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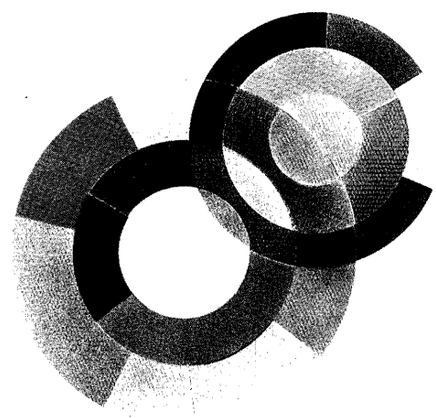

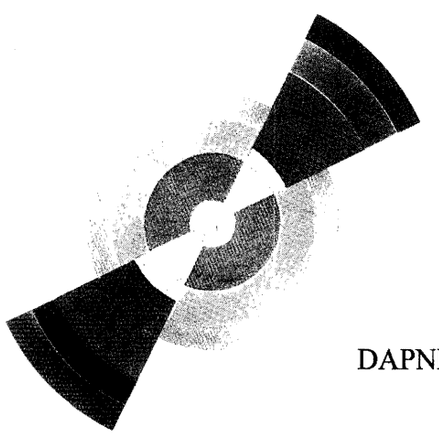

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PROGRESS ON THE CONDUCTOR FOR THE SUPERCONDUCTING TOROIDS OF THE ATLAS EXPERIMENT

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Progress on the Conductor for the Superconducting Toroids of the ATLAS Experiment

L. Rossi[(1)], G. Volpini [(1)],C. Berriaud[(2)], I.L. Horvath[(3)] , J. Neuenschwander[(4)]

Abstract--**The production of the conductor for the superconducting toroids of the Atlas experiment at LHC (CERN) is under way. The conductor is obtained by coextruding a big Rutherford cable with very pure aluminum. All toroids, one Barrel Toroid (BT) and two End Cap Toroids (ECT), request a conductor with a critical current of about 60 kA at 5 T, 4.2 K and a RRR in excess of 800 (at zero field), together with a very good bonding between cable and aluminum: 20 MPa for the BT and 15 MPa for the ECT. So far four long lengths, approximately 7 km out of the 90 km of the total need, have been successfully produced, thus demonstrating the feasibility of the process. The paper describes the results of the R&D phases and the results obtained in this first production. The critical current degradation due to cabling and coextrusion was found quite moderate (7-8% in total), despite the low copper content of the strands (Cu:NbTi = 1.09-1.18). The bonding was also very good with values well in excess of the specification. A special control system based on continuous ultrasonic inspection was used in the coextrusion line to monitor the bonding quality in real time during production.**

I. Introduction

ATLAS is one of the two general purpose detectors that will be installed on the LHC at CERN [1]. One of its main components is the very large size magnetic system [2], whose total cost has been evaluated to be about 75 M. It is composed of a thin solenoid [3], of a central Barrel Toroid [4], BT, and of two identical End Cap Toroids, ECT [5].

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All toroids have a peak field on conductor of about 4 T and are composed of 8 coils per toroid. All coils are vacuum impregnated with epoxy resin and are indirectly cooled. The choice to use an aluminum stabilized conductor obtained by coextrusion has been dictated by economic reasons and by the necessity that the thermal contraction of the coil has to match the thermal contraction of the coil casing, a rigid box made of aluminum alloy, glued to the coil with epoxy resin [4,5]. Also the vast experience in the detector magnet community accumulated in many successful projects, all based on Al coextruded conductor and indirect cooling, has strongly influenced this decision [6]

The very large size of the magnets, their enormous stored energy, more than 1500 MJ for the whole system, and the necessity of stability margin led to a design of a conductor which is at least five times bigger in cross section than the ones used in previous large projects [7]. For this reason many European Institutes are jointly working on the project since the R&D phase (1995-98) and are now following the starting of the real production to guarantee a strict quality control of such a difficult conductor. Short lengths (200 m) of the conductor have successfuly tested in a small (2m × 0.7m) race track coil. The first complete test of long lengths (2 × 1.6 km) will be in spring 2000, when the BT model coil, named B_0 coil (9 m × 5 m in size), already wound and impregnated, will be tested at CERN.

II. Main Characteristics of the Conductor

The characteristics of the conductor have been determined by many requirements:

1) Stability: the conductor operates at 20.5 kA at a max. temperature of 4.8 K in a peak field of about 4 T. In order to have an enthalpy margin of about 2 kJ/m^3 we need a temperature margin of about 2 K before the start of the current sharing regime. The required critical current, normalized to the standard condition of 5 T - 4.2 K, is then fixed to 58 kA for BT and 60 kA for ECT.

2) Protection: to limit heat generation following a quench and to be able to absorb all the stored energy in the

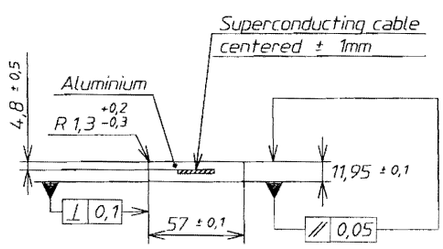
conductor without danger, it is required large cross section (600 mm^2 for BT and 430 mm^2 for ECT) of stabilizing material with very high conductivity. Actually this helps also stabilization, of course: a previous 3-D study with transient effects has shown that after I_c the stabilizer cross section and RRR are the most effective parameters for stability [8].

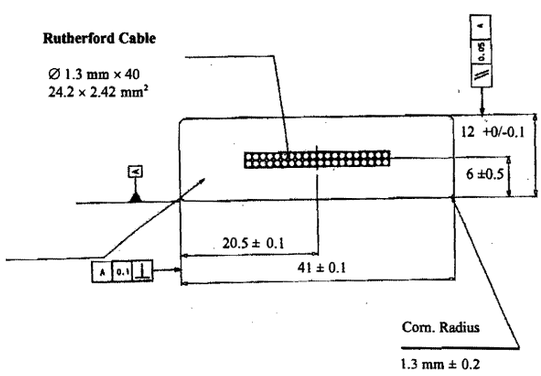
3) Avoid movements: the superconductor inside the stabilizer must not move under any circumstance. For this it is required that the bonding between superconducting cable and stabilizer must withstand shear strengths of 15-20 MPa.

4) Dimensional tolerances: a reasonable winding accuracy must be assured. Tolerances of 0.1 mm are needed to avoid problems in fitting the coils in their casings with bladders technique [9] as well as to avoid resin rich zones.

The conductor is manufactured by two suppliers: Europa Metalli (Italy) with coextrusion at Alcatel Cable Suisse for half conductor and Vacuumschmelze (Germany) with coextrusion in Seneffe (Belgium) for the other half.

In Fig. 1 a sketch of the two conductors with indication of size and tolerance is reported whereas the main characteristics of the conductor are reported in Table I.





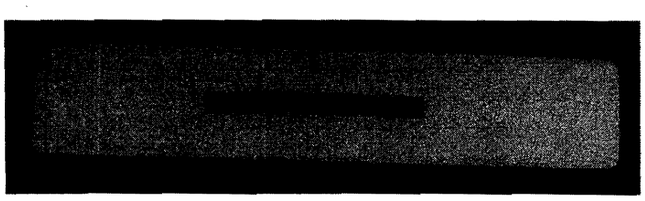


Fig. 1. Sketch of BT conductor (up) and of ECT conductor (down) with tolerances indicated. The picture is a cross section of a BT (courtesy of Vacuumschmelze).

TABLE I
MAIN PARAMETERS OF THE BT AND ECT CONDUCTOR

		BT	ECT
GEOMETRY			
Dimension (bare)	mm^2	57 × 12	41 × 12
Unit length BT	m	1730	820
ELECTRICAL CHARACTERISTICS			
Operating current	A	20500	20500
Critical current @ 4.2K, 5T	A	58000	60000
Operating peak field	T	3.85	4.13
Operating temperature	K	4.8	4.7
Working point on load line (I_{op}/I_{max})		0.63	0.62
ALUMINUM STABILIZER			
Pure aluminum cross section	mm^2	628	430
RRR @ zero field, zero strain		800	600
Bonding cable-Al	MPa	20	15
STRAND AND CABLE †			
Ø NbTi filaments	μm	50	50
Ø strand	mm	1.25	1.3
Cu/sc ratio*		1.2	1.2
Cu RRR		90	90
Twist pitch	mm	50	50
No. of strand in cable		40 (38)	40
Cable size (indicative)	mm^2	27.9×2.25	24.2×2.42
Cable transposition pitch	mm	178(233)	178(233)

† These parameters are actually different for the two companies. In parenthesis are indicated alternative values.
* In order to keep traceability of the strands during coextrusion, few strands have a lay-out with Cu/NbTi ≅ 1.08

III. WIRE AND CABLE

A. Wire

The wire, is designed based on a current densities of 2800 A/mm^2 at 5 T, with the minimum copper content considered compatible with the cabling, see Table I, in order to be less expensive. A cross section of the wire is given in Fig. 2.

The wire is composed of standard high homogeneity NbTi filaments protected by a Nb barrier (4% in weight of the NbTi ingot) to assure optimum quality during drawing and is 100% eddy current cross checked at different stages. The uniformity of the superconducting content all along the wire is monitored by an on line continuous alpha measurement apparatus [10].

The cold work and heat treatment process have been adapted to the necessity of withstanding coextrusion temperature in excess of 400 °C for few minutes. A preliminary investigation was done by measuring the critical current degradation vs. different time/temperature conditions of a virgin wire. The results, plotted in Fig. 2, indicates that a stop of 5 minutes at 400 °C results in a 10% I_c degradation, a figure a little bit more optimistic than the 20% reported in [11]. However it should be noted that the same stop at 430 °C doubles the degradation.

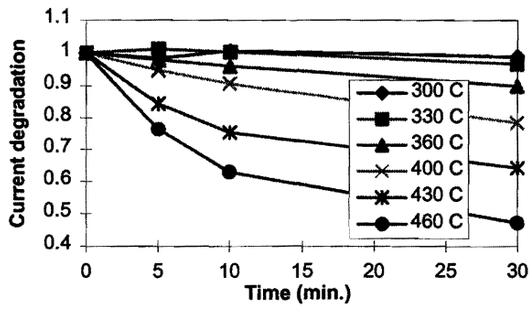


Fig. 2. Ic degradation vs. time at temperature to simulate an accidental stop of the press during the coextrusion process.

B. Cable

This big Rutherford cable is not trivial to manufacture because of the low copper content and the number of strands. For the coextrusion process the cable must be stable enough to avoid strands to bulge out if in the press the tension on cable changes, otherwise there is the risk of breakage of the cable in the mandrel-die passage inside the coextrusion press. For the same reason any cross-over of strands must be absolutely avoided. Even if from the point of view of the electrical stability cross-overs are not dangerous on such a conductor (that works in the magnet at less than 40% of its critical current, with plenty of stabilizer), the cable is prone to break when a cross-over enters into the coextrusion chamber. For the same reason cold junctions in the strands must be avoided.
To check for cross-overs all long the 2 km cable, apart from accurate visual inspection, one manufacturer set up a system based on eddy current [10]. Cable size is continuously measured during fabrication (within few microns).
Ic degradation due to cabling has been extensively studied by measurement of strands extracted from cable. After few tests it was found a set of cabling parameters that, despite the low copper content, gives very low degradation.

IV. COEXTRUSION

Coextrusion of the superconducting with the pure aluminum has four important goals:
1) to produce a conductor with the requested tolerances possibly without further rolling or skin-passing;
2) to create the requested bonding between superconducting element and matrix;
3) to avoid a severe reduction of the critical current (our goal was to limit I_c degradation to less than 10% from virgin wire. Given 2-4% of degradation for cabling, this allow only 6-8% degradation for coextrusion. Since temperature can vary between 390 and 420 °C for a time of 30-100 s, according to the process and the speed used, one can see from Fig.2 that this goal is at the limit of the present technology.
4) to preserve, as much as possible, the very good RRR of the aluminum, see table I. We are using Al 99.998%, that has a RRR of more than 2500 in the billet.

Coextrusion of the cable from Europa Metalli is carried out in Alcatel (CH) where a 3500 tons continuous press is available, while Vacuumschmelze carries on the coextrusion of its cables at Seneffe (B) in very well computer equipped 4000 tons press. The latter is not continuous but the stop to fed the aluminum billets is very short, typically 30 s, such as there is no danger for I_c. A further main difference between the two presses is that in Alcatel the cable is fed from the back and it remains always straight while the aluminum billets are inserted from the top; in Seneffe the cable is fed from aside, turning 90° inside the press, while the aluminum billets are pressed from the back.
In the continuous press the cable has an easy handling, and the bonding between aluminum and cable is not difficult to achieve, but the flow of the aluminum in the coextrusion chamber is more complicated making not trivial reaching the geometrical tolerances.
In both systems all the parameters are continuously monitored, including coextrusion velocity and size of the conductor. Typically the speed is 1.1-1.2 m/min. in the continuous press and 2.5-3.0 m/min. in the other press.

A. Coextrusion results

After few tests we obtained in february 1998 a preliminary conductor length of 130 m with good results: only the I_c degradation was still too high 13% [12]. At the end of 1998 good short samples were produced. In February 1999 we had the first long BT unit (1800 m), necessary to start the winding of the B0 model coil, [13]. Afterwards prototype lengths of the ECT conductors have been successfully produced with the following results:

1) the shape is good and uniform all along the length of the conductor. In the continuous press some parameters must be manually tuned during production;
2) the bonding is very good: typical values are between 35 and 45 MPa, a factor two beyond specifications
3) the current degradation is very low: is less than 10% from virgin wire (including 2-3% due to cabling). In Fig. 3 is reported the statistics for one of the two producer, of the current in wires in the virgin state, after cabling and after coextrusion, that shows the the final I_c is comfortably higher than the specifications.

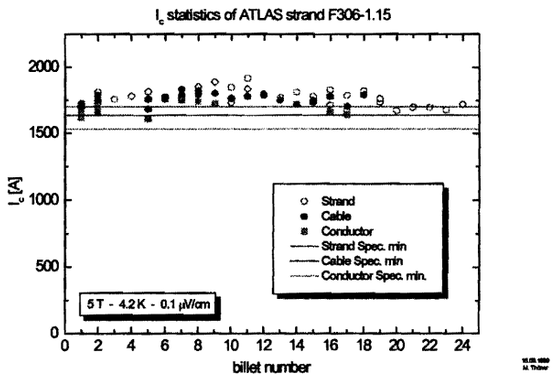


Fig. 3. Statistic of the critical current on superconducting wires at various stages of conductor manufacture (Vacuumschmelze conductor).

4) The aluminum RRR on finished conductor is well above 1000 for the continuous press and over 1500 for the stop-and-go press, the difference being due to the different cleaning condiction.
5) The contact resistance between cable and aluminum matrix has been measured on few samples with results better than 10^{-11} Ω·m (at zero field).

The results for the conductors produced in the continuous press are summarized in Fig.4, where the total current of the cable inferred by measurements on strands is reported.

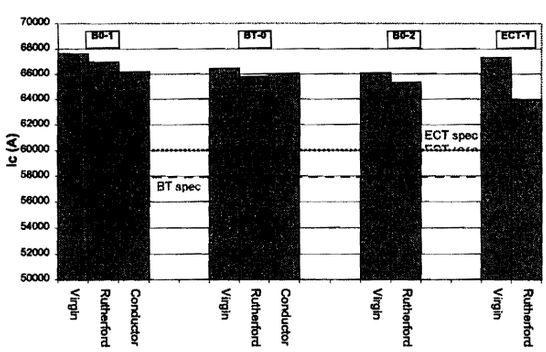


Fig. 4. Total current of few conductors and cables based on I_c strand measurements (Europa Metalli conductor).

B. Quality control

A sophisticated system to monitor the quality of the conductor on line during the coextrusion process has been developed and is now in running very well.
It includes a unit that monitors and records all the press and cable pre-heating parameters as well as laser micrometers, for the contactless measurements of the conductor profile during production.
The main innovation is a Phase Array System for the continuous bond evaluation by ultrasonic (US) measuring technique. Alarms levels for the bond as well as for the dimensional tolerance are specified in advance and alarm numbers are written by means of an Ink Jet printer onto the upper surface of the produced conductor. This has proved to be very useful especially at the Senedffe press, where conditions for good bonding are a little bit more difficult to achieve. New interesting effects, detected by US images, concerning proabable concentrations of impurities in the matrix at the billet change are under investigations.

V. Conclusions

The R&D for the conductor of B0/BT/ECTcoils has come to an end and the production is in progress. The main accent now is in the control systems and in the strict quality assurance plan: this is a key point for having a good success in producing unit length that are worth 150 k each one. So far 5 units of B0/BT conductor and 6 units of ECT conductor have been successfully produced.

VI. Acknowledgements

The authors thanks the laboratory teams involved in this work and Europa Metalli SpA, Alcatel Cable Suisse and Vacuumschmelze Gmbh for the effort done and for providing the data.

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