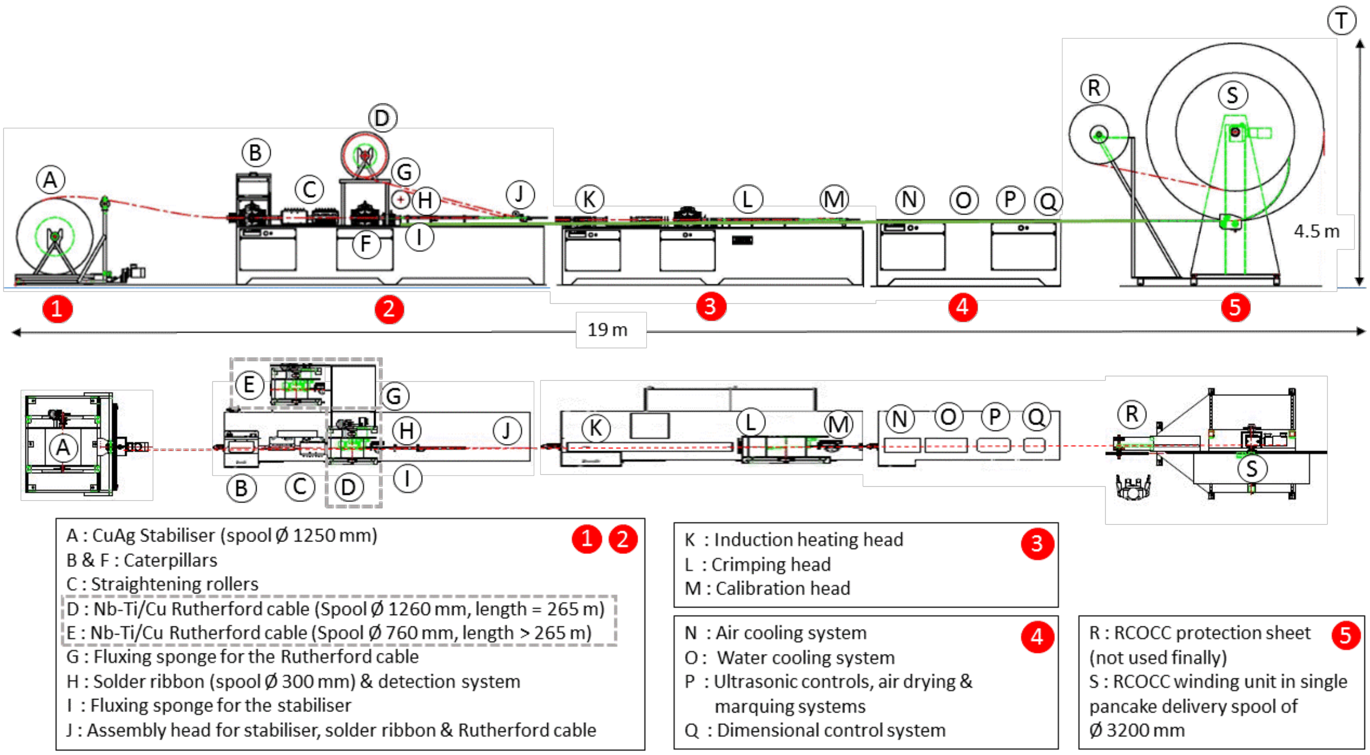

Fig. 2. Production line of the Cu/Nb-Ti Rutherford Cable On Conduit Conductor (RCOCC).

III. In-Laboratory Industrial Assembly of the RCOCC

A. *R&D and prototyping*

The two main requirements for the industrial assembly of the RCOCC were: i) State-of-the-art soft-soldering of the Rutherford cable on the Cu-Ag hollow stabilizer of 265 m unit lengths; ii) Strict control of the amount of the soft-solder alloy for the assembly to control the adjacent contact resistance. This later point constitutes one of the novelties of the RCOCC and has driven specific R&D programs for the selection of the soft-solder alloy and flux, the heating process [5],[7] as well as experimental tools for the characterizations [9].

To control the adjacent contact resistance between strands, induction heating was chosen to melt soft-solder ribbons instead of the melted solder bath usually used in industry. This approach also offers the advantage of reducing the environmental impact by minimizing the release of heavy metal vapors. Mechanical properties of soft-soldered RCOCC obtained from various ribbons of solder alloy have been thoroughly tested and analyzed leading to the final choice of $Sn_{61.5}Pb_{37}Sb_{1.5}$ alloy with a liquidus temperature of 190°C. The final thickness and width of the soft-solder ribbon used are 0.11 mm and 14 mm, respectively.

B. *The RCOCC industrial assembly line*

No industrial partner was found for the production of the RCOCC mostly because this assembly was considered too risky for a standard tendering procedure. The only way to continue the project was to internalize such a production in the laboratory and place a call for tenders to build the production line. Thanks to a fruitful collaboration with Ravni Technologies, the industrial assembly line was delivered and installed at LNCMI-Grenoble first half of 2016.

The layout of the production line of the RCOCC is shown in Fig 2. It can be split in 5 major parts, the 3 first ones are shown in Fig. 3: *1)* The unspooling drum of the Cu-Ag stabilizer. *2)* The straightening rollers, the fluxing unit, the assembly head for the stabilizer, the soft-solder ribbon alloy and the flat Rutherford cable. *3)* The open induction coil [5], the crimping and calibration heads. *4)* The air cooling followed by water cooling system, the ultrasonic control system to monitor the quality of the soft-soldering, the air dryer and the dimensional control system. *5)* The winding unit to form a single pancake coil of 2 m internal diameter for the RCOOC delivery in unit length of 265 m (Fig. 4). Attention has been paid to have the minimal bending radius larger than the maximum one of the final double pancake coil winding.

C. *RCOCC control tests*

During the production, the ultrasonic signal to control the quality of the soft-soldering was recorded continuously as well as four temperature measurements (one thermocouple sensor per conductor surface) and the RCOCC dimensions (Table V). A sample of 2 m long was extracted from each produced length of RCOCC for thorough quality control tests and measurements. This allowed affirming that no degradation of the mechanical and electrical properties of the RCOCC components have been introduced during the assembly, soft-soldering and dimensional calibration processes. The ultimate shear stress between the Rutherford cable and the Cu-Ag stabilizer has also been measured on extracted samples in the range 24–37 MPa at room temperature and the adjacent contact resistance $R_a \approx 0.5$–$0.6\ \mu\Omega$ at 4.2 K (Table V).

For the whole production consisting in 44 single pancakes of RCOCC, only one single unit length had to be rejected. It was used for the validation of the coil winding line and the impregnation process. A total of 24 minor non-conformities were detected, among which 14 had no impact on the quality of the RCOCC produced and 10 requiring dedicated corrective actions including one stop and restart.

Fig. 3. First parts of the RCOCC production line including unspooling and straightening units, assembly and induction heating heads, crimping and calibration modules.

Fig. 4. Movable winding unit (in vertical direction) of total maximum height of 4.5 m. Each produced 265 m long RCOCC unit length is wound in a single pancake of 2 m internal diameter prior to their delivery to the coil winding manufacturer.

TABLE V
MAIN PARAMETERS OF THE RCOCC
(OBTAINED FROM THE OVERALL PRODUCTION)

Parameters	Values(Max/min)
Width[a]	17.92 ± 0.05 mm
Height[a]	12.96 ± 0.04 mm
Unit length (x 44)	265 m
Cross/adjacent contact resistances R_c / R_a[b]	> 100 / > 0.5 μΩ

[a]From continuous measurement control during the production on straight RCOCC prior to its winding in single pancake of 2 m internal diameter in its delivery spool.

[b]Effective contact resistance R_a deduced from dedicated thermometry measurements at 4.2 K [7] performed on samples extracted from the production; it is an effective value as it includes the heating coming from the interfilamentary contributions.

IV. CONCLUSION

The production of all RCOCC unit lengths was completed end of July 2017 with the last delivery to the coil manufacturer end of September 2017. This milestone can be considered as one the first great achievements of the new Grenoble hybrid magnet project.

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