23. CONDUCTOR CHARACTERISATION AND PRE-INDUSTRIALISATION

23.1 INTRODUCTION

The interest of the international collaboration for the CMS detector is not only focused to the development of the detector system and subsystems (calorimeter, muon detector, tracking,...) but also to the huge superconducting solenoid, which constitutes the core of the detector itself.

The CMS solenoid project can be considered as going beyond the actual limits of available detector magnet technology. As an example one of the most advanced magnets of this kind is the solenoid constructed more than 10 years ago for the ALEPH experiment at LEP [11-2]. Compared to ALEPH, the CMS solenoid has a field 2.5 times higher, 20% larger bore, 80% longer length and 20 times the stored energy.

To meet this challenging goal and carry out a safe and reliable design, a better knowledge of material properties, cable technology and winding techniques are needed, together with more information on developments of superconducting wires, cable technology and winding techniques. This know-how should be developed at industrial level.

Therefore, intensive R&D programmes were set up in 1993 by the participating institutes, CERN, CEA Saclay, INFN Genova and ETH Zürich.

23.2 MANUFACTURING SAMPLES

As explained in Chapt. 12, in order to build the reinforced conductor from an extruded insert two alternative solutions are considered: the first one using the electron beam welding technique and the second, as a back-up, the soft soldering technique.

Manufacturing lengths of 200 to 300 meters by either method requires the use of an industrial production chain. This chain consists of three play-off drums for the extruded insert and the two reinforcing profiles. Before assembly, each profile has to be straightened, unwarpped, and cleaned, then after soldering or EB welding the final conductor must be machined. In both cases large equipment is needed both to pull the conductor and take up the finished lengths. This is shown in Fig. 23.1.

A sample length, 250 m long, with an insert of 70 mm x 10 mm and a 32 strand Rutherford type cable has recently been produced. This enables tooling and production techniques for the pre-industrialisation phase to be developed.

The goal of these activities should be the continuous industrial production of a 200 m long prototype conductor before the end of 1998.

For the prototype lengths a 36 strand Rutherford type cable will be used. Then the high purity aluminium will be extruded around the flat cable by a continuous extrusion process. Two industrial processes are envisaged for this activity: the so-called Conform method, or an aluminium press which is used for the sheathing of electrical power cables and fibre optical cables. Both allow for a continuous process over the full length of the cable. In the Conform process the aluminium is fed into the machine in wire form, while in the Press process ingots of aluminium are used. In both cases the aluminium is fed in from the top of the machine and the Rutherford cable inserted horizontally along a straight line [23-6].

To define the extrusion tools, on-line tests are necessary. These tests will be carried out using superconducting cable, because the mechanical behaviour of superconducting flat cable is essentially different from flat cable made of hard copper wires. For these trials we will use low purity aluminium (Al-99.7%) for cost reasons. The final extrusion tests will be done with high purity aluminium Al-99.998% and with the Rutherford type cable.

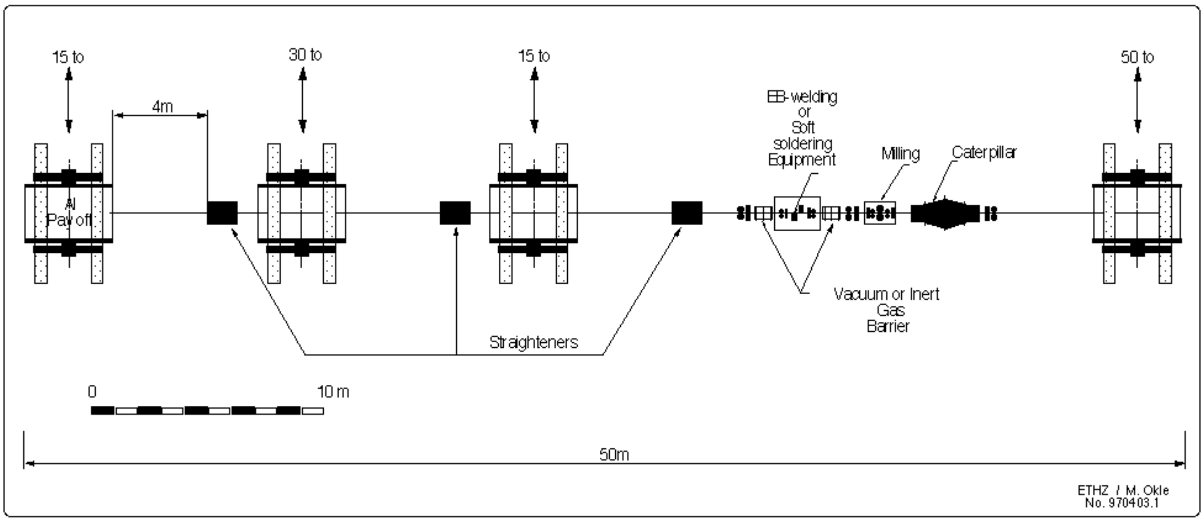

Fig. 23.1: Process line for the final CMS conductor manufacturing.

23.3 TESTS AND MEASUREMENTS TO ENSURE CONDUCTOR QUALITY

These tests are to enable us to understand and qualify all of the conductor production steps in order to optimise the manufacturing process. Some of these tests will be used later, during the manufacturing process to check that the production conforms to the specification.

23.3.1 SC strands

Controls and tests will be in accordance with the Quality Assurance Plan of the companies and they will include chemical analysis of source materials, eddy current measurements on the whole length of the finished wire, continuous checks of the strand diameter, spot checks of Cu/SC ratio, and measurement of the RRR of the copper matrix, and of the critical current.

23.3.2 Rutherford type cable

Manufacturing a cable with 36 strands of 1.28 mm diameter and a length of up to 12 km is a challenging task. Three main problems are seen:

a) the critical current degradation at the cable edges,
b) the conductor dimensional stability,
c) the wearing of the cabling tools.

It is important that during the pre-industrialisation phase a specific R&D programme is planned in order to understand how to optimise the manufacturing process. For example, the compacting of the cable must be made as tight as possible in order to reduce voids inside the cable, but on the other hand it must not induce a critical current degradation exceeding 5%.

To control the cable quality, checks on broken filaments will be carried out on short samples taken from the beginning and the end of the cable. Critical current measurements on single strands extracted from the beginning and the end of the cable will ascertain that the degradation is within the tolerances. During the manufacturing process on-line dimensional measurements will be performed.

23.3.3 Mechanical bonding at the SC cable/Al interface

After extrusion, 250 mm long short samples destined for tensile tests will be cut from the extruded conductor to measure the bond quality. To prepare the samples, the aluminium is first removed from the flat cable for a length of 25 mm and then the conductor is cut using the wire erosion technique. One elongation sensor is attached to the superconducting cable and the second one to the aluminium surface. The distance of the two heads is 20 mm, i.e. an elongation of 0.2 mm under load is equivalent to a 1% strain. The tooling for bond measurements is shown in Fig. 23.2. According to the results of the mechanical analysis, and applying a safety factor of 1.5, the measured bonding strength must always be higher than 30 MPa.

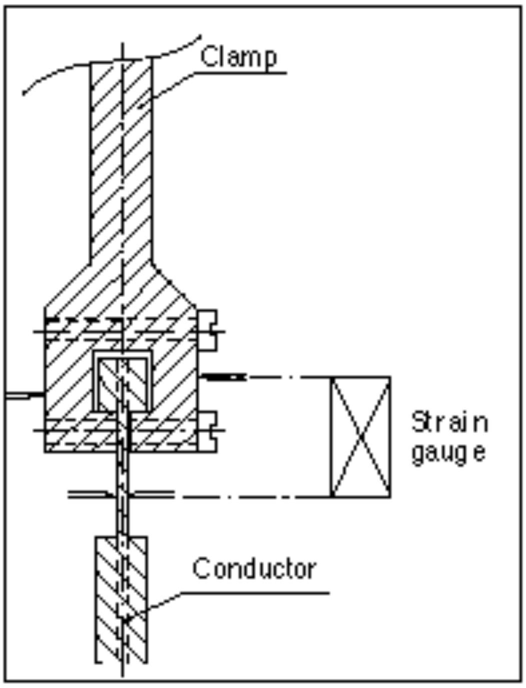

Fig. 23.2: Tooling for mechanical bond measurements.

23.3.4 Bending tests

Bending tests will simulate the winding process used to manufacture the coil or the technique used after the extrusion process to collect the conductor on the take-up spool. Therefore, short samples, taken from the beginning and from the end of each conductor production length, will be bent under a press to the proper radii. After straightening, the samples will be tested both by ultrasonic testing and by the mechanical bond test as described above in paragraph 23.3.3.

23.3.5 Macro and micro photography, electrons micro probe analysis

Samples taken out of the extruded cable will be cut and polished for electron micro probe testing. If a diffusion area of 1 to 3 μm thickness can be observed, like the one seen on Fig. 23.3, then the bonding between the aluminium and the copper matrix is of sufficiently high quality.

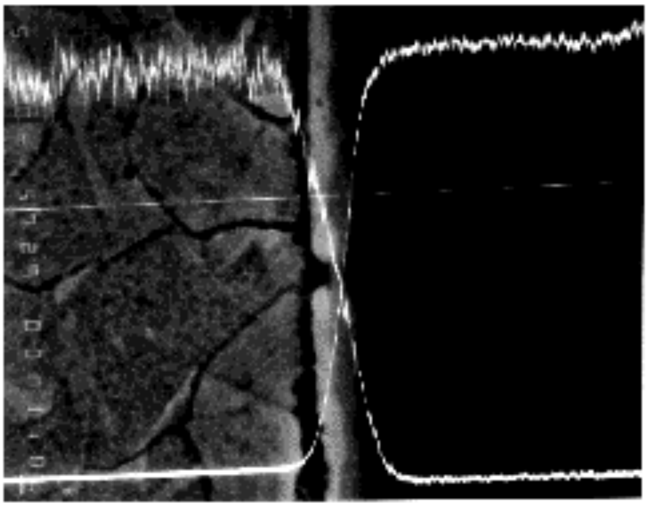

Fig. 23.3: Microphotograph of the conductor cross section. Between the etched copper matrix of the superconductor strands and the aluminium surface of the stabiliser, a diffusion layer of 3 μm thickness can be seen.

23.3.6 Ultrasonic testing

Short samples will be taken from the beginning and end of each production length and prepared for ultrasonic testing. For these tests the pulse-echo ultrasonic method is used. In this method the sensor constitutes the ultrasonic transmitter and receiver. During a short time interval the sensor head transmits US pulses, then during the next interval it receives the echo together with any reflected error echoes.

For the on-line bond measurement a new method, the Phase Array US testing, is proposed. However, before using this method, further R&D work is needed, as described in paragraph 23.4.2.

23.3.7 Measurement of the residual resistivity ratio (RRR)

The residual resistivity ratio (RRR) allows an easy check of the purity of a metal. In general, the RRR is influenced by all the effects that pertain to the electrical resistivity (impurities, defects, mechanical deformations, magnetic fields, etc.). The RRR is defined as the ratio between the room temperature electrical resistivity (or resistance) divided by the 4.2 K electrical resistivity (or resistance). Obviously in superconductors the latter temperature must be increased above the critical temperature.

$$\mathrm{RRR} = \frac{\rho(300\mathrm{K})}{\rho(4.2\mathrm{K})} = \frac{R(300\mathrm{K})}{R(4.2\mathrm{K})}.$$

It is interesting to note that in the case of aluminium and its diluted alloys the temperature coefficient of the resistivity $\frac{d\rho}{dT}$ is constant between 77 K and room temperature [23-1]. This allows an easy correction of the reference temperature which may be also at 273 K instead of 300 K.

Particular precautions are required for RRR measurements of pure aluminium. As an example any heat treatment (soldering) may remove defects and the RRR is changed [23-3]. Mainly for this reason the current contacts are made by screwing the copper blocks to both ends of the sample. Typical dimensions of an Al sample are 4x4x40 mm or 3x3x40 mm.

Voltage taps are fixed with the help of silver paint. Since strain can considerably influence the RRR and its field dependence [23-2], care was taken to ensure a strain free mounting. Only one current contact is fixed to the sample holder while the other one can move freely. The aluminium sample is mounted to ensure that there is no bending strain due to Lorentz forces.

The next step is to measure the electrical resistance at room temperature and zero applied field by ramping the current up to 20 A. The sample is then cooled to 4.2 K and the same measurements carried out with a perpendicularly applied magnetic field between zero and 6 T. After warming up to room temperature the sample resistance is rechecked and compared to the value before cooling.

Typical measurement errors of this method are below ± 2%. In Fig. 23.4 and Fig. 23.5 RRR measurements of selected 4N8 aluminium samples are shown. The RRR vs. field of the Al stabiliser from two different ATLAS conductors (GEC-ALSTHOM and Europa Metalli) are compared.

23.3.8 Ic measurements on single strands after extrusion

After extrusion, short 2.5 m long samples will be prepared, for critical current measurements. The aluminium around the Rutherford type cable will be removed by etching and single wires extracted out of the flat cable.

The samples will be arranged in one of the allowed configurations for critical current measurement, the critical current being defined according to the resistive criterion (10^{-14} Wm for the NbTi component).

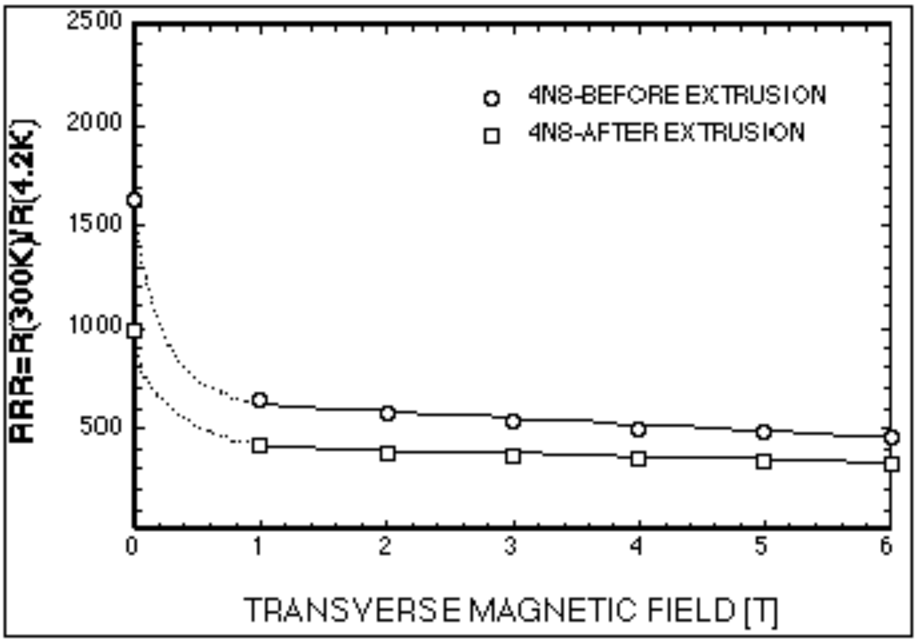

Fig. 23.4: The residual resistivity ratio of 4N8 (99.998%) aluminium vs. transverse applied magnetic field before and after extrusion.

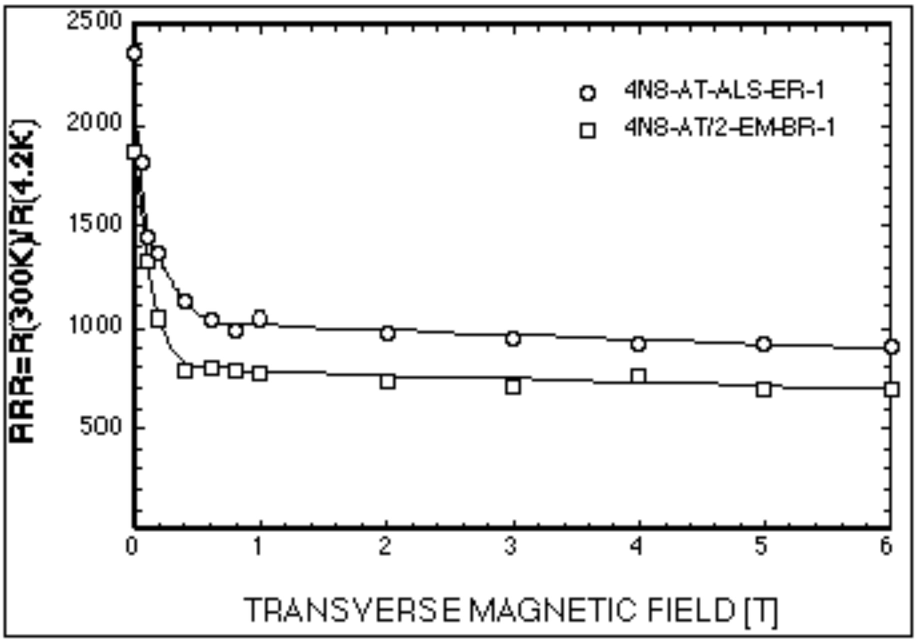

Fig. 23.5: The residual resistivity ratio of 4N8 (99.998%) aluminium stabiliser vs. transverse applied magnetic field from the ATLAS conductor delivered by GEC-ALSTHOM (ALS-ER-1) and Europa Metalli (EM-BR-1).

23.3.9 Ic and MQE measurements on the full conductor

The critical current and the MQE of the conductor will be measured at INFN-Genova using the MA.RI.S.A. test facility. The critical current measurements will be performed either on the Rutherford cables extracted from the stabilised conductors by alkaline etching, or directly on the stabilised conductor (without reinforcement).

The measurement set-up is schematised in the Fig. 23.6. It is composed of a superconducting solenoid and cryostat with a double wall insert to separate the magnet helium bath and the experimental zone. The measurements are performed on samples arranged in single turns. The Rutherford type cables are soft soldered to copper rings while the aluminium stabilised conductors are placed into an aluminium alloy cylinder and clamped by conical rings. Due to the solenoidal configuration the stabilised conductors can only be measured with the field applied parallel to its wide face.

The main features of the MA.RI.S.A. facility are the following:

- Maximum background field (at the sample)	6.5 T
- Free bore	420 mm
- Maximum transport current	
Power supply	10 kA
Transformer method	70 kA
- Length of sample	1.3 m
- Sample temperature range	2 to 300K

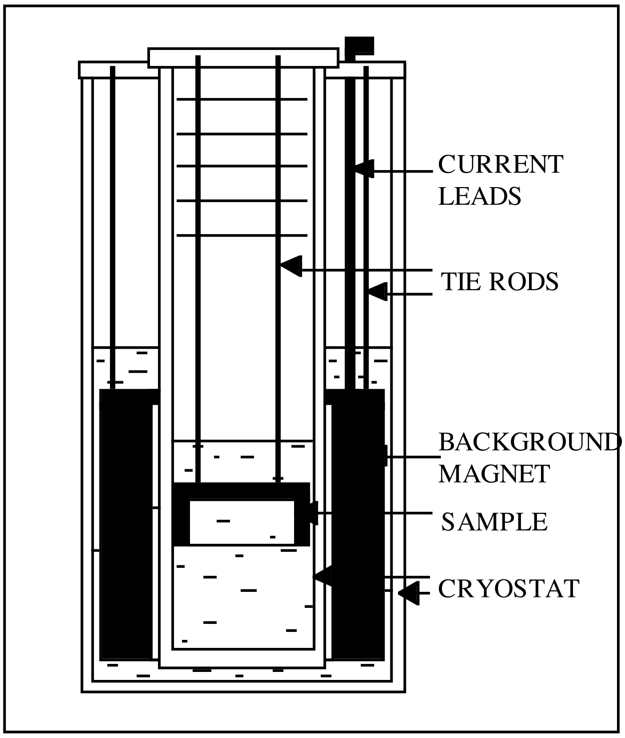

Fig. 23.6: Schematic view of the MA.RI.S.A. test facility.

Ic measurements

The critical current is defined by the resistive criteria $r_c = 10^{-14}$ Wm. The critical magnetic field is defined by the peak field criteria, i.e. the external field plus the maximum value of the self field in the cable. The critical current will be measured at T = 4.2 K as a function of the critical magnetic field.

The critical current measurements will be performed using the direct transformer method: the sample is the secondary winding of a transformer, the primary is the background magnet. The sample is arranged in a loop with a low resistance joint ($R< 2\cdot10^{-9}$ W) obtained by soft soldering, and is directly cooled by the helium bath. The transport current is measured via the self field using Hall probes, while the voltage is measured at two voltage taps placed diametrically opposite one another and equidistant from the joint.

The current is induced in the sample by decreasing the background field. When the critical current is reached, the magnet ramp is stopped so that the sample current decays allowing the voltage-current to be measured at a constant background field.

The transformer method can also determine the joint resistance by measuring the current decay when the sample is in the superconducting state.

MQE measurements

The minimum quench energy is measured on a short sample of the insert (Rutherford and pure aluminium) arranged in a single turn loop, with the field applied parallel to the wide face. In this case the sample is indirectly cooled in order to simulate the actual situation inside the magnet. The current is induced as in the critical current measurement. When the nominal current is reached the magnet ramp is stopped so that the measurement is performed at constant field. During the measurement, the sample current decays slowly (t » 500-1500 s), because of the joint resistance. A pulse disturbance is given using a heater glued onto the conductor. The pulse energy is increased step by step until the conductor quenches. The MQE is the minimum energy required to produce the transition of the conductor [23-4].

23.3.10 Final conductor characterisation in the SULTAN test facility

The high field, large bore test facility SULTAN, which was built by EPFL/CRPP/ Switzerland and ENEA/Italy, is primarily devoted to qualification tests of full-size cable-in-conduit conductors. However, the existing capabilities are well adapted to the characterisation of the full-size conductor of the CMS solenoid.

The split coil magnet system SULTAN allows radial access of samples to the 12 Tesla centre region. It is equipped for this purpose with a vertically installed insertion unit permitting sample insertion and removal without warming up the background field coils. This unit also comprises a 100 kA superconducting transformer for supplying current to the sample. In the high field zone a pair of pulsed field coils provide additional AC testing capabilities. The pulsed field is applied perpendicular to the conductor and to the background field. Both the sample and the joints can be tested, in the second case the sample is installed in a higher position to ensure that the joint is in the middle of the high field region.

The main features of the SULTAN facility are listed below:

- Maximum background field	12	T
- Maximum transport current	100	kA
- Length of high field zone	0.6	m
- Critical current criterion	0.1	µV/cm
- Range of conductor temperature	4.5 - 10	K
- Helium inlet pressure	10	bar
- Range of mass flow rate	0 - 10	g/sec

The cross sectional dimensions of the clamped sample must be smaller than 92 mm x 142 mm.

23.3.11 Further facilities for conductor characterisation in NHMFL

Another possibility to characterise the complete conductor is to use the facilities of NHMFL, in Tallahassee. The high field, high current test facility at NHMFL was developed as part of a joint research effort with Oxford Instruments. The facility is primarily devoted to the qualification tests of full-size cable-in-conduit conductors. It consists of a 13 T, 150 mm bore, split solenoid magnet that is integrated with a structural cryostat and a 250 kN capacity hydraulic test machine. The system has access to the main power supply of the laboratory and is currently configured for transport currents of up to 12 kA in the sample, this is imposed by the size of the vapour-cooled current leads. The main power supplies can be configured for currents up to 80 kA. Critical current as a function of magnetic field and/or strain can be measured in monolithic, cabled and cable-in-conduit conductors. The magnet has a horizontal bore and samples are inserted through a 30 mm by 70 mm radial access slot. The facility is currently being used to verify performance of full scale cable-in-conduit-conductors for the 45 T hybrid magnet that is currently under construction at NHMFL. Some of the test facilities important specifications are given below.

For the 13 T Split Solenoid Superconducting Magnet: the field can be increased to 15 T with insertion of Holium pole pieces. The main characteristics are as follows:

- 150 mm bore,
- 30 x 70 mm fixed gap,

- 4 K operation temperature,
- magnet bore orientation can be varied.

The Structural Cryostat which allows a pulling force to be applied to the conductor has the following characteristics:

- 250 kN capacity hydraulic test machine,
- Sample insertion without warm-up of magnet or cryostat,
- Digital test control and data acquisition.

Although, only 12 kA current leads are presently available, power supplies are available with up to 80 kA and a 10^{-5} ripple.

23.4 RUNNING AND PLANNED R&D ACTIVITIES FOR CONTROL METHODS

23.4.1 RRR measurements under cyclic strain

High purity aluminium used for the stabilisation of superconducting cable achieves very low electrical resistivity at 4.2 K even at high magnetic fields. However, the resistivity is strain dependent, especially with cyclic strain. In aluminium stabilised superconducting magnets a strain induced increase of the resistivity can be observed after only a few charging cycles of the magnet. Measurements on both of the most favoured aluminium purities, 4N and 4N8, are foreseen in collaboration with GAP/University of Geneva and EMPA. In the meantime the low temperature equipment at the University of Geneva is being re-built and improved. Two sets of samples are prepared and ready for measuring [23-5].

23.4.2 Ultrasonic Testing of Aluminium Stabilised High-Current Superconducting Cables

Single Probe Ultrasonic Testing

Modern ultrasonic testing is a well-known non-destructive technique to detect regions of delamination. EMPA's laboratories are involved in projects in Europe (CERN: CMS, ATLAS), in USA (Fermilab D0) and Japan (KEK), and a large variety of aluminium stabilised superconducting cables, in different development and production stages, have been tested.

Short samples were analysed with ultrasonic C-scan imaging applying the pulse-echo immersion technique. Focused ultrasonic probes with nominal frequencies up to 50 MHz were used in conjunction with a high-precision mechanical scanner. The quality of the bonding is controlled by measuring the echo amplitude caused by the interface between the extruded high-purity aluminium and the flat-band-cable or between the aluminium alloy and the high-purity aluminium. Any delaminations are indicated by an enhanced echo amplitude.

Figure 23.16, p. C-49, shows 20 MHz C-scans of two different samples of the Fermilab D0 cable. In the upper sample we perceive the regular structure of the flat-band-cable. The echo amplitude is relatively low: the bonding is homogeneously good. The lower sample, however, reveals enhanced echo amplitudes: the high-purity aluminium is debonded from the flat-band-cable. For comparison, a test-block with flat bottom holes has been imaged.

Electron beam welding has been successfully used to join strips of high-strength aluminium alloy to high-purity aluminium as explained in paragraph 23.5.1. Test samples with different production speeds have been imaged with ultrasound (see Fig. 23.15, p. C-49).

At 1.8 m/mn practically the whole width (40 mm) is welded. At the higher production speed of 6.0 m/mn only half of the profile is joined.

For quality control it is desirable to continuously monitor the bond-quality along the whole cable length (up to 80 km). Mechanical (x-y) scanning of the complete bond-area, however, takes too much time. As a first step we performed a partial bond-test with two fixed 10 MHz point-focused probes. The echo amplitude of 1 mm bond-width was recorded as a function of the position. In this way we have continuously tested 5 km Fermilab D0 cable on both sides. The major part of the cable showed no indications (Fig. 23.7, upper part), however, one section revealed a 0.5 m long delamination (Fig. 23.7, lower part).

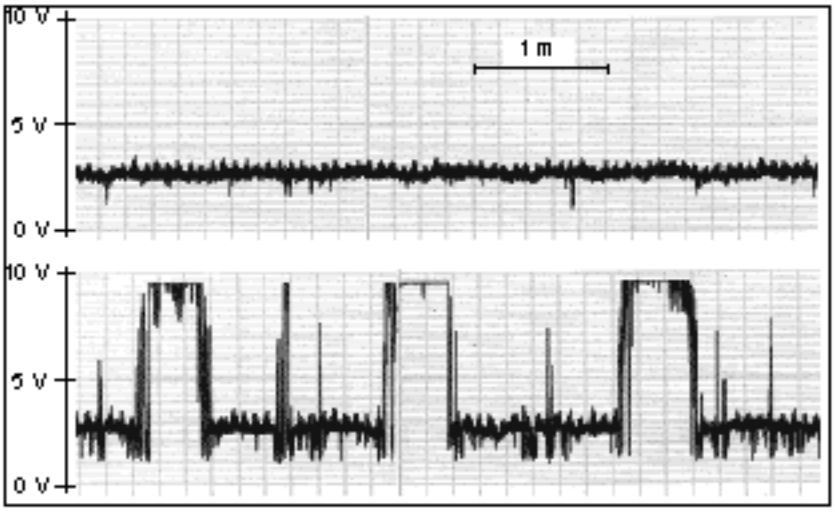

Fig. 23.7: Continuous ultrasonic testing of bond-quality of the Fermilab D0 cable.

Phased Array Ultrasonic Testing System

In May 1996, in collaboration with EMPA, a feasibility study was initiated to design a phased array probe to evaluate the detection of artificial defects in superconducting cables. This ongoing R&D work should enable the quality of the bond between the aluminium and the copper surface of the superconducting strands to be controlled over the whole width and length of the conductor during its manufacture.

In this technique, the sound beam will electronically scan the cable perpendicular to the direction of production. This explains why this method is fast enough to allow a continuous analysis of the complete bond. First phased array results are encouraging.

The phased array technique requires multi-element transducers and sophisticated electronics. Electronic scanning is achieved by successively firing groups of elements. The sound beam moves along the array probe. Since no mechanical motion is involved, very high scanning frequencies are possible (kHz). This should allow a 100% testing of the bond area.

ETH and EMPA in co-operation with the French enterprise NDT Systems S.A., are currently performing a feasibility study. A new 10 MHz linear array probe with 128 elements was designed and manufactured. A large number of test samples are to be investigated with the new probe in conjunction with the appropriate electronics and software. First results on Fermilab D0 samples are encouraging (Fig. 23.17, p. C-49). The flat bottom holes (Ø = 1, 3 and 5 mm) in the upper sample are easily visible. In the lower, Fermilab D0 test sample disbonded areas (yellow/green/blue) are clearly distinct from the correctly bonded areas (red)

[23-8, 23-9].

23.4.3 Eddy current testing

The eddy current testing is a dry process which would require a shorter time to scan the surface, as the speed could reach 60 m/mn, but it has to be validated on aluminium stabilised superconductors by performing preliminary modelisation tests to determine the limits of the method, and to optimise the sensors. Several sensors must be connected in parallel and perpendicular to the conductor axis. Inner defects influence the mutual inductances and can be detected. A diagnostic of each component of the CMS conductor requires a multi-frequency acquisition. An electromagnetic map of the specimen can be obtained. An example is provided on Fig. 23.18, p. C-50, corresponding to a hole drilled in a ferritic stainless steel sheet. The detection is theoretically easier with aluminium than with steel.

23.5 DEVELOPMENTS FOR FIXING THE REINFORCEMENT

23.5.1 EB welding

The high performance superconducting magnets used in the large detectors for High Energy Physics, such as the CMS detector at LHC and the magnets of magnetic storage devices (SMES) have mechanical stresses on the conductor which go beyond the yield stress level of the high purity matrix stabiliser, especially when aluminium is used and mechanical reinforcement must be added to the conductor, as explained in Chapt. 11. A novel method has been studied to join high strength aluminium strips to a high purity aluminium stabiliser by using electron beam (EB) welding. EB welding, combined with roll-pressing under vacuum, provides minimum heat input on the conductor in comparison with other welding techniques. For example a temperature of 160°C has been measured at a distance of 5 mm from the weld. This method allows very long conductor lengths to be produced and repaired without loosing expensive material.

As this process has to be adapted to the high purity aluminium on the one side and to the high strength material on the other we did tests on the improved EB welding machine at CERN, in collaboration with CERN and with PTR Präzisionstechnik GmbH, the EB welding machine manufacturer.

Within this R&D programme the following aluminium alloys have been tested: AA-5083, AA-6082, AA-7020. The next step will be to test the high strength material AA-2219 together with the insert, recently produced for the CMS pre-industrialisation programme. The schematic view of the EB welding system is shown in Fig. 23.8, [23-7, 23-10].

As was shown by finite element computations (see Chapt. 14), the reinforcement has to be attached to the stabiliser by a metallic bond. To control the quality of the EB weld, cylinders of 10 mm diameter were prepared using the wire erosion technique. Test samples, to measure the shear strength, were taken at the root area, from the beam inlet, and half way down. Two samples extracted from a similar area were always tested together using an adequate shear stress measuring device. These tests have shown that the average value for two comparable samples lies between 63 and 86 MPa. This is quite high for aluminium for which some porosity of the weldment has always to be considered. On-line control of the EB welding can be carried out using the phased array technique as described in paragraph 23.4.2.

An other task to be undertaken is the adaptation of industrially used vacuum gates to the cross section of the CMS conductor. Because the electron beam requires a vacuum higher than 10^{-4} mb, the atmospheric air pressure has to be reduced step by step to this level. For the continuous welding process it is foreseen to provide graded vacuum gates at the inlet and at the outlet of the vacuum chamber. The main problems to be solved are the form and the wearing out of the sealing of the gates during the continuous manufacturing process.

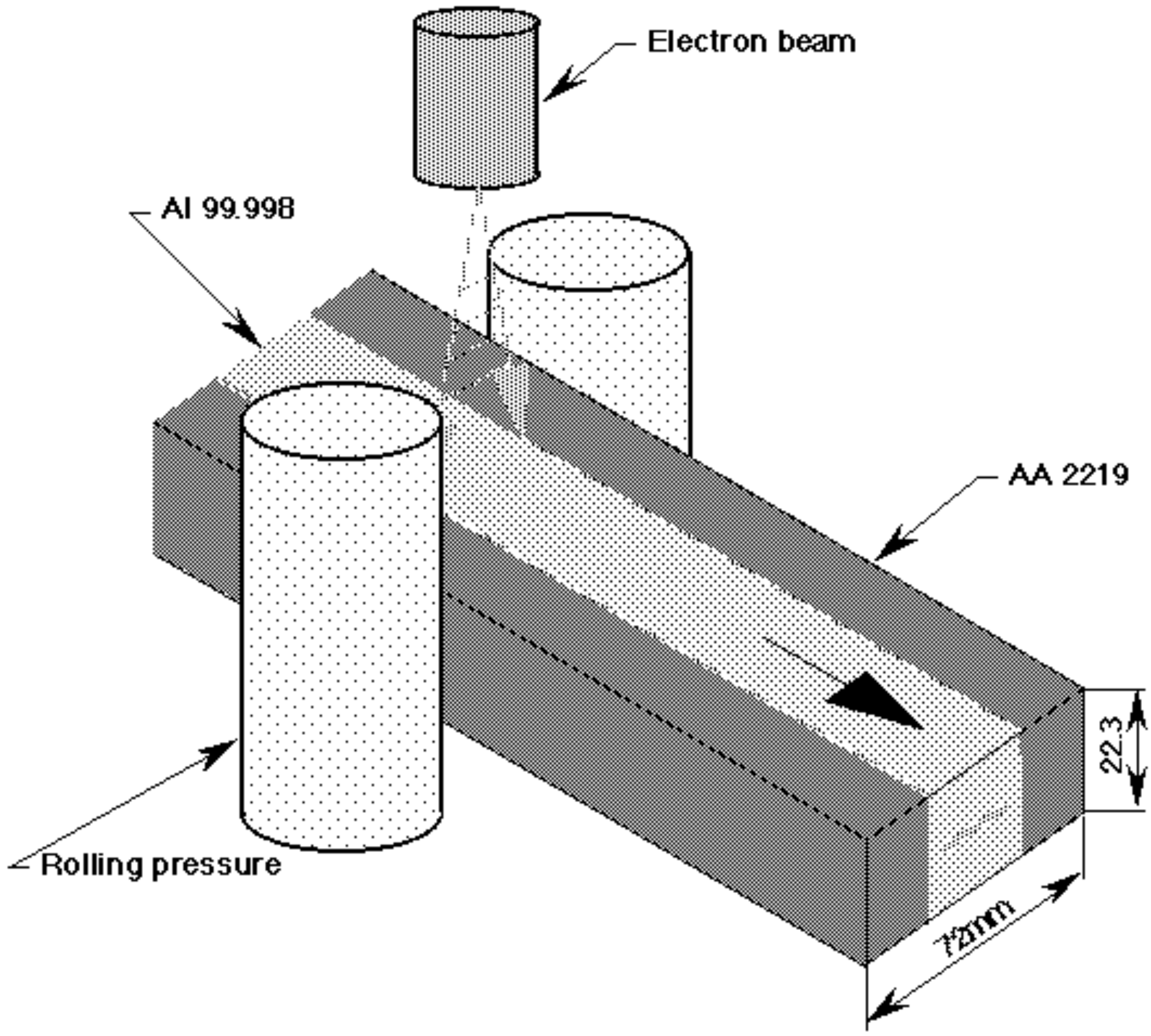

Fig. 23.8: Scheme of the Electron Beam Welding System.

23.5.2 Continuous soft soldering of aluminium

The continuous soft soldering process is an alternative method, providing a back-up for the EB welding solution as described in the Chapt. 23.5.1. In addition, as this technique is readily available for low speed production, it can be used early on with a minimum of investment to produce the 200 m long lengths of conductor which will allow us to start the winding tests with a mechanically representative conductor.

Soft soldering tests have been carried out using cream solder or soldering sheets with flux at Saclay, the bonding tests on aluminium alloy have shown good mechanical properties, in particular shear stress > 45 MPa at 77 K [23-18, 23-19, 23-20]. These characteristics could be improved by soldering in a bath which would limit the amount of bubbles due to the flux being trapped when pressing the components together.

Conductor test assemblies will be undertaken to check the improvement [23-21]. The continuous soldering principle is shown on the Fig. 23.9: the method retained is based on the assembly of the components in the vertical position to ease evacuation of the bubbles trapped between the components.

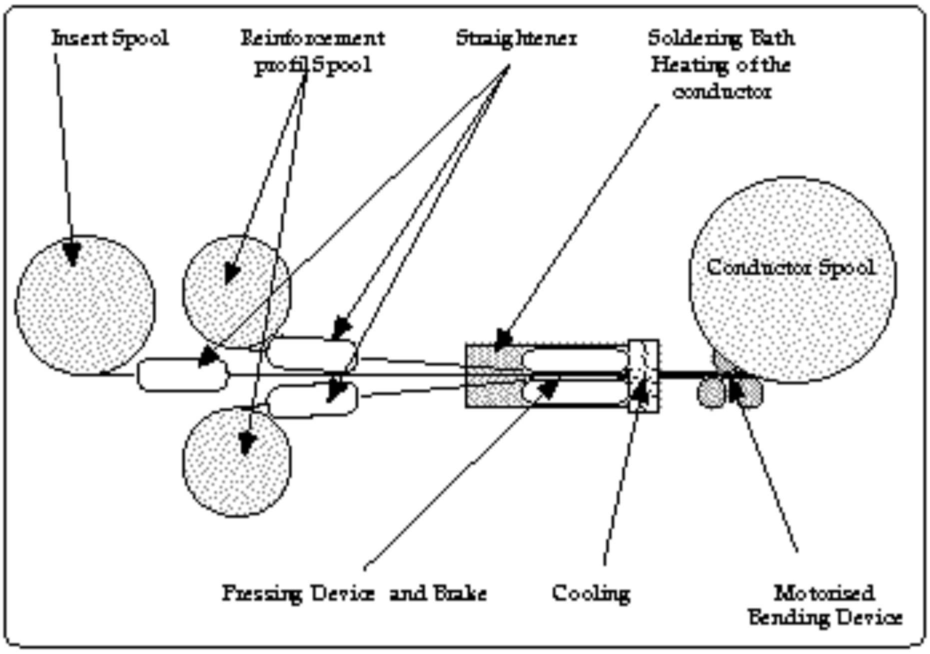

Fig. 23.9: Continuous soldering principle.

The conductor components are inserted inside a gutter, closed on one side by a slotted flange allowing the components to pass with a flow of solder between them. The other side is closed by a one slot flange permitting the conductor to exit. A pump compensates the leaks by transferring solder from a lower tank where it is maintained at the melting temperature by an oil heating system.

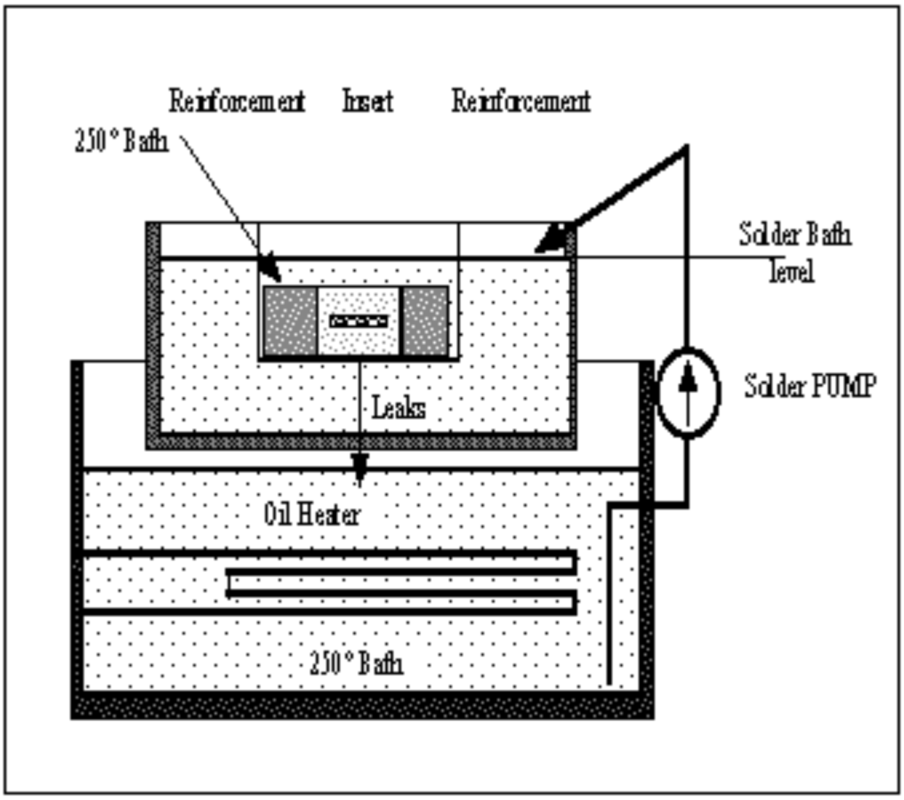

Fig. 23.10: Bath principle component side.

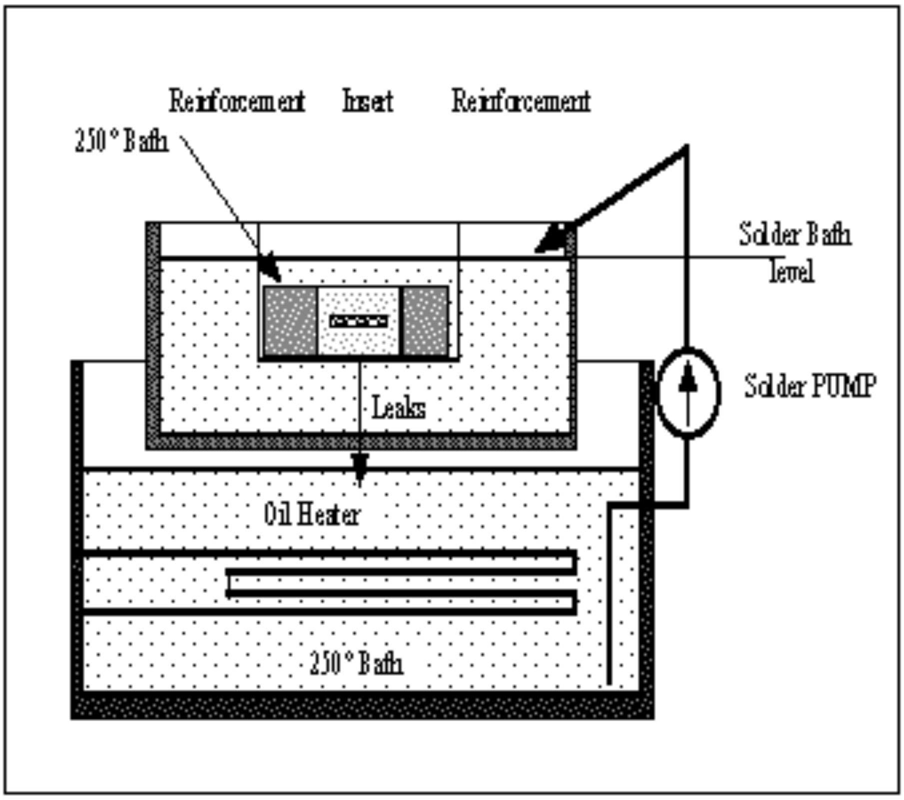

Fig. 23.11: Bath principle assembled conductor side.

The components are heated in the gutter by the solder to the proper soldering temperature. Then the components are pressed together in the bath and cooled down after leaving the gutter.

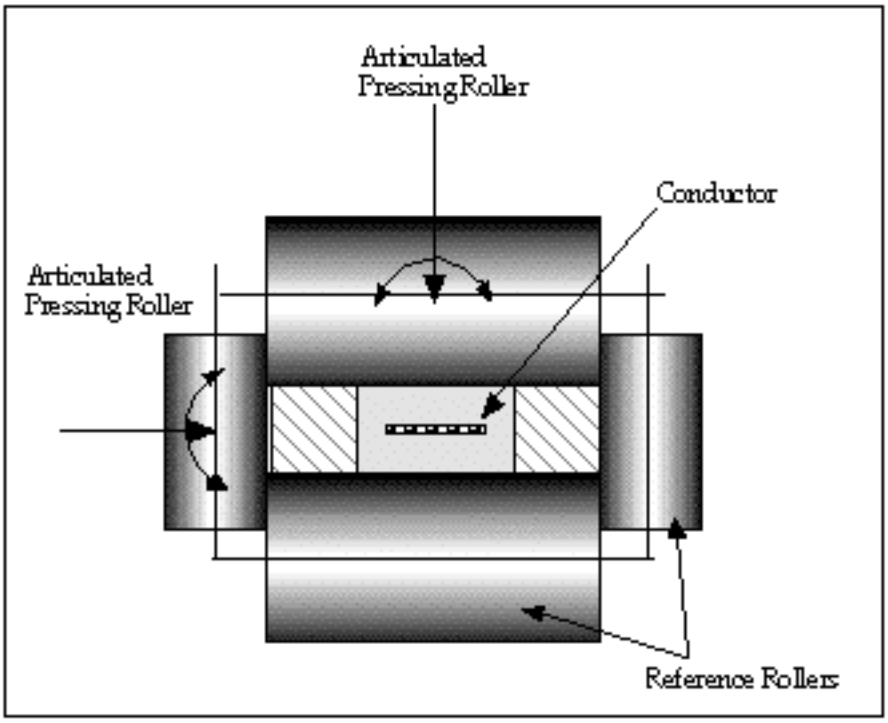

Fig. 23.12: Pressing system in the soldering Bath.

For the final production, the vertical roller system described above can be replaced by a caterpillar equipped with a brake.

The conductor is then spooled and the machining of the final cross section is carried out in another manufacturing line.

23.6 JOINTS

23.6.1 Joining the insert

As said in chapter 12, the extrusion process will be carried out, starting from a 12 km Rutherford cable, until the extrusion process must be interrupted for any reason. If long enough, say more than 2 km, this length will be accepted as a production length. The lengths of insert will be joined together on the CERN site to provide the 12 km long insert required to wind one layer, before adding the reinforcement. Thus CMS requires long unit lengths of insert, to limit the number of joints inside a layer, however, no strict value will be imposed for the definition of a unit length, but the permissible number of joints will be limited.

Clearly these joints cannot be cooled locally by a liquid helium heat exchanger. The joining process must thus be fully qualified in order to produce reliable joints of high quality, especially offering an electrical resistance lower than 10^{-9} W.

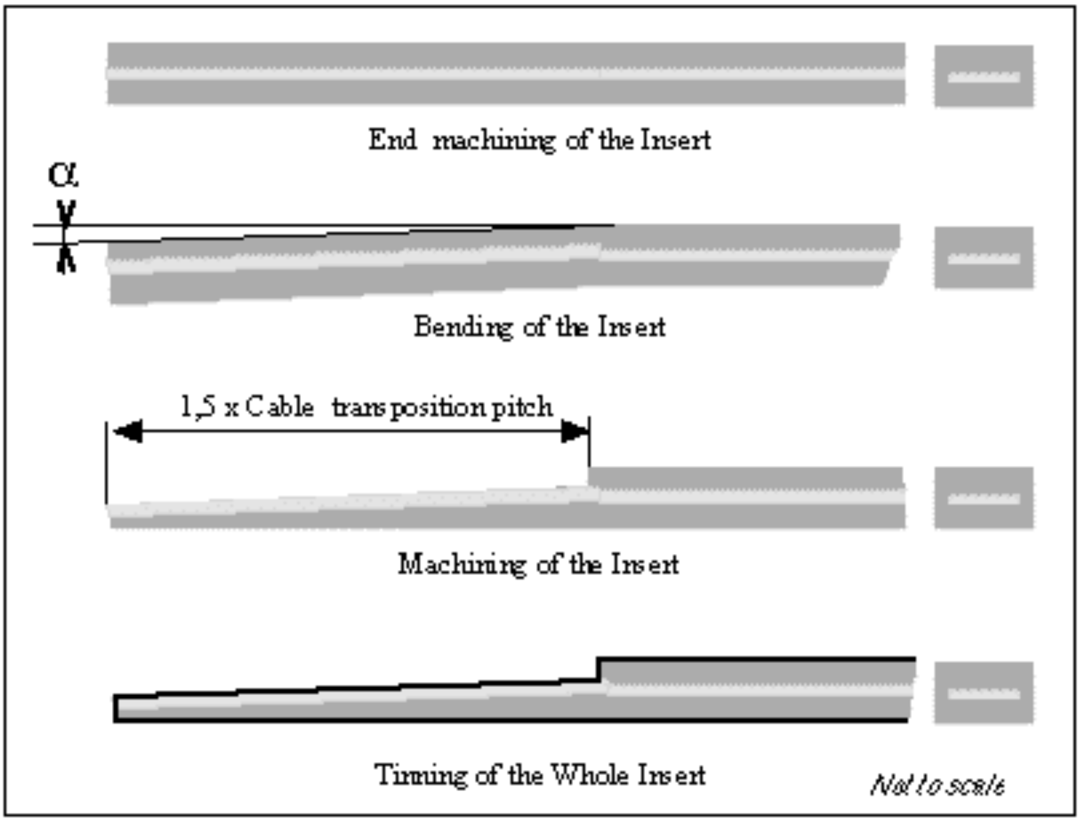

Fig. 23.13: Machining and tinning of an insert end to prepare for a joint. An alternative way is to leave 5 mm of pure aluminium over the insert and use EB welding.

The two insert ends will be prepared by bending and machining like shown in Fig. 23.13 to expose the two Rutherford cable which can then be tinned and soft soldered together in a conventional way. Although first temperature measurements are encouraging, a soft solder with a sufficiently high melting point must be used to support later the addition of the reinforcement by EB welding (see Fig. 23.14).

One will take advantage of the large width of the aluminium insert, i.e. 22.3 mm, and of the presence on site of a dedicated EB welding equipment, to develop a joining method using the EB technique. In this case, after bending, the machining will leave 5 mm of pure aluminium over the Rutherford cable and the joint will be done by EB welding the two inserts through the pure aluminium. First temperature measurements indicate that a distance of 5 mm from the weld is sufficient to protect the superconductor against overheating during EB welding. This method would provide a metallic joint which could be tested by non destructive methods to ascertain the joint quality.

A development program will follow the first production of real insert to fully qualify the joints, and the joining process. Both methods will be developed in parallel.

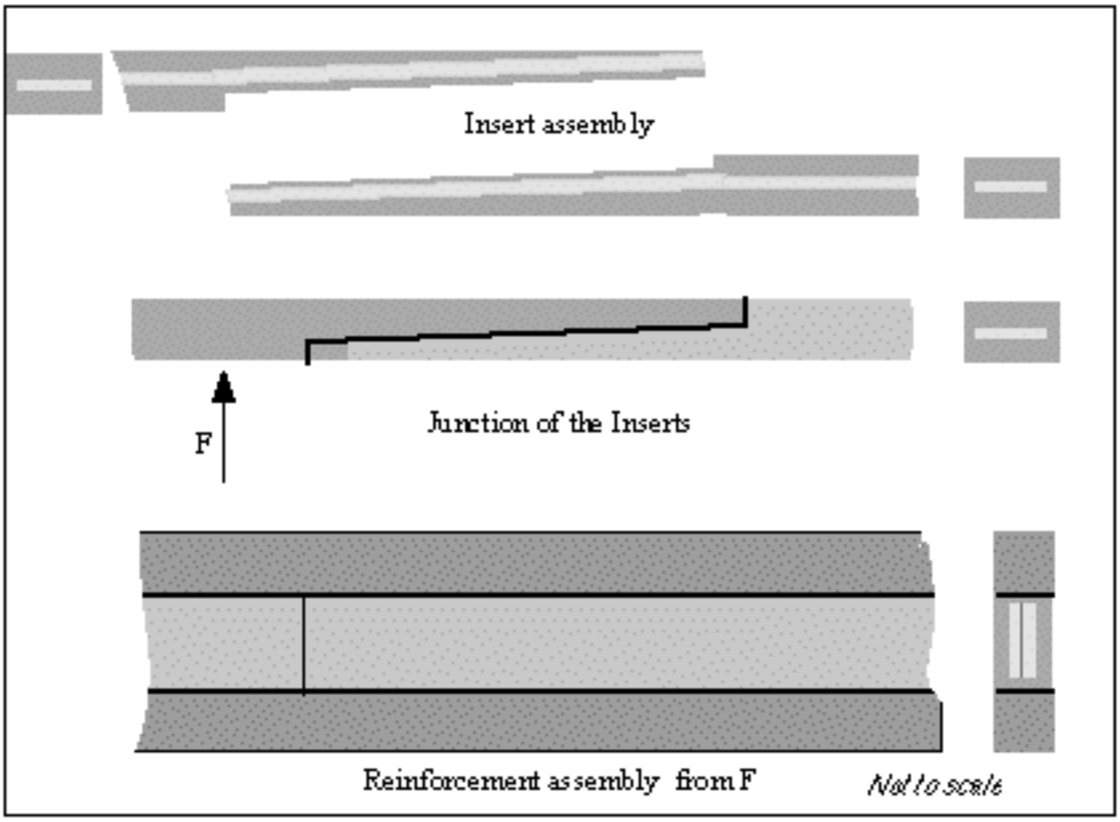

Fig. 23.14: Position of the joint with respect to the reinforcement.

23.6.2 Joining the reinforced conductor

This case must also be developed in order to repair lengths of reinforced conductor which may be damaged by accident.

Due to the presence of the reinforcement, joints on the finished conductor are more complex for the CMS conductor than for other aluminium stabilised conductor.

One possible method to join the conductor consists of welding the aluminium alloy reinforcement, and soft-soldering the insert. As the insert cannot support the welding temperature, if a welding method like TIG is used, it will be locally removed on a sufficient length, and be re-introduced as a segment, between the butt welded external sections. As a consequence, each conductor joint would actually include two electrical joints.

However, here again, advantage can be taken of the presence of an EB welding equipment on site, to develop a joining method for the reinforced conductor based entirely on the use of EB welding.

23.7 PRE-INDUSTRIALISATION

The pre-industrialisation program can be divided into 3 main stages:

1) Production of laboratory short samples to show the feasibility of the “block” conductor and prepare the tooling (activity 1).
2) Proceed toward continuous process engineering (before mid ‘98) and have all the elements to confirm the final choice (EBW or SS reinforcement fixation) and make the call for tender (activity 2, 3, 4).
3) Industrial production phase (end ‘98 beginning ‘99). At this stage the required

investment is not negligible so that any tooling has to be foreseen in the optics of the final production (from activity 5 onward).

Table 23.1 resumes the main activities of the pre-industrialisation program [23-22].

To have a complete view of the pre-industrialisation activities for the coil, this table must be interfaced with Table 24.1, which concerns the winding test, as all the produced lengths of conductor will be used, in the best possible way, to perform winding tests.

Table 23.1
Synthetic table of the pre-industrialisation activities foreseen for the conductor.

	Activity	Time Scheduled	Institute	Goal	Actions to be taken
1	Produce 200 m of Rutherford type cable with 36 strands for the “block” insert	July 97	ETH	To make 200 m of block type extruded insert	ETH/CERN
2	Extrude all the available cable in the form of “block” type insert	August 97	ETH	Have a real insert to perform short length samples of conductor	ETH
3	Make different short length samples of conductor with Soft Soldering and EBW	End of August 97	ETH/ Saclay	Qualify the fixation process at “laboratory” level	ETH SACLAY CERN
4	Organise, if needed, the extrusion of the block insert with the final Rutherford	End 97	ETH	Have an up to date insert to perform tests (winding and conductor)	ETH CERN SACLAY

5	Produce 250 m (or more) of final conductor with laboratory Soft Soldering line	June '98	Saclay	Prepare a significant length to feed the first set of "winding" test	Organise tendering and delivery of straightening devices, spooling, caterpillar etc. (CERN)
6	Design and construction of vacuum gates for continuous EBW Engineering of the continuous EBW line	Feb. '98	ETH	Qualify the continuous EBW process and continuous testing	Procurement of vacuum gates and design of the EBW line (ETH)
7	Engineering of the continuous industrial Soft Soldering line	July '98	Saclay	Qualify the continuous Soft Soldering process and continuous testing	Design the final continuous Soft Soldering tooling (Saclay)

Choose the fixing technology					
8	Produce 1 (or 2) km of extruded insert with final cable	Sept. 98	ETH/ Saclay	Have an insert for the final assembly technique Have a final conductor for representative winding test	Buy the cable and tooling (ETH) Organise extrusion (ETH)

At this stage the call for tender can be launched (autumn '98 by ETH).

9	Produce 2 km of final conductor (first stage after tender)	April '99	ETH	Test the final industrial production process and go towards a significant winding test	Define final tooling (ETH/Saclay) Call for tender (around Oct. 98) (ETH)