Large Hadron Collider Project

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Review of the R&D and Supply of the LHC Superconducting Cables

D. Leroy

Abstract

The construction of the superconducting magnets for the LHC machine has required the supply of ~ 7350 km of superconducting cables. The delivery of cables which is completed at 97% has made use of a large part of the world wide production capacity. Ten contracts have been placed with firms in Europe, Japan, USA. The Nb-Ti and the Nb materials have been contracted by CERN. Before tendering and placing the contracts, a R&D program has combined studies at CERN and orders of finished cables of significant lengths to industry. The report will present the main results of the R&D program, the characteristics of the LHC cables, the encountered difficulties and the obtained successes during the long duration fabrication contracts of the highly sophisticated LHC superconducting cables.

CERN, Accelerator Technology Department, Geneva, Switzerland

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CERN
CH - 1211 Geneva 23
Switzerland

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Review of the R&D and Supply of the LHC Superconducting Cables

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Index Terms—LHC, Nb-Ti, superconductor, critical current, magnetization, inter-strand resistance, Minimum Quench Energy.

I. INTRODUCTION

THE LHC colliding accelerator presently in the phase of installation has required the fabrication and the reception of 1265 tonnes or 7350 km of superconducting cables including the spares, manufactured from 5928 Nb-Ti/Cu composite billets [1]. The 1248 dipoles have 2 layers of high aspect ratio cables called respectively Cable 01 and Cable 02. The 400 quadrupoles and the 178 km of bus bars are fabricated with the Cable 02. The twin aperture dipoles contain 4 unit lengths (UL) of Cable 01, named UL1 and 4 unit lengths of Cable 02, named UL2. The twin aperture quadrupoles need 2 unit lengths of Cable 02, named UL3.

The R&D program, which started in 1988 has been addressed to the main cable characteristics influencing the magnet qualities in terms of maximum operation field, magnetic field precision and magnet stability. They are the critical current density at 1.9 K in the range 9-10 T, the magnetization of the strands and the Nb-Ti filament size, the precise dimensions of the cables and the inter-strand resistance between the crossing strands in the cables. The R&D program has combined studies at CERN and orders to industry of finished cables, long enough to build model and prototype magnets. R&D contracts have been placed with major European companies during the years 1988-1994. Prequalification contracts have been placed in the years 1995-1996 involving European, Japanese and American firms. In

total, 36 tonnes of superconducting cables have been ordered for the R&D phase, before placing the final contracts.

The contracts for the LHC cables have been signed at the end of 1998. The contracts, which have been distributed between 6 firms, are based on a specification and a contract organization aiming to guarantee the high technical requirements, the homogeneity of the production in each LHC octant and the on-time cable delivery. The Nb-Ti and Nb raw material has been supplied by CERN to the European companies via a contract with only one supplier [2]. The production of the LHC cables including spare cables will end in spring 2006.

The total quantity of UL amounts to 5197 UL1, 5286 UL2, 854 UL3 and 178 km of bus bars. The contingency is of the order of 4 %. A contract for 432 km or 24.5 tonnes of cables having a width of 8.5 mm and needed for the insertion MQM magnets has also been placed and represents 570 UL of various lengths, made from 122 billets.

II. R&D PHASE

A. Historical Review, Critical Current density.

The development of the cables is closely linked to the development of the magnet models and prototypes designed with the use of Nb-Ti at 1.9 K to reach a target quenching field of 10 T. At the beginning, from 1988 to 1993, the main goal of the superconducting cable R&D was to obtain high critical current densities at 10 T and 1.9 K, in Nb-Ti filaments of 5 μm suitable for the accelerator magnets.

In 1989 and 1990, several contracts, amounting to 16 tons, have been placed for 17 mm cables for the construction of 50 mm bore, 10 m long prototypes. This first generation of cables had a width of 17 mm and consisted of 26 strands of 1.29 mm for cable 01 and 40 strands of 0.84 mm for cable 02.

In 1993, a cable of 16.7 mm has been used to build a very successful twin-aperture model magnet, the best one obtained with cables and strands having 5 μm filaments. The strand for cable 01 of 1.1 mm has 20328 filaments of 4.8 μm . The critical current density reached is 1620 A/mm², 10 T and 1.9 K. Around 10 T, the dJc/dB is 487 mm²T⁻¹. The cabling degradation is 3 %. The field shift at the same current between 4.2 K and 1.9 K is 3 T. The cables have a compaction of 91 %. This cable has been the reference for the design of the final LHC cables. Fig. 1 shows a cross-section of the arrays of the 4.8 μm filaments.

Fig. 1. 20328 Nb-Ti filaments of 4.8 μm in a strand of 1.1 mm diameter assembled in a double stack process

In 1993, the design of the magnets for LHC has changed: the operation field was reduced to ~ 8.5 T, the bore increased from 50 mm to 56 mm and the length increased from 10 m to 14.2 m. The cable width went from 17 mm down to 15 mm and the filament size went up to 7 and 6 μm , acceptable from the field quality point of view in 56 mm bore magnets.

B. Pre-qualification program

In 1994 and 1996, 19 tons of material have been ordered in European, Japanese, and American firms as a prequalification program. Table I summarizes the critical current density results of the pre-qualification program for the European firms.

In the same pre-qualification program, firms have been asked to use the raw material Nb-Ti from 4 different suppliers. The results have shown that the critical current densities depend essentially on the heat treatments applied by the strand manufacturers.

TABLE I
RESULTS OF THE PRE-QUALIFICATION PROGRAM IN CRITICAL CURRENT DENSITIES

	Strand 01	Strand 02
Supplier	Jc(10 T, 1.9 K) [A/mm ²]	Jc(9 T, 1.9 K) [A/mm ²]
B	1670	2300
C	1490	2000
D	1670	2370
E	1620	2140

The average value of dJ_c/dB is $500 \text{ A/mm}^2\text{T}^{-1}$ at 10 T and the average value of dJ_c/dT is around $500 \text{ A/mm}^2\text{K}^{-1}$ at 1.9 K.

As a result of the pre-qualification program, the critical current densities have then been specified to 1500 A/mm^2 , 10 T, 1.9 K for the strand 01 and 2060 A/mm^2 , 9 T, 1.9 K for the strand 02, respectively, in filaments of 7 μm and 6 μm for the final tendering in 1997. These current densities look conservative in order to cope with the various suppliers needed for a mass production and are consistent with the magnet design operating field of 8.4 T.

III. CABLE GEOMETRY, TOPOLOGY

A. Cable topology

The cable geometries have been studied using a 2D projection technique of the different sides of strand extracted from the R&D phase cables [3]. From the measurements, a topological modeling has been built, to obtain a good simulation of the deformed strand in the cables as shown in Fig. 2. The values of the inner free volume of superfluid helium and the inner free surfaces between the 2 layers of strands in the cable have been calculated. They play a major role since the cable insulation fills partially the voids between the strands on the external faces of the cable,

Passing from the first generation of 17 mm cables to the final LHC cables of 15.1 mm, the cable compaction was decreased from 92.5 % to 90 %. The cooling efficiency in area, defined as the ratio of the exchange surface with liquid helium (inner free surface) to the wire volume has increased by 15 %. The cooling efficiency in volume defined as the ratio of the inner free volume to the wire volume has been increased by 25 %.

Fig. 2. Reconstructed de-cabled strand

B. Cable heat reserve and time constant characteristics

From the modeling, a few thermal cable characteristics have been deduced. The inner free volume of helium between the two layers of strands represents ~ 5 % of the total volume of the strands. The free inner surface of the strands amounts to 25 % of the total strand surface. With these values, the cable heat enthalpy reserve has been estimated at 42 mJcm^{-3} and the time constant for the heat transmission from strand to helium has been estimated at 11 ms between 1.9 K and 3.3 K (maximum temperature of the coils at top energy) [4]. The presence of helium compensates the loss of metal enthalpy at 1.9 K.

A considerable effort has been devoted to the thermal transfer via the helium through the insulation at 1.9 K to have a Kapton® insulation disposition allowing a stationary heat transfer capable to extract a heat deposition of 10 mW/cm^3 [5].

IV. INTER-STRAND RESISTANCE

The value of the electrical resistance between two crossing strands plays an important role on the coupling currents induced between the strands of the cable, resulting in dynamic distortions of the magnetic field, on the uneven current

distribution between strands due to non-uniform cable-to-cable joint resistance, on the boundary-induced coupling currents [6] and on the cable stability against thermal disturbance [7, 8]. Based on a theoretical study [9] and the measurement of dynamic field errors on model and prototype magnets, the lowest values acceptable for LHC have been deduced. The Cable 01 R_C should be $\geq 15 \mu\Omega$, and the Cable 02 R_C should be $\geq 30 \mu\Omega$. The R&D work aimed at 20 and 40 $\mu\Omega$, respectively.

A. R&D PHASE

The main goal of the R&D program was to define a coating which can be industrially deposited and well controlled. The values of R_C are governed by the resistive barrier surrounding the strands, the coating material, the strand deformation, the contact area, the coating roughness and the local pressure at cabling. Special developments have been made at the cabling level in order to fabricate and evaluate cables with a metallic ribbon (Stainless Steel, Ti, Ta) between the strand layers in the states: non-soldered, partially soldered or soldered with a porous metal to improve the cable electrical stability. The thickness of the foil is in the range of 25-50 μm . The values of R_C are around 1 Ω for cored cables before heat treatment.

Curing of magnet coils under pressure changes the R_C more than any other step. For example, cables with bare Cu strands ready for coil manufacturing have an R_C of 10^2 to $10^3 \mu\Omega$. After curing at 190 $^\circ\text{C}$, their R_C drops to 0.5 to 2 $\mu\Omega$.

1) Coating Materials and R_C values

R_C has been measured as described in [10] on strands coated with different materials as SnAg5%wt, SnNi30%wt, Ni, Ni electrochemical, ZnNi15%wt, NiP13%wt, Zn Passivated, Zn, Oxidized Cu. The results are reported in Table II.

TABLE II
MATERIALS STUDIED IN THE 3-POINTS EXPERIMENTAL SET-UP

$\mu\Omega \text{ mm}^2$	Material	Comments
10	SnAg5%wt	Hot dipping-Soft coating
200	SnNi30%wt	Electrochemical plating
500	Ni	Electrochemical plating
	ZnNi 15%wt	Ni oxidizes preferentially to Zn
1000	Ni+NiP 13%wt	NiP layer added on Ni- Hard coating
	Zn	
10^4	Passivated	Oxide layer added by passivation-cracks easily
	Zn	
10^6	Oxidized Cu	CuO_2 resistive layer-cracks easily

The values reported in Table II are normalized in $\mu\Omega\text{mm}^2$, product of the resistance times the contact area. From this data, the R_C can be estimated, knowing that the contact area for crossing strands in a cable approaches 1.25 mm^2 for a loading force larger than 280 N.

2) R_C measured on cables

R_C has been measured on a stack of cables as described in [11]. In these measurements, R_C is measured on cables as received from the supplier and measured after a heat treatment simulating the curing of the coils under a pressure of 30 MPa. The temperature of the coil curing has varied from 165 $^\circ\text{C}$ to 195 $^\circ\text{C}$. Table III shows the measurement results of R_C for different cables.

TABLE III
RC MEASURED ON CABLES IN VARIOUS CONDITIONS ($\mu\Omega$)

Material	As received	After curing	As received pre-heated cable at 200 $^\circ\text{C}$	After curing pre-heated cable at 200 $^\circ\text{C}$
SnAg5%w	10-50	0.5-4	100-200	17-23
Bare Cu	80-700	0.5-1.6		
Sn Ni	70	15	-	-
35%w Ni	500	50-60	-	-
CuNi45%w	100	2.5	600	130
Stainless Steel core	780 ⁽¹⁾	115	-	-
Ti core	400 ⁽¹⁾	55	-	-

(1) are calculated values. Ti can be anodized

Fig. 3 shows a cored cable. The R_C of such a cable does not depend too much on the core resistivity but more on the foil deformation, on the contact geometry after cabling and on the presence of oxides.

Fig .3. A cored cable

B. The SnAg5%wt coating

The SnAg5%wt coating was selected for the production of the LHC main magnet cables. The SnAg5%wt coating is made by hot dipping the strand in a SnAg5%wt bath.

The coating thickness consists of a layer of SnAg5%wt followed by a double layer of CuSn intermetallics: a Cu_3Sn intermetallic called ϵ -phase and a Cu_6Sn_5 intermetallic called η -phase. After the cable heat treatment in air at 200 $^\circ\text{C}$, the coating is transformed into an intermetallic layer of small grains Cu_3Sn , accompanied by CuO [12]. During the heat-treatment, the surface roughness of the coating layer is increased. The coating thickness must be below 1 μm .

During the magnet coil curing, the conductor is warmed up typically to 190 $^\circ\text{C}$ at a pressure of ~ 50 MPa for ~ 30 min. The contacts between strands close hermetically under pressure. Micro-contacts flatten and oxygen easily diffuses from the contact surface inside the coating. As no additional oxygen can reach the contact, concentration of oxygen in the contact drops and so the R_C decreases. The depletion of O causes the R_C drop. The thickness of the pure SnAg5%wt layer differs among firms. The thickness of the pure SnAg5%wt layer is the parameter to be controlled during production.

The coating thickness which has a major effect on R_C has been controlled during fabrication and measured at CERN by

a coulometric methodology [2, 13]. After cabling, the cables are heat treated in hot air at 200 °C. As other effects, this heat treatment of the cables at 200 °C for several hours removes the residual mechanical stresses introduced during cabling, and improves the Residual Resistivity Ratio (RRR). After heat treatment at 200 °C for several hours, a cable has a contraction of less than $3 \cdot 10^{-4}$ during the coil curing at 190°C for 30 min.

V. MQE

The stability of superconducting strands and cables can be characterized by their Minimum Quench Energy (MQE), i.e. the minimum energy pulse of short duration to trigger a quench. Measurements on strands have been performed at CERN, BNL, Rutherford during the R&D phase.

A. MQE on strands for small extend (0.6mm) and short pulse duration(40 μ s) [14]

The MQE measurements have been performed on strands at CERN. The measurements have revealed that the most important parameter of the MQE at 1.9K is the volume of helium in contact with the strand. The RRR, when larger than 100, has not a significant effect. The MQE on strands varies from 10 μ J in adiabatic conditions to 1000 μ J in open bath for a 0.825 mm strand at 0.8 I_c current.

B. QEM for long extend (40 mm) and short pulse (12 μ s) (RHAL) [15]

Measurements of stability have been performed at RHAL (Rutherford Appleton Laboratory) for a perturbation of long extend (40 mm) and short pulse duration (12 μ s) [15]. It is an investigation of the Quench Energy Margin (QEM) of strands exposed to transient, spatially distributed disturbances. In adiabatic conditions (under vacuum) the QEM is 1000 J/m³ for a wire of 0.825 mm at 0.8 I_c current. At 1.8 K, the QEM goes up to 6000 J/m³. The simulation was in good agreement with experiments with a He channel length $L=85\mu$ m, cooled surface fraction $f=0.8$, heat transfer coefficient $a_k=458 \text{ W m}^{-2} \text{ K}^{-n}$ and $n=3.5$. The heat transfer coefficient plays an important role. QEM has been measured on strands of different surface treatments. All the coated strands exhibit a QEM greater than the oxidised copper strand.

C. MQE on cables [16]

At BNL, stability measurements have been performed on cables by placing heaters on the cable at various positions. All the measurements show a “kink” separating the zones where the strands behave collectively below 0.8 I/I_c at 4.2 K and 0.6 I/I_c at 1.9 K depending on the helium volume inside the cable and on the thermal conductance between the strands. Above the kink, at 0.9 I/I_c , the MQE value is around 100 μ J, below the kink at 0.7 I/I_c , the MQE rises to 5000 μ J. Trials have been made to introduce a porous solder in the cable to improve the stability and move the kink to higher reduced currents but this technology was complicated and not reproducible.

VI. SPECIFICATION

Table IV shows the main characteristics of the main arc dipole and quadrupole cables specified for LHC.

The LHC critical current density in each strand type has been chosen in order to cope with the values obtained by the different suppliers in the R&D phase so that the critical current densities stay in the control limits of 6σ requested for a mass production.

For LHC it is required that 4 UL of each cable are produced in the same cabling run and receive the same heat treatment (HT).

Cold welds within an UL are forbidden, but can be used in between UL to make it possible to produce long cabling runs. Very good traceability is required for the distribution of the UL and the cold welds within the cabling run.

During cabling the relative cable dimensions (width, mid-thickness, and keystone angle) are recorded on-line using a so-called CMM (Cable Measuring Machine), developed in the US laboratories, using a transverse pressure of 20 MPa. Moreover, at the beginning and the end of the cabling run the absolute value of the mid-thickness of the cable is measured on a stack of 10 cables compressed at the specified 50 MPa in a dedicated fixture (10-stack method). The cabling line is equipped with a Cable Inspection System (CIS) to check the cable defects (see paragraph X.B.1 of this paper).

TABLE IV
MAIN CHARACTERISTICS OF THE LHC MAIN MAGNET SUPERCONDUCTING STRANDS & CABLES

STRAND	Type 01	Type 02
Diameter [mm]	1.065	0.825
Cu/SC ratio	1.6-1.7	1.9-2.0
Cu/SC control limits	± 0.03	± 0.03
Filament diameter [μ m]	7	6
Twist pitch [mm]	18	15
Number of filaments	~ 8800	~ 6400
Coating type	SnAg _{5%Wt}	SnAg _{5%Wt}
Strand I_c [A]	515 @ 1.9K, 10T	380 @ 1.9K, 9T
I_c control limits [%]	± 4	± 4
J_c [A/mm ²]	1530 @ 1.9K, 10T	2100 @ 1.9K, 9T
ΔM (0.5T, 1.9K) [mT]	30	23
ΔM control limits [%]	± 4.5	± 4.5
CABLE	Type 01	Type 02 & 03
Number of strands	28	36
Width [mm]	15.100	15.100
Thickness thin edge [mm]	1.736	1.362
Thickness thick edge [mm]	2.064	1.598
Mid thickness(50MPa)[mm]	1.900 $\pm$ 0.006	1.480 $\pm$ 0.006
Keystone angle [deg]	1.25 $\pm$ 0.05	0.90 $\pm$ 0.05
Cable I_c [A]	13750 @ 1.9K, 10T	12960 @ 1.9K, 9T
Cabling degradation [%]	< 5	< 5
Inter-strand resistance [$\mu\Omega$]	10-20	20-40

VII. ORGANISATION OF THE CONTRACTS

A. Allocation of the Contracts for the Cables

Table V shows the allocation of the various contracts signed in 1998 and slightly redistributed in 2000. All the LHC cables are manufactured from Nb-Ti and Nb supplied by Wah-Chang (USA). The Nb-Ti bars and Nb sheets for the European strand manufacturers have been supplied by CERN (thanks to the USA contribution to LHC). The contract

awarded to Wah-Chang concerns the supply of 490 tonnes of Nb-Ti (47.0 ± 1.0 % weight Ti) and 26 tonnes of reactor grade Nb sheets.

TABLE V
CONTRACTS

Supplier	Strand Country	Production		
		Cable 01	Cable 02	Cable 03
Alstom	France	5 octants	3 octants	3 octants
EAS	Germany	3 octants		
OCSI	Italy		2 octants	2 octants
OK	Finland		1 octant	1 octant
OKAS	USA		1 octant	1 octant
FEC	Japan		1 octant	1 octant
Raw		Material		
Wah-Chang		8 octants	8 octants	8 octants

1 octant cable 01=616 unit lengths of 460 m

1 octant cable 02=616 unit lengths of 750 m

1 octant cable 03=108 unit lengths of 660 m

B. Relationship with the Strand Manufacturers

Holding points have been incorporated in the follow-up of the cable contracts to obtain a high degree of confidence in the fabrication: the billet approval, the approval of the cable maps, the approval for shipment and the provisional acceptance given when all the data conform to the cable specification. For many suppliers, the scheme of follow-up appeared at the beginning as a constraining scheme, but after discussions, they have understood that CERN goals were equivalent to the supplier success. A very good correlation between the CERN and the supplier measurements has been imperative.

VIII. CERN MEASUREMENT EQUIPMENT AND THE MANAGEMENT INFORMATION SYSTEM (MIS)

A large cable storage area for up to 400 magnets and a specific measurement laboratory have been set-up at CERN to perform the large number of measurements required by the Technical Specification. They have been described in [2].

A Management Information System (MIS) for the cable production follow-up has been developed at CERN. It is not only a Data Base but a strong management tool with many applications for the close follow-up of deliveries, the rapid decision on the quality of the billets, the cable strand map and the finished cables. Statistical tools are also incorporated. The firms have access to load their mandatory measurements. The measurements made at CERN are automatically recorded, analysed and commented.

MIS involves the labelling, the cutting of samples and their distribution in the various test stations at CERN for measurements at room temperature and at low temperature of the strands, the cable samples before heat treatment and the final delivered cable UL. All the samples are archived. The approved UL are stored, grouped following their characteristics before the expedition to the Cold Mass Assembler. An application selects as well the correct cable for the replacement of cables in case of problems at the magnet coil manufacturing.

In total, the laboratory has treated 65000 virgin strand samples and 4000 cable maps, for the qualification of 6050

billets and 11550 UL received. The number of strand measurements at low temperature (Ic virgin, Ic de-cabled, RRR, Magnetization) amounts to 55500. At room temperature, 153000 measurements have been performed on the strands (Copper to superconductor ratio, Sharp bend test, spring back test, dimensions, filament twist pitch, SnAg_{5%wt} coating). For the approval of the cables, 2600 Ic cable measurements (majority of them at BNL) and 5550 Rc measurements have been performed at low temperature. At room temperature, the verification of the cable dimensions and surface quality have been performed on 5500 UL for a total of 11550 UL received (i.e 50% of the production).

IX. RESULTS

Some measured results of the most important characteristics of the specifications, such as raw material quality, Ic, Cu/Sc ratio, Magnetization, cable dimensions, cable Ic, Rc are presented in the following sections.

A. Raw Material Quality

During production, the Ti range was reduced from just over 1.5% to less than 0.8% on the ingot sidewall. In addition, the frequency of Nb-rich inclusions was minimized. The grain size in the finished Nb-Ti bars has an average value of 3.45 ASTM with σ of 0.27. The Nb-Ti billet diameter variation dropped from a range of 0.09 mm to 0.04 mm while deviation from the nominal diameter was reduced from nearly 0.13 mm to less than 0.025 mm during production.

B. Strand critical current density at 1.9 K

Table VI shows the results of the average strand critical current density measurements performed at CERN at 1.9 K. All the critical currents measured on the strands are above the minimum specified limit.

TABLE VI
MAIN CRITICAL CURRENT DENSITY AT 1.9 K

Supplier	Jc, avg [A/mm ²]	σ [A/mm ²]	CV [%]	ΔB [T]	$\sigma_{\Delta B}$ [T]
Strand	01@10 T				
01 B	1708	37	2.1	3.11	0.02
01 E	1684	25	1.5	3.05	0.02
Strand	02/03@9 T				
02 B	2353	36	1.5	3.05	0.02
02 C	2292	41	1.8	3.03	0.03
02 D	2376	29	1.2	3.06	0.02
02 G	2360	50	2.1	3.02	0.02
02 K	2276	32	1.4	2.93	0.02

The overall Coefficient of Variation (CV) for each supplier is defined as the standard deviation divided by the average value of the sample set produced up to now. The CV values indicate a small variability in all the processes that influence the critical current density. The field shift at the same current

between 4.2 K and 1.9 K varies from 2.93 T to 3.11 T depending on the supplier.

C. Mixing of strands in cables for copper to superconductor ratio (Cu/Sc)

During the fabrication of billets, the Cu/Sc ratio is not constant all over the length due to the end effects at extrusion. The curve of Cu/Sc ratio shows a bump of higher Cu/Sc preceded at the head of the billet by a lower Cu/Sc ratio. The firm has to cut the transition length of billet with a ratio out of the specified limits. The part of the billet with a higher ratio than the specified value has been accepted when the critical current was higher than the specified values. The bump length can represent 5 % of the billet length. It has been accepted to incorporate in the cable maps a few bump lengths under strict conditions which maintain the cable critical current within the control limits.

D. Cable dimensions.

The dimensional measurements of the LHC cable production are reported in Table VII. They have been performed using the CMM (Cable Measurement Machine), in combination with the absolute value obtained from the 10-stack method. The mid-thickness of cables 01 and 02 are well within the specification limits. The standard deviation for both cables is within 1 to 2 μm .

TABLE VII
CABLE DIMENSIONS AT THE VARIOUS CABLING FIRMS

Firm	Width		Mid thickness		Keyst. angle	
	Aver. [mm]	σ [μm]	Aver. [mm]	σ [μm]	Aver. [°]	σ [°]
Cable 01						
01B	15.090	1	1.900	1	1.255	0.015
01E	15.090	2	1.900	1	1.244	0.014
Cable 02						
02B5	15.090	1	1.480	1	0.903	0.013
02B8	15.091	1	1.480	1	0.902	0.016
02C0	15.090	3	1.480	2	0.899	0.018
02C9	15.092	2	1.480	1	0.903	0.016
02D	15.085	2	1.480	1	0.882	0.013
02G	15.090	1	1.480	1	0.899	0.016
02K	15.091	1	1.480	1	0.898	0.015

E. Magnetization

Tables VIII and IX shows the average values of the measured width of the magnetization loop (ΔM) for strand and cables at 1.9 K, 0.5 T. Some billets have been rejected due to the high magnetization value. As explained in [2] the origin of these high values is mainly related to an exceptional large deformation of the filaments. The deformation of the filaments has its origin during extrusion and can occur in single stack as well as in double stack billet assembly. The concerned strand manufacturers have been forced to take actions to provide a better follow-up of the billet assembly and of the extrusion (temperature, time, speed and pressure) to avoid the rejection of billets for magnetization reasons. 50 % of the billet rejection is for such reasons. The mixing of strands with higher magnetization values has been authorized in some cable maps at the condition that the magnetization value of the cable was in the control limits of the specification as shown in

Table IV.

TABLE VIII
WIDTH OF STRAND MAGNETIZATION AT 1.9 K, AND 0.5 T

Supplier	Number of billets	Average of ΔM [mT]	σ [mT]	Cv [%]
Strand 01				
01 B	1703	27.09	1.2	4.4
01 E	343	30.74	1.46	4.7
Strand 02/03				
02 B	895	21.91	0.98	4.5
02 C	998	22.64	0.63	2.8
02 D	525	20.97	0.37	1.7
02 G	361	21.66	0.45	2.1
02 K	848	22.01	0.36	1.7

TABLE IX
AVERAGE WIDTH OF THE CABLE MAGNETIZATION AT 1.9 K AND 0.5 T

Supplier	Number of Cable Maps	Average of ΔM [mT]	σ [mT]	CV [%]
Cable 01				
01 B	938	27.06	0.58	2.1
01 E	378	30.81	0.8	2.6
Cable 02/03				
02 B	702	21.87	0.42	1.9
02 C	626	22.63	0.48	2.1
02 D	242	20.98	0.21	1.0
02 G	399	21.66	0.33	1.5
02 K	533	21.96	0.27	1.2

Thanks to the controlled mixing of strands in the cable maps, the width of the cable magnetization was kept within the specified limits.

F. Cross-contact Resistance

Table X shows the average value of the inter-strand resistance R_c . Even if the coating thickness measured using the coulometric method both at the company and at CERN is controlled with a standard deviation of about 0.08 μm , the standard deviation on R_c is high. All the values of R_c , which are larger than the minimum requested are acceptable for LHC. The CV values are of the order of 50 % indicating a large variability of the process.

TABLE X
AVERAGE CABLE INTER-STRAND RESISTANCE

Supplier	Average R_c [$\mu\Omega$]	σR_c
Cable 01		
01B	43	21
01E	35	16
Cable 02 03		
02B5	122	41
02C0	125	65
02C9	96	41
02D	24	18
02G	40	18
02K	65	23

G. Cable critical current at 4.2 K

The average critical current of all the measured cables (Table XI) are above the specified values by about 8 %. No

cable has a critical current lower than the specified value.

The critical current of the cables have been measured at BNL only at 4.2 K on cable samples cut before the heat treatment. CERN performs as well critical current measurements at 4.2 K and 1.9 K on cable samples not measured at BNL and on extracted strands after the cable heat treatment. Based on the average critical current reached by each manufacturer, the temperature margin of the dipoles at 1.9 K and 8.4 T operation field is around 1.6 K for the inner layer cable (cable 01) and 1.7 K for the outer layer cable (cable 02). The cable degradation does not exceed 3 %.

TABLE XI
AVERAGE CABLE CRITICAL CURRENT AT 4.2K AND FIELD SHIFT

Firm	Average Ic [A]	CV [%]	Field Shift [T]
Cable 01@ 7 T			
01B	15258	2.4	3.11
01E	15398	1.8	3.05
Cable 02/03 @ 6 T			
02B5	15146	1.8	3.05
02B8	15315	0.9	2.93
02C0	14823	1.6	3.03
02C9	14958	1.0	3.03
02D	14957	1.3	3.06
02G	15518	1.6	3.02
02K	15113	1.4	2.93

X. EXPERIENCE AND OBSERVATIONS

A. Cold Welds

The cold welds must be excluded. After many trials based on eddy current detection, no suitable equipment has been found to detect cold welds during cabling. The cold welds are indicated and checked by the contract follower on the cable map. In-site inspectors verify that the produced cable run is in conformity with the cable map. Cold welds have to be cut and archived by the firm. Verification of the archiving is made by the contract follower. All the verifications made have been conclusive on the validity of the process. Unfortunately, a cable with 36 cold welds fabricated at the beginning of the production, has been delivered to a cold mass assembler. The magnet was dismantled and the cable replaced. From this time, the controls have been reinforced and the traceability is very good.

B. Cabling problems, Tin lumps, Cross-over, Sharp edges, Burrs, Cable surface quality

1) Strand Cross-over, Tin lumps

The strand cross-over and the tin lumps on the strands have been detected by a Cable Inspection System (CIS), designed by CERN, and installed on each cabling line under the responsibility of the cabling company. The CIS has cameras installed to see each wide side of the cable. It has a pre-alarm system to record each picture with a possible defect. The image is analysed on line and informs immediately the operator on the type of defects. The tin lumps cause a large

deformation of the strand on the cable surface. Correction actions have been taken on the SnAg coating line, to detect and repair the tin lumps in the re-spooling line before cabling.

2) Sharp edges and surface conditions of the cables

During production, these problems have been very difficult to solve and are not yet solved. The control of the sharp edges is very difficult for the cabling operation. The sharp edges depend on the shape and precision of the mandrel, the relative position of the mandrel compared to the high precision rollers and on the cabling machine performances. Cabling is a subtle process demanding to adapt the optimum rollers to the strand lot. When this is not the case, damages on the form of copper clusters or deterioration of the cable surface quality occur.

XI. DELIVERY

A. Raw Material

The delivery of the raw material has been completed in June 2004. The maximum production rate has been of 130 tonnes in the year 2003. The complete delivery amounts to 494 tonnes or 4207 Nb-Ti bars in 536 lots of fabrication.

B. Cables

All the LHC billets have been produced. The delivery of the cables is completed at 97 %. In Fig. 4, the integrated billet and cable delivery situation in August 2005 are presented.

Fig. 4 Production of the LHC billets and cables

C. Statistics on rejection

On a total of 6050 billets, 55 billets have been refused by CERN for Ic or magnetization reasons. From the 55 refused billets for the magnet coils, 20 have been nevertheless accepted for bus-bars. On a total of 11550 UL (97 % of production) received, 242 (2.10 %) have been sent back (for repair of burrs or bad surface quality), 38 (0.33 %) have been rejected by CERN, 94 (0.81 %) have been declassified at CERN from Cable 02 into Cable 03. The same number has been declassified in firms. Declassification means that cable maps foreseen for Cable 02 production are transformed partially in Cable 03 of shorter lengths. Declassification reveals in fact problems during cabling.

D. Remarks on deliveries

The start-up of the LHC cables production has been longer

than foreseen by 2 years. The reasons of the longer start-up are mainly the setting-up of new high production-rate lines with new machines to be commissioned and a number of wire breakages larger than expected at the beginning. The time of fabrication of a finished billet is around 9 months at the beginning of the contracts to come down to 6 months at the middle of the contract. The time of reaction is then long before the modification or improvement can be introduced. The companies have made all the efforts to find the sources of problems and apply corrective actions. When the quality became stable, the companies gradually improved the production rate within one year to arrive at a billet fabrication time of 6 months. The Cable inspection System (CIS) has been very useful to assure the companies that cables with surface defect will not be shipped by miss-inspection. Another important aspect is the good correlation between the company and CERN measurements to be achieved before increasing the production rate. The supply of high quality raw material by CERN has allowed supplier to avoid too many questions on the raw material quality as origin of the problems.

XII. CONCLUSION

The average critical current of all the measured cables are above the specified values by about 8 %. Problems have occurred with the strand magnetization due to extrusion variations. The strand magnetization which is correlated to parameters as strand diameter, Cu/Sc ratio, filament diameter, filament spacing, critical current density, and copper RRR is a good indicator to evaluate the strand production homogeneity and stability. The results of the interstrand resistance show that the process has still a large variability. It is a process still in evolution. The cabling operation has a too large variability.

The good correlation between the CERN and the company's measurements, has allowed a precise follow-up and an increase of production rate.

The long R&D programme has been fruitful in tackling all the problems related to a high rate production of superconducting cables suitable for LHC

The CERN test equipment for reception and acceptance of the LHC strands and cables have faced with great success the large quantity of measurements.

All the Nb-Ti and Nb have been supplied within the tight specification. All the strand manufacturers have fulfilled the very demanding LHC specifications

The delivery of the LHC main arc magnet cables is completed at 97 %. The fabrication of 6050 billets and 11907 Unit Lengths (excluding the spares) of cables will be concluded before November 2005. The execution of the contracts for the LHC superconducting cables can be considered as a great achievement.

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