Status of the LHC Superconducting Cable Mass Production

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Abstract—Six contracts have been placed with industrial companies for the production of 1200 tons of the superconducting (SC) cables needed for the main dipoles and quadrupoles of the Large Hadron Collider (LHC). In addition, two contracts have been placed for the supply of 470 tons of NbTi and 26 tons of Nb sheets. The main characteristic of the specification is that it is functional. This means that the physical, mechanical and electrical properties of strands and cables are specified without defining the manufacturing processes. Facilities for the high precision measurements of the wire and cable properties have been implemented at CERN, such as strand and cable critical current, copper to superconductor ratio, interstrand resistance, magnetization, RRR at 4.2 K and 1.9 K. The production has started showing that the highly demanding specifications can be fulfilled. This paper reviews the organization of the contracts, the test facilities installed at CERN, the various types of measurements and the results of the main physical properties obtained on the first batches. The status of the deliveries is presented.

I. INTRODUCTION

THE CONSTRUCTION of the LHC machine requires the fabrication of 1232 twin, 15-m long, dipoles and 400 two-in-one, 3.2-m long quadrupoles in the main arcs [1]. Additionally, dipoles and quadrupoles of the same type have to be installed in the lines between the main arcs and the experiments. Dipoles and quadrupoles are powered in a separated electrical serial connection, and distributed equally in 8 octants. A total of 160 km of SC bus-bars will connect the dipoles and the two types of quadrupoles (focusing and defocusing).

The dipoles will operate at 1.9 K at an envisaged operating field of up to 9 T. The design is based on a two-layer $\cos\theta$ structure with grading between the inner and outer layer using two different SC cables, in order to reduce the cost and the field distortions at injection.

The three main points in this design are:

- The quantity of superconductor material is determined considering the actual maximum field seen by the strands of that layer.
- The quantity of copper in each layer is determined so that the magnets can be safely protected in case of a quench. The optimization of the Cu/SC ratio takes into account that the firing quench heaters are located on the external surface of the outer layer of cables in which, as a consequence, most of the dissipated energy will be absorbed in case of a quench.

- The diameters (and hence the magnetization) of the NbTi filaments in the strands of each cable are a balance between the manufacturing cost and the quality of the magnetic field (mainly the sextupole and the decapole components) at the injection field (0.5 T).

The cables for the inner and outer layer of the main dipole magnets are called Cable 01 and Cable 02 respectively. It has been decided, for economical reasons, to use for the quadrupole cables and the bus-bars the same cable as the outer cable of the dipoles. The quadrupole cables are called Cable 03. In total LHC requires the fabrication of 7000 km of cable, corresponding to about 240 000 km of strand, manufactured from about 7000 NbTi billets.

A strong Quality Assurance system, based on Statistical Process Control (SPC) methods, has been put in place in order to ensure the homogeneity of the production and increase the confidence in the quality of the SC cables. Key characteristics of the strand and cable are measured and displayed during the entire manufacturing period. A center line and upper and lower control limits are defined so that, when the process is in control, nearly all the sample points will fall between the control limits. A point outside the control limits requires a corrective action from the manufacturer to eliminate the cause. The control limits have to fall inside the specification limits. The target is to have the control limits at $\pm 3\sigma$ of the statistical distribution.

Each strand manufacturer has to perform systematic quality control on the strands and cables. CERN has installed a dedicated test laboratory (see Section IV) for various cold and warm measurements to verify the results from industry.

In Section II the specification of the cables will be briefly described with emphasis on some specific characteristics. In Section III some organization features of the contracts are described. In the last sections some results are presented of the cables as produced so far and a status is given of the actual and planned production.

II. SPECIFICATION

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

The LHC critical current density in each strand has been optimized to have the largest possible critical current density (J_C) at 9–10 T at 1.9 K while, at the same time, reducing as much as possible the J_C at 0.5 T and 1.9 K.

Two specific requirements of the LHC cable specification concern constraints on the magnetization (M) and the interstrand contact resistance (Rc), both more stringent as compared to previous superconducting accelerator magnets. They are due

TABLE I
MAIN CHARACTERISTICS OF THE SUPERCONDUCTING 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 (μm)	7	6
Twist pitch (mm)	18	15
Number of filaments	8800	6425
Strand I_C (A)	515 @1.9K, 10T	380 @1.9K, 9T
I_C control limits [%]	±4	±4
Jc (A/mm^2)	1530 @1.9K, 10T	2100 @1.9K, 9T
M (0.5T,1.9K) [mT]	30	23
M control limits [%]	±4.5	±4.5

CABLE	Type 01	Type 02 & 03
Number of strands	28	36
Width (mm)	15.1	15.1
Thickness thin edge [mm]	1.736	1.362
Thickness thick edge [mm]	2.064	1.598
Mid-thickness (50MPa) [mm]	1.900+/-0.006	1.480+/-0.006
Keystone angle [deg]	1.25+/-0.05	0.90+/-0.05
Transposition pitch (mm)	115	100
Cable I_C [A]	13750 @1.9K,10T	12960 @1.9K,9T
Cabling degradation [%]	<5	<5
Inter-strand resistance [μΩ]	10-20	20-40

Fig. 1.   Correlation of the difference Δ between the diameters of the bare wire and the wiping die and the SnAg coating thickness.

to a larger dynamic range of the field in the magnets (from injection to operating field) and a larger width of the cables.

A. Magnetization

The LHC cables require a high current density J_C at high field and a low magnetization (being proportional to J_C times the filament diameter) at low field, in order to reduce field distortions. Measurements of the strand magnetization loop [2] and simulations of the magnet harmonics during the R&D phase have lead to the choice of 7 μm for strand 01 and 6 μm for strand 02 or a maximum width of magnetization loop (at 0.5 T, 1.9 K) of 30 mT and 23 mT respectively. The filament sizes of strand 01 and 02 are chosen in order to limit the negative sextupolar harmonic content at injection [3].

B. Rc Control

Another important aspect of the LHC cables is a better quantitative control of Rc, not only to reduce the cable losses during a field sweep but more importantly to limit the harmonic errors during the ramp-up of the machine. In a transposed cable coupling currents are induced between strands when submitted to a varying magnetic field. These coupling currents increase strongly with increasing cable size and are inversely proportional to Rc and can therefore, for a given cable, only be limited by increasing Rc. However, a large Rc reduces the current sharing capabilities of the cable and hence the stability of the magnet at high fields. For these reasons Rc is specified to be the minimum value which can be allowed from the point of view of beam optics [4].

Rc is controlled by adding a fixed layer of SnAg on the strands followed by a cable heat treatment (HT) in air [5], [6]. Without HT Rc would be smaller than 1 μΩ after coil curing. During this heat treatment Sn diffuses in the copper which is
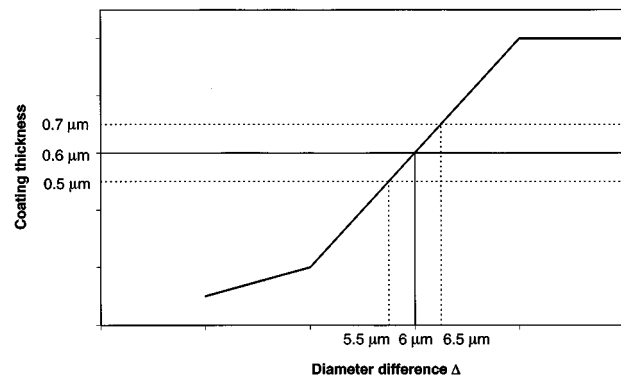
then oxidized, causing the required increase in Rc. Typically a 0.5 ± 0.1 micrometer thick layer on the strands requires a cable heat treatment of about 8 hours at 200 °C to obtain the required Rc. A thicker SnAg layer (about 1 μm) leads to too long HT duration, whereas a thinner SnAg layer requires a HT which is too short to be uniform over the entire spool. After cabling, the cables are wound on a metallic spool with a stainless steel mesh separating each layer to allow the hot air circulation between the cable layers in the oven. A cable, heat treated at 200 °C for several hours, has a contraction of less than $7 \cdot 10^{-4}$ avoiding additional thermal contraction of the coil during curing at 190 °C for 30 min.

A process for controlling the SnAg layer has been implemented by each company. The required SnAg layer is obtained by passing the bare strand through a SnAg bath at given speed and temperature. Directly in series with the bath a so-called wiping die is placed. The exact diameter of the wiping die in relation to the diameter of the bare strand and the tinning bath properties determine the final thickness of the SnAg layer (see Fig. 1). It took some time to put in operation this technology but now control to within 0.1 μm is achieved. The layer thickness is checked by a coulometric methodology during the coating process.

The relationship between the coating thickness and the diameter difference between the bare wire and the wiping die has to be established for each coating line since it depends on the strand speed and the tin bath temperature of the coating process. Typically 0.6 μm thick coating can be obtained with a diameter difference of about 6 μm. A very precise measurement of the diameters of the wire and the die is an important feature of this technology.

III. ORGANIZATION OF THE CONTRACTS

A. Allocation of the Contracts

Each two-in-one dipole consists of 4 unit lengths (ULs) of Cable 01 and 4 ULs of Cable 02, while one twin aperture quadrupole consists of 2 ULs of Cable 03 (PS: each UL will later on be cut in 4 pieces by the magnet manufacturer). The LHC cable contracts have been distributed among the main strand and cable suppliers all over the world resulting in an economical competition localized in the regions of the main contributors to the LHC project (Europe, Japan, USA). Table II

shows the allocation of the various contracts signed in 1998 and slightly modified in 2000.

B. Raw Material

All the LHC cables are manufactured from NbTi and Nb supplied by Wah-Chang, USA.

The NbTi bars and Nb sheets for the European strand manufacturers are part of the USA contribution to LHC, and are supplied according to a Technical Specification (TS) approved by the partners (strand manufacturers, CERN and Wah-Chang). The contract awarded to Wah-Chang (USA) concerns the supply of 470 tons of NbTi (47.0 $\pm$ 1.0% weight Ti) and 26 tons of reactor grade Nb sheets. The relationship between the partners is described precisely in the terms of the contracts (certificate contents, data base, SPC follow-up, approval criteria…).

The other suppliers (Furakawa and IGC) have their own TS and provide CERN with a copy of the certificates of the raw material they use for the LHC production.

The suppliers must also give to CERN copies of the certificates for the copper used in each step of the production: mono-billet, multi-billet of stacking stage 1 and 2.

C. Organization of a Cabling Run

For LHC it is required that 4 ULs of each cable are produced in the same cabling run and receive the same HT. This guarantees that the 4 ULs are as similar as possible, resulting in the best possible coil symmetry in a magnet.

Cold welds within a UL are forbidden, but can be used in between ULs to make it possible to produce long cabling runs. Very good traceability is required of the distribution of the ULs 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—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).

D. Holding Points

Holding points have been incorporated in the organization of the cable contract to obtain a high degree of confidence in the fabrication.

- The first holding point for the strand manufacturer is **the billet approval** issued when the measurements performed on billet samples at the company and at CERN demonstrate that the billet is in conformity to the strand TS.
- The second holding point concerns the presentation of the cabling run and **the approval of the cable maps**. CERN checks that all the strands used for cabling come from previously approved billets. It is also at this moment that the duration of the final cable HT is communicated to the supplier. A coating thickness slightly different than the specification value, can namely lead to a non standard HT.
- During the cabling run representative cable samples have to be cut off and sent to CERN. CERN will measure the

TABLE II
CONTRACTS

Company	Country	Cable 01	Cable 02	Cable 03
Alstom	France	5 octants	3 octants	3 octants
Europa Metalli	Italy	-	2 octants	2 octants
Furakawa	Japan	-	1 octant	1 octant
IGC	USA	-	1 octant	1 octant
Outokumpu	Finland	-	1 octant	1 octant
Vacuumschmelze	Germany	3 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

cable critical current, the edge conditions, and all the other cable characteristics necessary to check its conformity. Upon positive results and after receiving the complete and correct data and the certificate of conformity CERN issues **the approval for shipment**.

- Upon the cable reception at CERN, a dimensional control of the entire cable and the final measurement of Rc are performed. The certificates and the data are checked and **the provisional acceptance** is given if all conforms to the cable TS.

IV. CERN MEASUREMENT EQUIPMENT

A specific measurement laboratory has been set-up at CERN to perform the huge number of measurements. Incoming samples are labeled, cut and then dispatched to the following measurement stations (in parentheses are indicated the capacity of the test station given as the number of strand/cable samples that can be measured weekly).

Measurements at Room Temperature:
- 1 installation for Cu/SC measurements (300 s/week),
- equipment to measure the strand bending, the filament twist pitch, the strand spring back and the strand diameter (300 s/week),
- 2 installations to measure the SnAg coating thickness (300 s/week) via the coulometric method,
- 2 installations to measure the SnAg coating thickness (70 s/week) via the Atomic Absorption methodology (AAS),
- Equipment to measure the contraction of the cable during coil curing (5 ULs/week),
- 3 lines for the dimensional measurements of the cable partially equipped with an optical inspection system to check for cold-welds and strand cross-overs (30 ULs/week),
- Equipment to control the cable edges (45 ULs/week),
- Equipment to perform the cable sharp bend test (45 ULs/week),
- Equipment to measure the cable mid-thickness on a stack of 10 cable pieces (30 ULs/week).

Measurements at 1.9/4.2 K:
- 1 test station to measure the strand magnetization at 4.2 K and 1.9 K (35 s/week) [7],
- 1 test station to measure the strand RRR at 4.2 K (230 s/week),
- 1 test station to measure Rc at 4.2 K (16 s/week),

TABLE III
MAIN STRAND CRITICAL CURRENTS AT 1.9 K

Supplier	$I_{C,aver}$ [A]	σ [A]	$(I_{C,max}-I_{C,min})/I_{C,aver}$ [%]	CV [%]	Jc,avg [A/mm2]	σ [A/mm2]
Cable 01 @ 10 T						
B	566	14.9	18.3	2.6	1695	43
E	572	11.6	10.7	2.0	1699	31
Cable 02 @ 9 T						
B	423	9.3	12.6	2.2	2347	42
C	419	9.3	12.3	2.2	2301	42
G	430	8.6	11.5	2.0	2372	33
K	411	5.8	7.1	1.4	2257	28
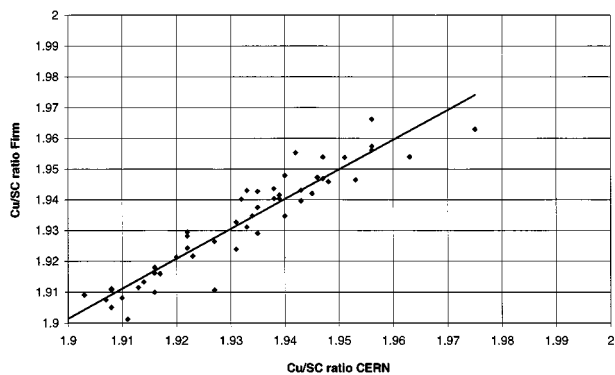
Fig. 2. Correlation between the Cu/SC ratio measurement between a company and CERN.
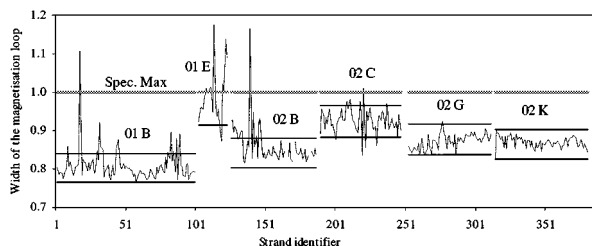
Fig. 3. Measured values of the width of the magnetization loop at 1.9 K, 0.5 T, normalized on the specified value of 30 mT for strand 01 and 23 mT for strand 02. The results are plotted in chronological order for each company. The indicated control limits are at ±4.5% of the center line.

- 4 test stations to measure the strand critical currents at 4.2 K and 1.9 K (sub-cooled) and at fields between 5 and 11 T (180 s/week) [8],
- 1 test station to measure the cable critical currents at 4.2 K and 1.9 K (sub-cooled) and at fields between 6 and 10.3 T, uniform over 1 m (4 s/week) [9], [10].

A large zone is installed for the reception and storage of cables for up to 400 magnets. Additionally, a large number of cable critical current measurements (up to 16 s/week) is performed at BNL as part of the U.S. contribution to the LHC.

V. RESULTS

Some measured results of the most important characteristics of the specifications, such as I_C, Cu/SC ratio, Magnetization, cable dimensions, cable I_C are presented in the next sections.

A. Strand Critical Current at 1.9 K

Table III shows the results of the strand critical current measurements performed at CERN at 1.9 K. All the critical currents measured on the strands are above the minimum specified limit. For all the companies the Process Capability Ratio Cpk [11] is above 1.35, indicating that the limits in the process are well above the lower specification limit.

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. A small CV indicates a small variability in all the processes that influence the critical current. It is expected that the variation in the strand I_C will decrease further, but unfortunately this criterion of ±4% around the average is not yet fulfilled for all companies. It is interesting to mention that the field shift at the same current between 4.2 K and 1.9 K varies from 2.9 T to 3.05 T depending on the supplier.

B. Copper to Superconductor (Cu/SC) Ratio

The Cu/SC ratio is measured by the chemical etching method for the absolute value measurement. The control of the homogeneity of the Cu/SC ratio all over the length of the billet is performed by an on-line electrical method at the companies premsies.

Fig. 2 shows a typical correlation between the measured Cu/SC ratio at CERN and in a company, both obtained by chemical etching. The values do not differ by more than 0.01 when the test procedures are fully respected. In specific cross-checks, the difference is lower than 0.005.

C. Magnetization

Fig. 3 shows the measured values of the width of the magnetization loop at 1.9 K, 0.5 T, normalized on the specified value of 30 mT for strand 01 and 23 mT for strand 02.

The figure shows that the values are slightly below the specification limit except for a few billets which have shown extremely high values and have been rejected. It has been demonstrated that the origin of these high values is mainly related to an exceptional large deformation of the filaments, and not to an increase in J_C at low field.

Fig. 4(a)–(d) show these deformed filaments and the related value of the magnetization. The deformation of the filaments has its origin during extrusion and can occur in single stack [Fig. 4(a)–(c)] as well as in double stack assembly [Fig. 4(d)].

All the strand manufacturers have taken action to provide better follow-up at the billet assembly and at the extrusion (temperature, time, speed, and pressure) to avoid the rejection of billets for magnetization reasons.

D. Cable Dimensions

All the reported dimensional measurements in this section have been performed at CERN on heat treated ULs using the CMM (Cable Measurement Machine), in combination with the absolute value obtained from the 10-stack method.

Fig. 5 shows the measurement of the mid-thickness of cables 02 supplied by all the vendors, and indicates the upper and lower Specification Limits. The result yields an average of 1.480 mm
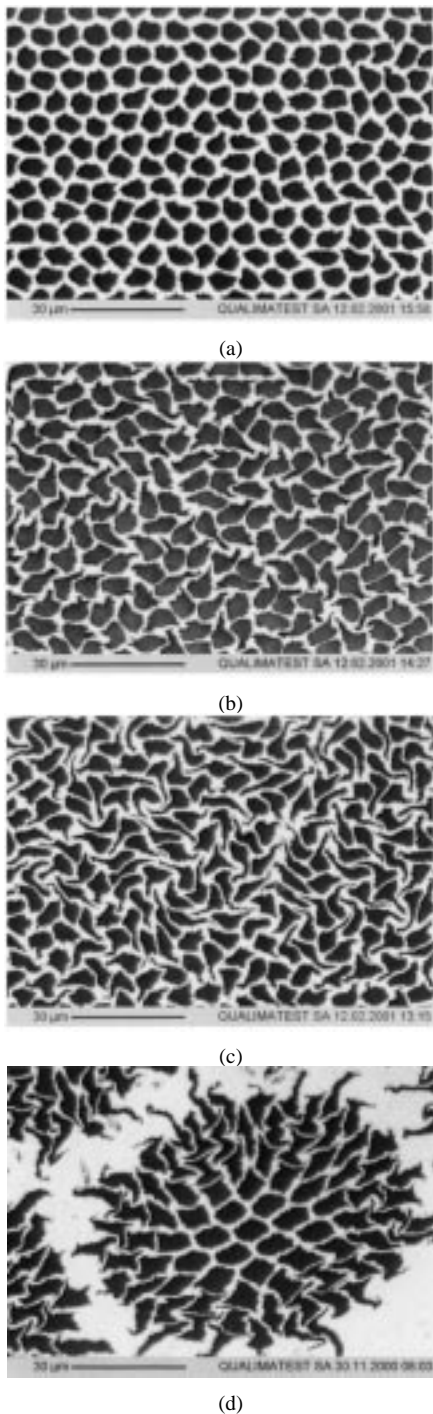
(a)

(b)

(c)

(d)

Fig. 4. Cross-section of a single stack 02 strand for (a) non deformed, (b) deformed, (c) heavily deformed filaments. Fig. 4(d) shows the cross-section of a double-stack 01 strand with heavily deformed filaments. The corresponding magnetization values are 19, 22, 26.8, and 35 mT.

with a standard deviation of 2 μm, and is therefore in very good agreement with the specified value of 1.480 ± 0.006 mm.

Fig. 6 is a distribution diagram of the mid-thickness of all the cables 01 supplied to CERN. Also for cables 01 the thickness is well within the specification limits.

During the cable measurements, it has been demonstrated by an intensive program of tests that the cables keep their transverse dimensions to within 1 μm even when the heat treated cable is respooled several times.
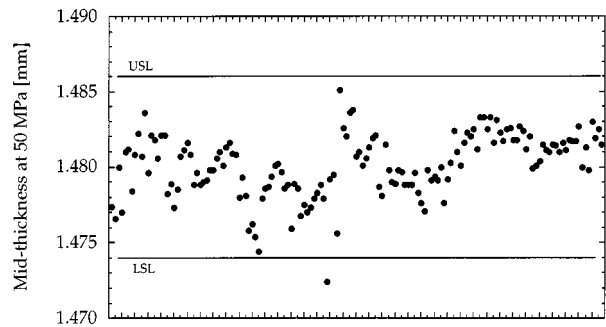
Fig. 5. Mid thickness at 50 MPa of the cables 02 measured at CERN for all the unit lengths produced by the various companies.
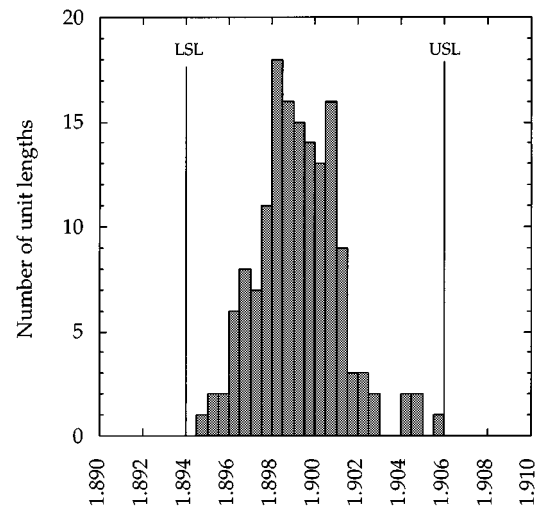
Fig. 6. Distribution of the mid thickness at 50 MPa for all the unit lengths of cable 01 produced by the various companies (average = 1.900 mm, $\sigma = 0.002$ mm).
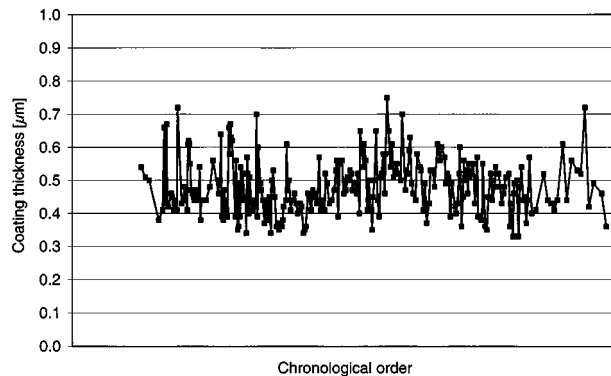

Fig. 7. Strand coating thickness for strands type 02 from one company.

The delivered cables do not present any sharp edges outside the 0.1 mm specified value due to a good cabling mandrel design which is well positioned in the Turk's head rollers. The typical cabling speed is 0.1 m/s.

E. Cable Critical Current at 4.2 K

The critical current of all the measured cables (see Table IV) are above the specified values by about 10%. The highest CV for the cable is 2% indicating that variations in the strand I_C, cable

TABLE IV
CABLE CRITICAL CURRENTS AT 4.222 K

Supplier	Average Ic [A]	σ [A]	Cv [%]	Degradation [%]
Cable 01 @ 7 T				
B	14804	289	2.0	-2.7
E	15504	139	0.9	-1.9
Cable 02 @ 6 T				
B	14841	243	1.6	-2.6
C	14623	135	0.9	-1.6
G	15298	159	1.0	-2.0
K	14894	182	1.2	-2.7
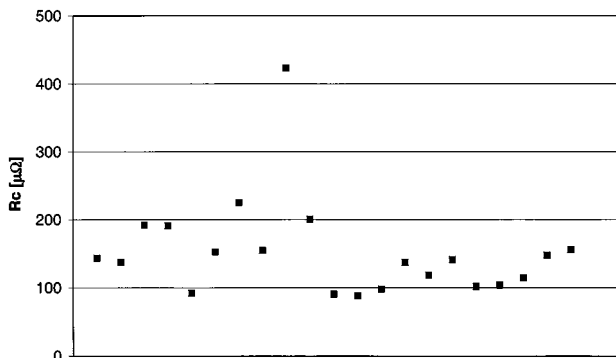
Fig. 8. Rc value on heat treated cables type 02 of one company.
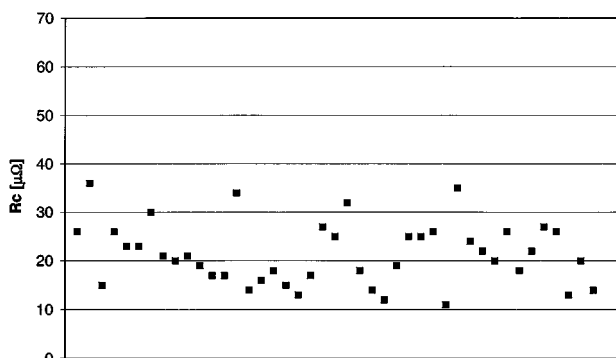
Fig. 9. Rc value along the length of a given UL of cable type 01.

transposition pitch, and cabling degradation do not contribute more than 2% to the I_C variation of the final cable.

F. Cross-Contact Resistance

Coating thickness is measured using the coulometric method both by the company and at CERN, and by the AAS method at CERN. Fig. 7 shows as an example the Atomic Absorption results on strands type 02 from one company since the start of the contract. The thickness is well controlled with a standard deviation of about 0.08 μm.

Fig. 8 shows the Rc value as measured on finished (heat treated) cables from one company. It shows that Rc is rather constant but still larger than the required value of 20–40 $\mu\Omega$. This problem will be solved by a small increase in the coating thickness or a decrease in the heat treatment duration.

Fig. 9 shows the variation of Rc along the length of one UL. The uniformity is very satisfactory, and confirms the tempera-
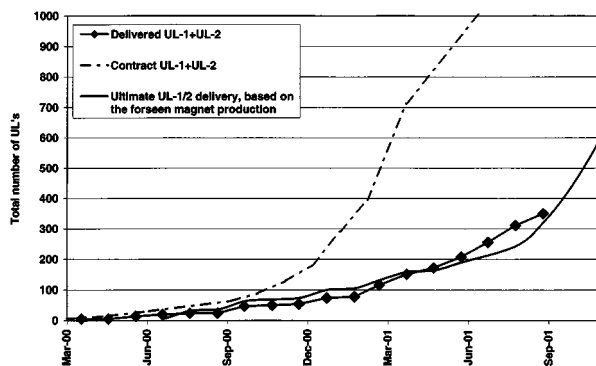

Fig. 10. Actual cable delivery as compared to the contractual delivery and the requested delivery for a foreseen magnet production rate of 5 magnets/week in April 2002 and 8 magnets/week in May 2003.

ture homogeneity inside the entire spool during the heat treatment .

VI. DELIVERY

The delivery of the raw material follows the expected delivery. At present (Sept. 2001) 199.6 tons of NbTi and 12.2 tons of Nb sheets have already been delivered and accepted by the European strand manufacturers. This corresponds to about 42% of the contract. The 47% weight Ti is controlled within ±1.0% at the center and at the periphery of the bars.

The produced cables are delivered with a delay of around one year compared with the contractual terms (see Fig. 10). The reasons of the delays are mainly the setting-up of new high production-rate lines with new machines to be commissioned and larger than expected number of wire breakages. The situation is now improving, mainly by removing in the plants the source of strand breakages (principally due to inclusions).

The production rate is expected to increase in all the companies in the period between September 2001 and March 2002 sufficiently to follow the planning. In Fig. 10 are presented the actual cable deliveries, the contractual deliveries, and the requested deliveries based on a foreseen magnet production rate of 5 magnets per week starting in April 2002 and increasing to 8 magnets per week in May 2003. For the time being, the cable production does not jeopardize the LHC project but it is vital to increase the delivery rate in the near future.

VII. CONCLUSION

The contracts for the LHC superconducting cables, representing during 5 years more than 28% of the annual production of superconductor in cost terms, have been signed in 1998. Seven companies, in Europe, the USA and Japan, are involved in this work.

All the NbTi and Nb is supplied by Wah-Chang; it is within the specification and is being delivered in due time.

All the strand manufacturers are able to fulfill the very demanding LHC specifications. Unfortunately a larger magnetization than specified, due to a large filament deformation originating during the extrusion process, has caused the rejection of a small number of billets. Corrective action has been taken. The inter-strand contact resistance is controlled by a strict con-

trol of the strand coating thickness associated with an adequate cable heat treatment on the spools. The obtained values are still a factor 2–3 larger than necessary for field quality reasons. The uniformity along a unit length of cable is very good.

The cable I_C is about 10% larger than the specified value, and the cable dimensions are well within the specified limits.

Quality control is performed both at the company's premises and at CERN. The correlation between the CERN and the company's measurements is very good, allowing a precise follow-up of the production.

The delays in cable deliveries are worrying but fortunately do not cause at present any delay on the LHC project. These delays have been caused by commissioning of new equipment and wire breakages. The number of wire breakages is decreasing and it is expected that the production rate will significantly increase in the near future.

The CERN test equipment for reception and acceptance of the LHC strands and cables can face the future high peak of production rate necessary to compensate for the delays in delivery of the initial phase of the LHC cable production.

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