ORGANISATION EUROPEENNE POUR LA RECHERCHE NUCLEAIRE
EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Laboratoire Européen pour la Physique des Particules
European Laboratory for Particle Physics

Group Code.: LHC-MMS/98-198 Rev. 2.0
EDMS No.: 312601
LHC Project document No.: **LHC-MB-CI-0006**

The Large Hadron Collider Project *IT-2997/LHC/LHC*

TECHNICAL SPECIFICATION FOR THE SUPPLY OF 1158 COLD MASSES OF THE SUPERCONDUCTING DIPOLE MAGNETS FOR THE LHC COLLIDER

Abstract

This specification concerns the assembly of 1158 cold masses of the twin-aperture superconducting dipole magnets for the Large Hadron Collider (LHC). Each cold mass has a mass of approximately 27.5 t and an overall length of 16.5 m. Deliveries are expected to start by mid 2002 and continue until mid 2005.

May 2001

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Definitions

Term	Definition
CDD	CERN Drawing Directory
EDMS	Engineering Data Management System
QAP	Quality Assurance Plan

1. INTRODUCTION

1.1 Introduction to CERN

The European Organization for Nuclear Research (CERN) is an intergovernmental organization with 20 Member States*. It has its seat in Geneva but straddles the Swiss-French border. Its objective is to provide for collaboration among European States in the field of high energy particle physics research and to this end it designs, constructs and runs the necessary particle accelerators and the associated experimental areas.

At present more than 5000 physicists from research institutes world-wide use the CERN installations for their experiments.

1.2 Introduction to the LHC Project

The Large Hadron Collider (LHC) is the next accelerator being constructed on the CERN site. The LHC machine will mainly accelerate and collide 7 TeV proton beams but also heavier ions up to lead. It will be installed in the existing 27 km circumference tunnel, about 100 m underground, presently housing the Large Electron Positron Collider (LEP). The LHC design is based on superconducting twin-aperture magnets which operate in a superfluid helium bath at 1.9 K. The 1232 arc dipoles and the 520 quadrupole magnets of the LHC, designed as twin-aperture structures, use NbTi superconducting cables for their coils. The magnets operate in superfluid helium at 1.9 K at a field varying between 0.54 T and 8.33 T for the dipoles, and at a field gradient up to 223 T/m for the quadrupoles.

1.3 The dipole magnet cold mass

1.3.1 General description

The cross-section of a LHC cryo-dipole is shown in drawing LHCLBA_S0003 “Standard cross-section”. It consists of a “dipole cold mass”, which contains all the components cooled by liquid helium, and equipment around it to form a cryostat. The dipole cold mass consists of an active part, which is the core of the magnet itself, providing two apertures for the “cold bore tubes” (i.e. the tubes where the proton beams will circulate), and of ancillary parts allowing operation at 1.9 K in superfluid helium. The dipole cold mass has an overall length of about 16.5 m (ancillaries included), a diameter of 570 mm (at room temperature) and a mass of about 27.5 t. The cold mass is curved in the horizontal plane with an apical angle of 5.1 mrad that corresponds to a radius of curvature of about 2812 m at 1.9 K, so as to match closely the trajectory of the particles.

* CERN Member States are: Austria, Belgium, Bulgaria, Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Italy, The Netherlands, Norway, Poland, Portugal, Slovak Republic, Spain, Sweden, Switzerland and the United Kingdom.

The active part is made of:

1) Two dipole coils, each consisting of an upper and a lower pole. Each pole consists of two windings, called the inner and outer layers that are electrically connected in series. Within the layers, the conductor turns are grouped in blocks approximating the ideal current distribution generating a homogenous dipole field. The dipole coils are connected in series, so that the magnetic fields are in opposite directions in the two cold mass apertures.

   The coils are equipped with quench heaters, the purpose of which is to trigger a general transition from the superconducting to the normal conducting state (“quench”) in the case of detection of a local quench. The 16 quench heaters are electrically connected in series pairs, creating 8 parallel circuits.

2) A common non-magnetic, force-retaining laminated structure, made up of austenitic steel collars. This structure confines and pre-stresses the coils strictly maintaining their geometry in presence of the very high electromagnetic forces occurring during magnet testing and operation.

3) A laminated iron yoke split into two parts in the vertical plane of symmetry, providing the return path for the magnetic flux and conferring mechanical rigidity to the whole structure. The yoke is completed at the ends by nested non-magnetic/magnetic laminations to lower the magnetic field at the coil ends and to close the stray magnetic field.

4) Two laminated iron inserts placed across the vertical symmetry plane, completing the magnetic yoke and transmitting the vertical force between the collared coils and the yoke.

5) An austenitic steel shrinking cylinder, made up of two welded half-cylinders, surrounding the yoke. The shrinking cylinder gives to the cold mass assembly the stiffness necessary to contain the electromagnetic forces, it provides the inertia necessary to maintain the geometry of the cold mass on its supports and it acts as the major part of the helium containment vessel. In the latter function, it is able to resist pressures up to 20 bar, which occur when the magnet coils quench and energy is dissipated inside the cold mass. Quenches will occur during magnet testing before installation and may occur during magnet operation in the LHC tunnel.

6) Two austenitic steel end plates ending the active part at both extremities, and absorbing the longitudinal electromagnetic forces.

The active part is completed by two small sextupole (MCS) and two small decapole/octupole (MCDO) corrector magnets (also referred to hereafter as “spool pieces”). The sextupole spool pieces are installed at one end of the cold bore tubes, the decapoles at the other. The function of these spool pieces is to correct for the magnetic field imperfections arising in the dipole magnet due to persistent currents in the superconducting cables and due to the iron saturation. The decapole/octupole correctors are installed on only a half of the total number of cold masses. The space thus left available in the remaining half of cold masses is kept in reserve for other correctors should they be needed.

Items 1 and 2 together with the related cold bore tubes constitute a sub-assembly that will be hereafter referred to as the “collared coils”.

The main ancillary components are:

1) Superconducting busbars for the electrical connection of the adjacent dipole magnets, of their spool pieces and of the arc quadrupoles. At the cold mass end opposite to the coil connections (also referred as “non connection” or “lyre” side), the busbars are equipped with flexible U-shaped sections, the “lyre”, to cope with the thermal contraction and expansion occurring between 300 K and 1.9 K and vice-versa.

   Because of the scheme adopted for the electrical series connection of the dipole magnets, two different connection layouts are required. As a consequence, 50 % of the dipole magnets will be equipped with “type A” busbars and the other 50 % with “type B” busbars.

   Around the LHC ring, the dipole magnets will be installed in sets of six units, with either type A or type B magnets. The type A will be equipped with MCS and MCDO correctors, while the type B will be equipped with MCS correctors only.

2) A stack of protection diodes that protect the dipole magnets during quenches. These elements (positioned at the connection side extremity of the cold mass and installed during the cold mass manufacturing) will be submitted, in case of a quench, to a current pulse rising to about 12 kA within less than 0.5 s and decaying exponentially with a time constant of ~ 100 s.

3) The helium heat exchanger tube that carries a two-phase flow of superfluid helium at sub-atmospheric pressure.

4) Austenitic steel end covers complete the helium vessel The end covers are fitted with outlets providing the passages for the cold bores, the helium flow and the busbars to the adjacent magnet units. At the “lyre” end of the cold mass, the end cover outlets are equipped with bellows providing the flexibility necessary for the connection to the adjacent magnet. The end covers also carry the geometrical references necessary for the installation of the cold mass into the cryostat and the adjustment of the alignment references of the cryostat to be used for LHC installation and alignment.

5) Three cold mass support bases.

6) Auxiliary busbars tube (N-line) which also forms part of the helium enclosure, fixed to the shrinking cylinder by six supports.

7) Instrumentation wiring and the Instrumentation Feedthrough System (IFS).

1.3.1.1 Cold mass configuration

The cold mass is here specified in a configuration that allows the execution of the final room temperature leak and pressure tests, as shown in the drawings LHCMBB_S0001, and LHCMBA_S0007.

In this configuration, the cold mass extremities are designed to allow an easy and fast connection of the cryo-magnet to the test bench for the acceptance tests at liquid helium temperature performed at CERN.

Each type of cold mass assembly (type A and B) is specified in two possible test configurations:

- The so-called "standard test configuration" that will apply to the majority of the produced cold masses.
- The so-called "full test configuration" that will apply on a statistical basis to a minority of cold masses (max 10 %). By means of soldering additional connections between all the auxiliary busbars in the cold mass, this second configuration will permit a full test of the auxiliary busbars and corrector magnets during the cold tests at CERN. CERN will inform the Contractor in advance which cold masses are to be prepared in the "full test configuration".

All the relevant drawings are available for both test configurations.

1.3.1.2 Polarity of the protection diode stack.

For each cold mass, the polarity of the protection diode stack can by either "AR" or "AL" (Anode on the Right or on the Left). CERN will communicate for each cold mass the required polarity.

Combining all the specific needs and differences listed above, eight configurations are possible for the LHC Dipole cold masses.

1.3.2 Main parameters and design features

The main parameters of the dipole magnets are given in Table 1.3.2

The successful operation of LHC requires that the main dipole magnets be practically identical in their characteristics. This entails that relative variations of the integrated field and of the field shape imperfection not exceed the order of magnitude of 10^{-4} and that their reproducibility be within a fraction of 10^{-4} after magnet testing and during magnet operation. The above properties are provided by the coil geometry, which shall be accurate, reproducible and symmetric to within a few hundredths of millimetre, and by the structural stability, in presence of the electromagnetic forces, of the magnet assembly. The structural stability must, up to the short sample field limit of the superconducting (SC) cable, prevent any coil movement causing quenches. This aspect is particularly important for magnets operated at 1.9 K, where the materials show no effective heat capacity and any energy dissipated must be removed via the superfluid helium.

The accuracy and symmetry of the coil geometry is achieved by:

1) Tolerances ranging from ± 2 μm (e.g. diameter of the SC wire, thickness of the polyimide tapes for SC cable insulation) to ± 20 μm on the dimensions of coil components, tolerances of ± 0.03 mm on the average transverse dimensions of the finished coils and of ± 0.02 mm on critical dimensions of the fine-blanked austenitic steel collars. The overall accuracy of the coil geometry is finally achieved by fixing the position of the coil components by means of tooling of adequate accuracy and stability.

2) Manufacturing a cold mass from coils made with inner/outer layers wound with identical cables (i.e. from the same cable Contractor, and manufactured from the same tooling set (winding mandrel, curing mould, curing press) according to a tightly controlled manufacturing procedure (including close control of temperature and pressure during the curing of the layers).

3) Providing room in the coil cross-section for the fine tuning of its geometry without modification of the tooling, and/or using a different and appropriate curing cycle.

Furthermore, alternating their left/right orientation during the cold mass assembly will reduce systematic field errors within a cold mass caused by imperfections of lamination geometry. Systematic field errors caused by geometric imperfections and asymmetries of tooling will be dealt with by alternating the up/down orientation of the collared coils within the cold masses, so as to reduce the integrated field errors seen by the particles passing through the cold bores of successive dipole magnets.

The reproducibility of the integrated field strength requires a close control of coil diameter and length, of the stacking factor of the laminated magnetic yokes and possibly a fine-tuning of the length ratio between the magnetic and non-magnetic parts of the yoke.

The structural stability of the cold mass assembly is achieved by using very rigid collars and by opposing the electromagnetic forces acting at the interfaces between the collared coils and the magnetic yoke with the forces set up by the shrinking cylinder.

Table 1.3.2: Main parameters and characteristics of the LHC dipole cold mass

	Value	Unit
Injection field (0.45 TeV beam energy)	0.54	T
Nominal field (7 TeV beam energy)	8.33	T
Nominal current	11.8	kA
Operating temperature	1.9	K
Magnetic length at 1.9 K	14.3	m
Stored energy (both apertures) at 7 TeV	7.1	MJ
Ultimate operational field	9.0	T
Nominal short sample field limit	9.65	T
Distance between aperture axes at 1.9 K	194.00	mm
Bending radius at 1.9 K	2803.98	m
Distance between aperture axes at 293 K	194.52	mm
Bending radius at 293 K	2812.36	m
Inner coil diameter at 293 K	56.00	mm
Outer coil diameter at 293 K	118.60	mm
Number of conductor blocks / pole	6	
Number of turns / pole, inner layer	15	
Number of turns / pole, outer layer	25	
Electromagnetic forces / coil quadrant at nominal field Horizontal force (inner and outer layer) Vertical force (inner layer) Vertical force (outer layer)	 1.7 -0.14 -0.60	 MN/m MN/m MN/m
Axial electromagnetic force on both ends at nominal field	0.37	MN
Cold bore inner diameter at 293 K	50.00	mm
Cold bore outer diameter at 293 K	53.00	mm
Cold mass length at 293 K (active part)	15180	mm
Cold mass diameter at 293 K	570.0	mm
Cold mass overall length with ancillaries	16.5	m
Total mass	≈ 27.5	t

The dipole cold mass is assembled at room temperature, but will work at 1.9 K. The design is such that after welding the shrinking cylinder, contact forces are present at the vertical interface between the yoke halves (varying from 0.1 to 0.3 MN/m of length at different locations along the vertical interface) [1], at the inclined interface between the yoke, via the insert, and the collared coils (about 0.6 MN/m) and at the interface between the collared coils and the yoke in the horizontal plane (up to 0.15 MN/m). At room temperature, these forces are set up by the shrinkage of the welds between the two halves of the shrinking cylinder, which is submitted to a circumferential stress of about 150 MPa.

When cooling down, because of the larger thermal contraction coefficient of the austenitic steel of the shrinking cylinder and collars, with respect to that of the yoke steel, the above force distribution changes. At zero current and 1.9 K, the mating forces between the yoke halves rise to about 1.4 MN/m (corresponding to a circumferential cylinder stress of some 320 MPa), the force at the inclined interface between yoke and insert is about 0.4 MN/m and the force between collared coil and yoke in the horizontal plane is close to zero. The electromagnetic forces at high field (9 T) elastically deform the collars, which are then in firm contact with the yoke in the horizontal plane (contact forces up to 0.35 MN/m), and reduce the yoke halves mating force above the insert to some 1.0 MN/m.

The sensitivity of the above force distribution in the cold mass structure to tolerances of collars, laminations, inserts, coil pre-stress and shrinking cylinder circumferential stress, as known from model work with actual components and as specified in this Technical Specification, was checked by F.E.A. computations applying statistical methods. Some 3000 geometries were computed at high field conditions; in all cases strictly positive contact forces were found at the above interfaces between yoke halves and between the yoke and collared coils.

1.3.3 Acceptance tests

A considerable number of tests and inspections are mandatory in the course of the cold mass assembly. It is the aim of the intermediate tests at the Contractor’s premises to detect possible defects at earliest possible stage, thus allowing their swift correction.

These tests, their conditions and acceptance criteria are described in this specification and its Annexes. The description of the mandatory tests and the referenced Sections and Annexes are summarised in the form of an Inspection and Test Plan (ITP), presented in the Annex B2.

The Safety Tests on completion of the manufacture of the cold mass (Pressure test, X-ray tests and other destructive and non-destructive tests) are introduced in Section 7.3 “Safety Requirements” and are described in detail in Annex B33 “Safety Tests”.

The Contractor shall implement the CERN ITP plan without any restriction of its content. Should some of the checks and measurements specified in the ITP be sub-contracted, the Contractor will remain fully responsible of their reliability as well as for the final results, which shall be recorded in appropriate assembly and control reports.

The Contractor shall establish, also according to the contractual Quality Assurance Plan, his own ITP plan that shall include, as a minimum, the CERN ITP.

The cold masses shall pass a series of manufacturing tests performed at room temperature at the premises of the Contractor, followed by acceptance tests performed at 1.9 K at CERN.

[1] All the forces reported in this section are per metre of length per quarter of dipole cross-section.

The room temperature tests and measurements, performed by the Contractor within the scope of the Contract, shall systematically include:

- Verification of the integrity of the electrical insulation and impedance of various circuits.
- Geometrical measurements accurate to within 0.1 mm r.m.s. of horizontal curvature, vertical straightness, position of the ends of cold bore tubes and of other outlets for magnet interconnection, position of the support bases, minimum inner diameter of cold bore tubes.
- The measurements of tilt of the magnetic mid-planes, parallelism of the field direction in the two apertures (the Annex B1 gives the acceptance criteria for these parameters).
- The measurement of magnetic field quality and the integrated field strength. The purpose of these measurements is to allow the possibility of fine-tuning the magnetic length. This can be done by small change in the number of magnetic laminations in the yoke blocks (maximum 5 laminations).
- Examination of welded joints.
- Room temperature pressure and leak tests.

CERN will take full responsibility for the field quality of magnets that have followed the correct assembly procedure and have been made fully conforming to CERN conceptual drawings.

CERN may find it necessary to fine-tune the field quality during production. This will be achieved by small changes in pole shim thickness or geometry of the copper wedges of the coil layer. CERN will take full responsibility for defining these changes, for supplying the components under CERN's responsibility and for the subsequent field quality obtained. Such fine tuning operation should not affect the Contractor's tooling. At the present time, it is envisaged that only one such operation would be needed.

Annex B1 gives details of the field quality measurements, fine-tuning and target values of magnetic multipoles that CERN aims to achieve.

Once a cold mass has successfully passed all the above tests and inspections and the corresponding data, records and reports are made available, CERN will agree on its transport to CERN.

After delivery of the cold masses to the CERN site, and prior to and/or after insertion in their cryostats, any of the factory tests may be repeated (as provisional acceptance tests at room temperature) before the provisional acceptance tests at liquid helium temperature (also called the "cold tests"). These tests will be made by CERN, at CERN's expense.

After successful completion of the provisional room temperature acceptance tests and cryostating, the cryo-magnet will be submitted to a series of provisional acceptance tests at liquid helium temperature, as detailed below.

The 1.9 K tests will systematically include:

- Verification of the integrity of the electrical insulation and impedance of various circuits.
- Training of the magnets above nominal field within a given number of quenches.
- The measurement of integrated field strength versus excitation, field quality at several field levels, tilt of the magnetic mid-planes, parallelism of the field direction in the two apertures.
- Leak tests.

The Contractor shall assume responsibility for obtaining the values of the mechanical, geometrical, electrical and magnetic characteristics as detailed in this Technical Specification, at 293 K and at 1.9 K, in so far as these characteristics depend on the correct execution of the activities covered by the scope of supply (see Section 2.1).

2. SCOPE OF THE TENDER

This Invitation to Tender constitutes the second phase of the LHC dipole cold masses procurement procedure described in detail in the document “Instruction to Bidders” appended to this Invitation to Tender. References will be made in the following to definitions, procedures and stipulations given in the above document.

2.1 Scope of the supply

This Invitation to Tender covers the assembly, testing and supply of a total of 1158 cold masses of the main superconducting dipole magnets for the LHC. Following the “Instruction to the Bidders”, the Bidders shall also quote the price for optional cold masses. CERN reserves the right to share the supply among two or more contractors.

The required work and supplies include:

- any study and design work for components and tooling procured under the responsibility of the Contractor and to be integrated in the cold mass design and construction,
- the procurement of all necessary raw materials and components, including consumables, under the full responsibility of the Contractor,
- the study, design, procurement, installation, commissioning, operation and maintenance of all new tooling and manufacturing facilities other than those previously provided by CERN,
- the operation and maintenance of the tooling and equipment previously supplied by CERN and lent to the Contractor for the execution of the Contract,
- the manufacturing drawings (see also Section 4.2.4),
- the establishment, implementation and maintenance of a documented Quality Assurance Plan fulfilling all the requirements of this Technical Specification,
- the manufacture, assembly and testing of the dipole cold masses according to this Technical Specification,
- the supply, by means of paper and/or computer readable files, of all reports and records of inspections, tests and measurements carried out within the scope of this Technical Specification, according to forms and formats required or agreed by CERN,
- the packing and safe transport of the cold masses to CERN.

2.2 Components supplied by CERN

CERN will supply to the Contractor the following items for the manufacture of the 1158 cold masses being the object of this Technical Specification:

1) Superconducting cables (for inner & outer layers),
2) Polyimide tapes for cable and copper wedges insulation (two types),
3) Copper wedges (4 types),
4) Polyimide (in rolls) for the coil ground insulation,
5) Collars (6 types),
6) Insulated cold bore tubes,

7) Low-carbon steel half-yoke and insert laminations,

8) Nested (non-magnetic/magnetic) half-yoke laminations(*) and non-magnetic insert laminations,

9) Busbars subassemblies (ready to be mounted),

10) Half-shells for shrinking cylinders,

11) Spool pieces (sextupole and decapole/octupole correctors),

12) End covers,

13) Helium heat exchanger tubes,

14) Interconnection bellows,

15) Instrumentation and wiring for the cold mass,

16) Protection diode stacks,

17) Line N tubes.

(*) CERN reserves the right to deliver the nested lamination already assembled in packs. For the purpose of bidding, the Bidder shall consider the delivery of loose laminations. The final decision will be communicated by CERN in due time. The Bidder shall make a separate quotation for the assembly of the nested lamination packs.

CERN assumes responsibility for the performance parameters determined by items and subsystems supplied by CERN, according to their technical specifications (see Annex C and G). The Contractor entrusted with the assembly of the dipole cold masses shall assume responsibility for the safe storage and the integrity on its site of the items delivered by CERN. Please refer to the Contract for the detailed stipulations about responsibility matters. A delivery schedule will be agreed between CERN and the Contractor.

For other matters regarding materials and components supplied by CERN, such as reception, storage, insurance, invoicing, payment, please refer to the corresponding Sections of this Technical Specification and to the contractual clauses.

2.3 Items not supplied by CERN

The Bidder shall assume that the procurement of any other item not explicitly mentioned in the above Section shall be under his responsibility. The technical specifications for these other items are to be provided by the Contractor in agreement with the corresponding CERN specifications, if any. All the related technical documents shall be approved by CERN before the manufacture of the item concerned may start.

The following items were “CERN Supplied Components” in the pre-series Call for Tender (IT-2708/LHC/LHC) they have now been transferred to the responsibility of the Contractor:

1) End Spacers, chips and wedge-tips sets (former Annex C4 in IT-2708/LHC/LHC),

2) Coil Inter-layers (former Annex C5 in IT-2708/LHC/LHC),

3) Layer-jump boxes (former Annex C6 in IT-2708/LHC/LHC),

4) Layer-jump filling pieces (former Annex C7 in IT-2708/LHC/LHC),

5) Cable stabilisers (three types) (former Annex C8 in IT-2708/LHC/LHC),

6) Quench heaters (former Annex C9 in IT-2708/LHC/LHC).

All the relevant technical specifications are attached in Annex G. A summary of the technical information is given in the Annexes of Section B. The Contractor shall be responsible for their procurement from the already selected CERN sub-supplier (where specified) or from another supplier to be selected by the Contractor. CERN will communicate lists of qualified and mandatory suppliers.

2.4 Tooling and other equipment provided by CERN

CERN will procure and lend to the Contractor for the execution of the Contract the hydraulic presses for the collaring of the coils and for the longitudinal welding of the shrinking cylinder with the welding equipment included. CERN will also procure and lend equipment necessary for the measurements of the geometry and elastic modulus of coil layers and poles, the magnetic measurement at room temperature of magnetic field characteristics, the electrical tests and the measurements of the cold mass geometry. These items were already provided by CERN under the Contracts signed after the Call for Tender IT-2708/LHC/LHC, but are listed and described in detail in Annex E for completeness.

2.5 Delivery Schedule

Please refer to the contractual documents.

3. TENDER PROCEDURE AND CONTENT

3.1 Instructions to bidders

The document "Instruction to Bidders" provides information and instructions about the following matters:

- the overall tendering procedure for the LHC dipole cold masses,
- eligibility of bidders, country of origin and subcontracting,
- content, clarification and amendment of bidding documents,
- preparation of tenders (language, documents, prices, currencies, validity, price revision),
- alternative proposals,
- tender opening and evaluation.

3.2 Pre-tender information and discussions

Bidders are strongly encouraged to contact CERN in writing to obtain written clarifications of the tendering documents (see Section 9 of the "Instruction to Bidders" document) and to visit CERN in order to inform themselves about CERN's tooling, testing equipment and assembly experience. In particular, CERN wishes to ensure that no doubt exists as to the interpretation of this specification.

3.3 Technical content of the tender

In addition to submitting the financial and administrative documents listed in Section 12 of the document "Instruction to Bidders", the Bidder shall in his tender provide convincing evidence that he has studied the requirements of this Technical Specification and the technical content of his tender in sufficient detail, so as to be able to provide the competence and resources needed in view of the Contract's execution.

For each of the topics below, in addition to completing the related sections of the Questionnaire, the Bidder shall provide appropriate information as follows.

3.3.1 Contract management

The Bidder's intended Contract management organisation shall be described. This includes:

- A chart showing the Bidder's organisation proposed in order to guarantee the fulfilment of highest requested production rate,
- The position within the Bidder's organisation and the description of the tasks, responsibilities and competence limits of the heads of department/service/team concerned with the Contract,
- The names and curricula vitae of the persons expected to be in charge of the major tasks in the Contract.

3.3.2 Procurement of materials and components

The Bidder shall describe how he intends to proceed from the administrative, technical and quality assurance points of view for the procurement of materials and components and the corresponding acceptance tests. The in-house administrative path shall be highlighted, detailing the responsibility levels and the application of quality assurance measure.

3.3.3 Tooling and manufacturing facilities

The Bidder shall identify, list and separately quote the dedicated tooling to be designed and procured, necessary for the Contract's execution at its premises or at those of its partner/subcontractors. The Bidder shall quote the tooling necessary for the manufacture and delivery of the cold masses, according to the contractual delivery schedule.

The manufacturing facilities, including the clean area, shop floor and layout, lifting and handling equipment and storage for incoming items shall be described.

The schedule for the availability of tooling and manufacturing facilities shall be given.

The tooling shall be qualified, inspected and maintained as explained and requested in Sections 4.2.7 and 4.2.8.

3.3.4 Quality Assurance

The Bidder shall describe the organisation, operation and auditing of the quality assurance system he intends to apply at his premises and at those of his partner/subcontractors. The Bidder shall provide examples from recent/current work. The Bidder's quality system shall comply with the requirements of the international standards ISO 9000 or equivalent and shall be certified by an accredited institution.

3.3.5 Manufacture

The Bidder shall provide a description of the manufacturing plan he intends to implement. Process flow charts shall supplement the narrative description of the manufacturing schedule, they shall be based on the “pre-series” production experience. The Bidder shall indicate the number of proposed work stations/posts for the cold mass manufacture and assembly and describe the activities/operations which will take place at each of these work stations/posts. He shall also provide for each of them the proposed number and qualification of the staff and a list of the tooling necessary. The estimated number of man-hours necessary for the execution of the manufacturing steps at each work station/post shall also be given, for the beginning of production and for the peak production rate.

3.3.6 Inspection and Test Plan

The Bidder shall provide a preliminary inspection and test schedule, identifying the sequence and type of inspections and tests to be carried out at each of the above work stations/posts. This Inspection and Tests schedule shall be based on the CERN “Inspection and Test Plan” described in the Annex B2. He shall also provide the proposed number and qualification of the inspectors and a list of the necessary instrumentation and equipment. The estimated number of man-hours necessary for the performance of the inspection and test steps at each work station/post shall also be given, for the beginning of production and for the peak production rate.

3.3.7 Test equipment

The Bidder shall ensure that he has all the necessary instruments and test equipment correctly functioning and calibrated (including the equipment described in Annex E), in order to fully confirm, before shipment of the cold mass, the quality and the performance at room temperature of the cold mass as a whole, as well as of its components.

3.3.8 Contract execution schedule

The Bidder shall provide a preliminary but detailed schedule showing the sequence of the design, procurement, commissioning, manufacturing, testing and delivery activities in view of the Contract execution.

3.3.9 Presentation of Tender

The Bidder may be requested to make a formal presentation of his tender at CERN. He shall be ready to do so within a week of notification.

4. TECHNICAL CONTRACT MANAGEMENT

4.1 Persons technically responsible at CERN

The following persons are in charge of the technical aspects of this specification and are available for further information which the Bidder may consider necessary:

Name	Tel-Fax	Email
J. Vlogaert	**Tel:** + 41.22.767.5385 **Fax:** +41.22.767.8280	Jos.Vlogaert@cern.ch
In case of absence: C. Wyss	**Tel:** +41.22.767.3764 **Fax:** +41.22.767.6300	Carlo.Wyss@cern.ch

4.2 Contract follow-up

4.2.1 Contract engineer

The Contractor shall assign the technical and management responsibility of the Contract to an experienced and competent Contract engineer who shall be responsible for all contacts with CERN throughout the duration of the Contract. A deputy contract engineer shall be designated to cover any absence of the contract engineer.

4.2.2 Manufacturing schedule

The Contractor shall supply, within two months after notification of the Contract, a detailed manufacturing and testing programme. The programme shall include preliminary dates for inspections and tests.

4.2.3 Progress report

A written progress report shall be sent to CERN every month until the delivery of the last cold mass.

The progress reports shall also cover the operations for the procurement and acceptance of components, whoever are their supplier.

The report format must be prepared following the information contained in Annex B36 “Planning and scheduling requirements”.

4.2.4 Availability of the tender drawings

All the tender drawings are available in “HPGL”™ format. This is the only valid format for the tender and contractual drawings.

With the aim of limiting the cost of the manufacturing drawings, CERN will make available to the Contractor the native CAD files (AutoCAD™ or Euclid 3™) of all the drawings attached to this Call for Tenders.

CERN will authorise the Contractor to access the CERN Drawing Directory (CDD) server. It will not be responsibility of CERN to transfer by any means these native files to the Contractor. CERN will promptly inform the Contractor about new releases of drawings available in the CDD server. An efficient Web connection to the CDD server will be necessary for sending and storing the Contractor's drawings at CERN. This is under the responsibility of the Contractor (see details in "Annex A" Section).

4.2.5 Approval of manufacturing drawings and technical specifications

The detailed manufacturing documents (in form of technical drawings and specifications) shall be submitted to CERN for approval (by electronic means). CERN will give its written approval or refusal within two weeks of receipt of the relevant technical documents. The manufacturing drawings and documents will be officially approved electronically and stored in the CDD Server by CERN. Component ordering and equipment manufacture shall not start before CERN's approval has been obtained.

4.2.6 Components supplied by CERN

CERN and the Contractor will review at regular intervals the planning for the supply of components and define the delivery schedule for the following six months. Please refer to the Contract for detailed stipulations about components supplied by CERN.

4.2.7 Qualification of tooling and manufacturing procedures

The Contractor shall implement, in agreement with the provisions of its Quality Assurance Programme, all measures necessary to qualify the suitability of tooling and manufacturing procedures. Whenever possible, functional tooling tests with dummy components shall be made and a sufficient number of sample assemblies submitted to non-destructive and destructive tests for the qualification of new tooling and/or manufacturing procedures.

The first acceptance and verification test(s) of large tooling (i.e. winding machines, curing presses etc.) shall be made using dummy cables. The procedure will be discussed case by case between CERN and the Contractor. Dummy cables are made of copper wires having the same diameter as the final strand and cabled in the same cabling machine as the final superconducting cable. All details concerning quantities and delivery dates shall be agreed with CERN.

The Contractor shall submit to CERN for approval, at least three weeks before their implementation, the above qualification procedures and their acceptance criteria and transmit to CERN the results of all the related shop-trials and bench-tests within two weeks of their performance.

4.2.8 Tooling inspection and maintenance

The Contractor shall carry out, in agreement with the provisions of his Quality Assurance Plan, a tooling calibration and maintenance programme. The aim of this programme is to guarantee that the tooling maintains its geometry and any other operational and functional properties necessary for its correct performance throughout the Contract performance.

The Contractor shall submit to CERN for approval an overall tooling inspection, calibration and maintenance schedule and inform CERN of the outcome of the actions undertaken in the completion of this schedule.

The Contractor shall inform CERN of the purpose and outcome of any major extraordinary operation on the tooling designed and procured by him within two weeks of its performance.

CERN’s approval shall be sought prior to any unusual operation on tooling and equipment provided by CERN.

4.2.9 Responsibility

The Contractor’s responsibility for manufacture/assembly is limited to the items and the sub-systems that are part of the supply (including all layouts, drawings, designs, specifications, reports, protocols, calculations and other documentation or information produced or prepared by him).

CERN assumes responsibility for performance parameters determined by CERN supplied items and sub-systems.

The Contractor shall be responsible for the correct performance of all items supplied by him, irrespective of whether they have been chosen by the Contractor or suggested by CERN. CERN's approval of the technical documentation and components does not release the Contractor from his responsibilities in this respect.

The Contractor shall take full responsibility for possible cold mass assembly faults as stated in Section 9 “Manufacturing tests and provisional acceptance at CERN”.

The Contractor shall be responsible for the tooling procured by CERN (see Annex E Section). This responsibility includes proper care during use, its maintenance, inspection and calibration necessary for the correct performances of the tooling. After the Contractor’s official acceptance of the CERN supplied tooling, the Contractor is not entitled to claim that CERN is responsible for possible technical problems and their consequences on the production planning arising from the use of this tooling.

Please refer to the Contract for the clauses detailing the Contractor’s and CERN responsibilities for the performance of the Contract.

4.2.10 Deviations from the Specification

CERN reserves the right to make minor modifications, e.g. fine tuning of component geometry and of assembly details, to this Technical Specification before the Contract is signed and also before the manufacturing drawings concerned have been finalised. These minor modifications will not entitle the Bidder to revise the tender price.

More substantial design modifications involving changes of materials and of assembly procedures may also be proposed by CERN and/or the Contractor following the results obtained on pre-series cold masses and other tests.

The positive or negative cost variations resulting from such possible modifications will be agreed by CERN and the Contractor.

4.2.11 Factory Access

CERN staff shall have free access to the factory, including any subcontractor’s premises, during the Contract period.

CERN will keep a resident inspector at the Contractor's premises. The role of this inspector does not include any decision taking concerning the manufacturing activities (See details in Section 8).

When possible, CERN will inform the Contractor about the visits of CERN staff with reasonable notice.

In particular, at the beginning of the production, CERN will ask to witness some critical operations (inspections, tests) during the cold mass manufacture at the Contractor's premises. CERN will indicate in due time which activities it intends to witness and the Contractor shall inform CERN at least 72 hours in advance about the execution date of the concerned activities.

The place of manufacture, as stated in the Technical Questionnaire, may be changed only after written approval by CERN.

4.2.12 Office space for CERN inspectors

The Contractor shall provide an adequate closed office space for the exclusive use of a resident CERN inspector and for CERN staff temporarily present at the Contractor's premises. This office space shall be equipped with at least two desks, two cupboards and a telephone line providing access (at CERN's cost) to an ISDN network, making it possible to deal simultaneously with phone calls, faxes and computer data exchange.

5. APPLICABLE DOCUMENTS

5.1 Standards

5.1.1 CERN standards

LHC Quality Assurance Plan Documents. These documents concern several aspects of Quality Assurance, and they are enclosed in Annex D.

5.1.2 International standards

The list in Table 5.1.2 is not exhaustive; it gives the standards presently referred to in this Technical Specification, for the purpose of the safety test on welded joints (see Annex B33). International standards are also referred to in the technical specifications of the components.

Table 5.1.2: List of applicable standards

EN 287-1:1992	Approval testing of welders for fusion welding. Steels
EN 288-3:1992	Specification and approval of welding procedures for metallic materials. Welding procedure tests for the arc welding of steels
EN 970:1997	Non-destructive examination of fusion welds. Visual examination
EN 1435:1997	Non-destructive examination of welds. Radiographic examination of welded joints
EN 571-1:1997	Non-destructive testing. Penetrant testing. General principles
EN 895:1995	Destructive tests on welds in metallic materials. Transverse tensile test
EN 10002-1:1990	Tensile testing of metallic materials. Method of test at ambient temperature
EN 876:1995	Destructive tests on welds in metallic materials. Longitudinal tensile test on weld metal in fusion welded joints
EN 875:1995	Destructive tests on welds in metallic materials. Impact tests. Test specimen location, notch orientation and examination
ISO 148:1983	Steel Charpy impact test (V-notch)
EN 10045-1:1990	Charpy impact test on metallic materials. Test method (V- and U-notches)
EN 910:1996	Destructive tests on welds in metallic materials. Bend tests
ISO 7438:1985	Metallic materials Bend test
EN 1321:1997	Destructive test on welds in metallic materials. Macroscopic and microscopic examination of welds
EN 10204: 1995	Metallic products – Types of inspection documents (includes Amendment A1)
EN 25817:1992	Arc-welded joints in steel. Guidance on quality levels for imperfections

5.2 Other references

For information, annex G contains a list of technical specifications for the procurement of components and tooling delivered by CERN. Technical specifications regarding the procurement of “pre-series” components presently under the responsibility of the Contractor are also attached.

6. TECHNICAL REQUIREMENTS FOR THE COLLARED COILS MANUFACTURE

6.1 Superconducting cables

6.1.1 General aspects

The dipole coils consist of two layers which are each wound with a different Rutherford type cable. The inner layer uses a cable (hereafter referred to as “Cable 1”) made of 28 NbTi composite coated strands of 1.065 mm diameter. The outer layer uses a cable (hereafter referred to as “Cable 2”) made of 36 NbTi composite strands of 0.825 mm diameter. The strands consist of NbTi filaments with a nominal diameter of 7 µm for Cable 1 and 6 µm for Cable 2, embedded in a copper matrix.

The values of the cable width given in Table 6.1.2 are the values precisely controlled during the cable production. When out of the cabling machine, these width tolerances increase to $15.10\,^{+0.08}_{-0.00}$ mm but experience has shown that the cable dimensions satisfy the requirements indicated in drawing LHCMB__A0002 under slight compression. The cables will be delivered in 4 unit lengths per pallet (a unit length is the length necessary to wind a layer). The Contractor shall establish the manufacturing plan such that the 4 unit lengths will be used in the same cold mass. Should one (or more) layer(s) be rejected during manufacture, CERN will choose one (or more) unit length(s) of equivalent characteristics.

The Contractor shall maintain the traceability of the cable used in each magnet, namely the batch delivery number and the cable identification code.

6.1.2 Cables

The superconducting cables will be provided by CERN together with test certificates. The main characteristics of Cable 1 and Cable 2 are given in Table 6.1.2, detailed specifications can be obtained on request. Annex C1 gives the list of measured characteristics given in a certificate of conformity. The Contractor shall send back to CERN, not later than 2 weeks after reception, a signed copy of the certificate of conformity as acceptance of the cable. Upon request, CERN will show the Contractor the quality assurance programme and the data of the cable fabrication.

Table 6.1.2: Characteristics of superconducting cables

	Cable 1	Cable 2
Width (during cable fabrication)	$15.10\,^{+0.00}_{-0.02}$ mm	$15.10\,^{+0.00}_{-0.02}$ mm
Mid-thickness at 50 MPa	1.900 ± 0.006 mm	1.480 ± 0.006 mm
Keystone angle	1.25 ± 0.05 degrees	0.90 ± 0.05 degrees
Transposition pitch	115 ± 5 mm	100 ± 5 mm
Number of superconducting strands	28	36
Minimum critical current at 1.9 K, with field normal to broad face	13750 A at 10 T	12960 A at 9 T
Minimum critical current at 1.9 K, of extracted strand	491 A at 10 T	360 A at 9 T
Residual resistance ratio	> 70	> 70
Transposition direction	Left-handed screw thread	Left-handed screw thread
Minimum unit length	448 m	740 m

6.1.3 Insulation of the cables

The cable insulation is designed to provide simultaneously the required electrical insulation level, allow for heat transfer (achieved by allowing superfluid helium to permeate the insulation and wet the conductors) and maintain the coil turns in their position.

Insulating the cables is under the responsibility of the Contractor and according to a procedure to be approved by CERN. The necessary polyimide tape (also called “film” in supplier’s documentation) will be provided by CERN according to the specifications in Annex C2.

Drawings LHCMB__0046 and LHCMB__0047 in Annex A give details of the cable insulation. It consists of three layers whose characteristics are given in Table 6.1.3.

Table 6.1.3: Characteristics of insulation layers

	Tape type	Tape thickness [µm]	Average tape width [mm]	Configuration (*)
Insulating layer 1	Polyimide	50.8 ± 3%	11.0 ± 0.10	gap $0.5\,^{+0.0}_{-0.4}$ mm pitch 11.3 mm
Insulating layer 2	Polyimide	50.8 ± 3%	11.0 ± 0.10	gap $0.5\,^{+0.0}_{-0.4}$ mm pitch 11.3 mm
Insulating layer 3	Polyimide with adhesive coating	68.6 ± 3%	9.0 ± 0.10	gap $2.0\,^{+0.2}_{-0.2}$ mm pitch 11.3 mm

(*) Values applicable at the steady state phase of the insulation process

Insulating layers 1 and 2 shall be wound from two diametrically opposed spools (the spools configuration is not represented in the drawings), so as to balance the force exerted on the cable by the wrapping tension applied to the polyimide tapes. The suggested wrapping tension is between 6 and 10 N.

The insulation layers 1 and 2 consist of overlapping the two 50 µm thick insulating layers by half their width (5.5 mm) so that a joined edge-to-edge insulation results (the cross-section resembles the insulation type 50 % overlapped).

The tape used for layer 3 is provided on one side with an adhesive coating, which becomes adhesive during a heat treatment at 190 °C, referred to as “curing” in paragraph 6.2.4. The insulating layer 3 tape shall be wound with its adhesive side on the outer surface of the insulated cable.

The cables shall be carefully cleaned on-line before wrapping the insulation. The cleaning operations proposed by the Contractor shall be laid down in a document (“Cable Electrical Insulation Procedure”) and submitted to CERN for approval. In particular, CERN will perform interstrand contact resistance measurements to ensure that the cleaning process does not deteriorate the cable electrical characteristics. Annex B4 gives some requirements for the cleaning process and other aspects to be taken care of during the cable insulation process.

Immediately after the wrapping of the first two layers, an on-line high voltage test shall be made for detecting insulation faults and their immediate repair. No more than one repair per cable unit length is accepted. Electrical tests during winding, the splicing of polyimide layers as well as the procedure for removing any insulation layer from a cable are detailed in Annex B7.

Should the partitioning the cable on a spool be required, each resulting shorter run shall be traceable with respect to its original spool and its position therein. Moreover, each new starting and finishing end shall be marked in blue and red colour, respectively, in the same direction as on the original length.

At the Contractor's premises, the insulated cable spools shall be stored in a temperature-and-humidity-controlled room prior to their introduction into the coil winding clean area, if they cannot be stored directly in the latter area. The storage conditions must comply with those laid down in Annex C2.

Each insulated cable length shall be delivered with a test protocol recording cable length, the references of the insulating tape reels used for each layer, the wrapping tension for each layer, the outcome of the electrical insulation tests, the details of any insulation repair, the date on which the cable insulation was completed, the number of and reason for the spooling and unspooling operations. The layout and content of any test protocol will be agreed between CERN and the Contractor before signature of the Contract.

6.2 Coils

6.2.1 General description

A twin-aperture dipole consists of two single dipoles, each around a beam channel. Each dipole has an upper and a lower pole which are identical. Each pole consists of a coil wound in two layers, called inner layer and outer layer, wound with Cable 1 and Cable 2 respectively.

The distribution of the cables in the two coil layers is shown on drawing LHCMB__A0002. The six sets of adjacent coil turns within the limits of the various copper wedges are defined as cable (or conductor) "blocks". The precise azimuthal and radial position of the cables/blocks is of the utmost importance for achieving the nominal magnetic field and its homogeneity in the beam channels.

The coil layers are separated by a 0.5 mm thick sheet made out of ULTEM™[2], which provides helium cooling channels (see drawing LHCMB__A0014). The layout of both layers combined is shown in drawing LHCMB__A0010, and of the two layers individually in drawings LHCMB__A0011, LHCMB__A0012. Please note that the plan views in all three cases show the coils with their curved end-parts developed on a plane. The longitudinal cross-section of the end parts is shown in detail in drawings LHCMB__A0028, LHCMB__A0029.

The interconnection of the two coil layers in the "layer jump" and "splice" regions is presented in the general assembly drawing LHCMB__A0001, in more detail in drawings LHCMB__A0022, LHCMB__A0023. A copper stabilising piece (see drawing LHCMB__A0048) is soldered to the inner layer cable. The assembly is bent to obtain the "S" shape using a dedicated mould. Finally, the outer layer cable is soldered to the inner layer cable, already provided with its own copper stabiliser. Details of the soldering operations are laid down in Annex B12.

Besides the conductors, each pole comprises four different copper wedges in the straight parts (drawings LHCMB__A0052, LHCMB__A0054, LHCMB__A0056, LHCMB__A0058) as well as 17 different "main" and 7 "chip" insulating end spacers in the curved parts. The copper wedges and the spacers are described in Annexes C3 and B6 respectively.

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[2] ULTEM is a trademark of General Electric, USA

6.2.2 Coil fabrication

The area where the coils will be manufactured is hereafter called “clean area”. It will have adequate air circulation, air filtration and an airlock access. The requirements of the clean area are described in Annex B3. No smoking, machining, welding or mechanical adjustment of metals is allowed in this area.

The general tooling necessary to wind a coil consists of:

- A table supporting the winding mandrel. For the winding of the layer ends, the mandrel shall be able to rock around its longitudinal axis, unless some other form of compensation in two axes is provided. Also a “pole” insert for the support of the end spacers shall be provided,
- A rotating support for the spool with the insulated cable and a brake which controls the tensile force on the spool. As the effective tensile force on the cable is variable due to cable sag and other effects, its precise value has to be determined during the winding of the first coil(s). All relevant factors shall be recorded for each turn in order to ensure the best possible repeatability for the subsequent series. In particular, the cable brake shall guarantee reproducibility of the tensile force of ± 15 N in the region 0 to 150 N, ± 20 N in the region 150 to 350 N and ± 30 N in the region between 350 and 800 N.

Continuous checking of the total electrical cable resistance and the insulation to ground of the coil during winding is required (see paragraph 6.2.7.1).

The two layers are wound and cured on different dedicated mandrels. A sorting strategy of the coils in the collared coil structure is given in Annex B13. This procedure shall minimise the effect on the field quality of systematic dimensions within tolerances but not nominal.

Mandrels and/or winding posts assembled from punched laminations shall be covered with a metallic protection sheet at areas in contact with the cable. In case of solid mandrel and/or winding post, the metallic protection sheet is not necessary.

6.2.3 Winding

Before winding, the mandrels, winding posts, protection sheets, screws, etc. shall be thoroughly cleaned and coated with an adequate “demoulding” agent. TEFLON™ [3] is the preferred substance which may however be banned by national legislation. In this case the Bidder shall propose a substitute product, for approval by CERN, that is compatible with the cable insulation and withstands temperatures up to 220° C.

Any component which may come in contact with the insulated cable must be carefully deburred to eliminate any sharp edge.

Winding of the inner layer starts at the “layer jump” where the electrical interconnection with the outer layer shall be made later. The cable end shall have been previously soldered to a copper stabilising support and bent using special tooling as detailed in Annex B12.

During winding, the conductors and spacers are maintained in place by tools designed for this purpose; in particular the conductor must always be clamped in place in the straight parts before winding the ends. Tooling for forming and pressing the conductors in the ends must also be used. The Contractor shall propose mechanical solutions meeting these requirements for approval by CERN.

[3] TEFLON is a trademark of Dupont De Nemours, USA

The conditions for winding the coils shall be those optimised during the manufacture of the pre-series units. All relevant winding parameters, such as the cable tension during all the winding phases, shall be presented and discussed with CERN for approval.

All the relevant winding parameters and measurements of each individual layer shall be recorded in the Traveller (as defined in Section 8.4).

The longitudinal copper wedges shall be insulated separately according to drawings LHCMB__A0051, LHCMB__A0053, LHCMB__A0055, LHCMB__A0057 and Annex B5. Insulating polyimide sheets and pre-formed caps protect the cable at the junction between the copper wedges and end spacers. CERN will provide polyimide insulating tape (the same as used for insulation of the cable). The pre-formed caps will not be provided by CERN.

The end spacers, chips and wedge-tips (see drawings LHCMB__A0011, LHCMB__A0012) and Annex B6 are made of EP-GC-22 (norm EN 61212-1) and ULTEM™ material. Their design provides an almost constant perimeter for the cable in order to minimise the deformation energy. As can be seen on drawings LHCMB__A0011, LHCMB__A0012, the cable blocks rest on the inner coil radius.

Before the end spacers are assembled in the coils, their surfaces in contact with the cables shall be covered with a thin layer of B-stage epoxy resin whose material specification is given in Annex B6. As described in this annex, it shall be applied with a properly controlled thickness in order to limit the obstruction of the helium cooling channels in the coil blocks.

CERN will ask for the measurement and recording of the inclination angle of the cable and its longitudinal position at the ends of the mandrel for each turn throughout coil winding in case of a change of components supplied either by CERN or by the Contractor.

Soldering of copper stabilisers to the cable ends according to Annex B12 and their insulation are the last steps of the winding procedure

6.2.4 Pressing and curing

6.2.4.1 Tooling

The curing press shall be capable of providing a force of at least 3300 kN per linear metre. Heating equipment is also needed allowing heating/cooling of the dedicated moulds up to 210 °C with temperature uniformity of at least ± 5 °C over a length of 15 m.

The mandrel, the winding posts and the moulds shall be of suitable geometrical accuracy to ensure tight and consistent tolerances in the finished coils. In case the Contractor needs to procure additional tooling for the purpose of the series production, its design shall be approved by CERN.

For the reception test of new tooling, temperatures and pressures will be recorded from an instrumented coil (or from the instrumented mould) during thermal cycles and at maximum temperature to demonstrate the homogeneity of the temperature distribution and of the coil size.

6.2.4.2 Pressing and curing operations

With the exception of some specific operations where temperatures above 200 °C are locally permitted for a short time (e.g. layer jump soldering as described in Annex B12), the cable shall never exceeds the threshold of 200 °C during curing or any other operations.

After winding, sizing bars are bolted to the two sides of the mandrel and pushed against the last turn of the layer. The sizing bar position shall be calculated also to accept oversized layers; for layers of nominal azimuthal dimension it shall be possible to insert shims of 0.5 mm thickness, coated with TEFLON™ (or other demoulding agent as explained in Section 6.2.3). If slightly different curing approaches are foreseen, they shall submitted as proposal to CERN and they shall have CERN approval prior to be utilised for the production of the coil layers.

The two outermost end spacers are put in place and pressed against the coil ends with the appropriate tooling. Step by step the winding tooling (or portion of it) is removed and replaced by the cover shell of the curing mould, previously sprayed with demoulding agent. At this stage of the process, the azimuthal length of the coil may be oversized by some millimetres. The covered coil and its mandrel are then inserted with care in the curing mould and the assembly thus formed inserted into the curing press.

The mould is first partially closed at room temperature. A phase of pressure and thermal cycles (as agreed between Contractor and CERN for the pre-series production) will then take place in order to settle the coils. The temperature is then gradually increased in the first warming phase by circulating heated oil through the tubes of the mould and mandrel. The pressure in the coil is increased from 10 to 80/100 MPa and then sizing is performed. Sizing can be performed at temperatures between 100 and 135 °C according to the gel point of the epoxy resin put on the end spacers. Subsequent phases of a further warming up, curing and cooling down complete the operation.

Table 6.2.4: Characteristics of the pressing/curing procedure

	Starting temperature	Final temperature	Maximum rate of temperature change	Duration	Pressure
Warming 1	Ambient	100/135°C	< 3°C/min	60 min	10 MPa
Sizing	100/135°C	100/135°C	None	30 min	70 to 100 MPa
Warming 2	135°C	190°C	< 3°C/min	30 min	10 to 20 MPa
Curing	190°C	190°C	None	30 min	< 80 MPa
Cooling 1	190°C	140°C	< 3°C/min	30 min	< 80 MPa
Cooling 2	140°C	Ambient	< 5°C/min	50 min	< 80 MPa

The mould gap, coil pressure and temperatures shall be controlled continuously and recorded together with the electrical resistance and inductance of the coil, “pressure” being understood as equivalent average stress on the flat plane of a layer whose width is about 2x15 mm. The temperature control during curing will ensure, in all phases, a maximum temperature difference between the left and right parts of the coil within ± 3 °C. The pressure difference shall stay within ± 5 MPa.

To monitor the reproducibility of the characteristics of the insulated cables through the curing process, tests with the mould of reduced length (150 mm) available from the pre-series production shall be scheduled at regular intervals.

For layers wound with cables from the same cable supplier, a test for the inner and outer layer shall be carried out every 20 cold masses. The cable for these tests will come from the parts left after the coil winding. The samples will be numbered, dated, measured and stored.

All data of the test shall be carefully recorded and communicated to CERN for information and analysis.

The same tests shall be carried out before winding layers with cables from a different cable supplier.

6.2.5 Surfacing the layer ends

When the cured layer is extracted from the press and from the top mould, the cover shells are removed from the heads of the winding. The conductor insulation shall be tested according to the procedures laid down in Annex B10. In case of failure, the repair procedure (if possible) will be established case by case in agreement with CERN.

At the ends of the layer, the outer radii of the cables differ from those in the straight section due to the inclination of the cables (see drawings LHCMB__A0011, LHCMB__A0012). The space between the conductors and the theoretical external layer radius shall be filled, after passing the electrical tests, with charged epoxy resin according to the specification in Annex B8.

6.2.6 Pole assembly

Insulating spacers made of ULTEM™ according to drawing LHCMB__A0014 and Annex B11 separate inner and outer layers. Two sets of distribution channels oriented at + 45 degrees on the front and at – 45 degrees on the reverse side ensure adequate helium flow. The spacers have reference pleats resting on the inner coil layer to facilitate the positioning.

Each outer layer is assembled on top of each inner layer. Close matching between the two layers is essential and shall be achieved, as far as the number of produced layers permits, by pairing units having similar azimuthal dimensions and elastic moduli within the tolerance limits. The two layers are then connected in series by soldering the cable end of the inner layer (already equipped with copper stabiliser) to the cable end of the outer layer at the so-called "splice" region. Special tooling is required to keep the parts in place during the soldering operation that shall be performed according to the specification given in Annex B12. The resulting splice is finally insulated, together with the layer jump, with the same type of insulation as the cables, or with a pre-impregnated ("prepreg") insulation type as presented in Annex B12. The Bidder will indicate the preferred option. The final choice shall be approved by CERN.

6.2.7 Electrical and mechanical tests

6.2.7.1 Short circuit detection during winding and curing. First high-voltage tests on finished layers

The DC resistance of the total cable length and the electrical insulation of the layer shall be continuously monitored at low voltage so that any short circuit between turns or from a layer to ground can be detected and repaired. The detection system for interturn short circuits shall be able to detect a 5 mΩ variation in the DC resistance of the cable. The system proposed by the Bidder shall be approved by CERN. After the curing of a layer, a high-voltage insulation test shall be carried out according to Annex B10. Acceptance is given by comparison with a reference coil.

6.2.7.2 Mechanical tests

The layer and pole size and the apparent elastic modulus shall be measured according to Annex B9 with the equipment defined in Annex E1.

The layer and pole deformation is recorded continuously during a controlled pressure cycle. At least three settling pre-cycles shall be performed before the measurement cycle begins. For each layer and pole, the difference between the average azimuthal size and the minimum and maximum size must stay within ± 0.05 mm. The average values shall be consistent with the drawings of Annex A (tolerance ± 0.03 mm). The data obtained are the basis for evaluation of the required pole shim thickness. The ultimate aim is to achieve an azimuthal dimension satisfying the field quality requirements within the admissible coil pre-stress range.

6.2.7.3 Electrical checks on the finished layers and poles

After the completion of the assembly and of the mechanical tests of a pole, the pole ends and the layer jump/splice region are placed on a insulating support in order to perform a second series of electrical tests, this time under pressure (see Annex B10). The same requirements concerning conducting/magnetic material, as specified in Annex E3, apply to assure the quality of the measurements performed under pulsed or AC conditions. The self-inductance and the coil resistance shall be measured with the instruments listed in Annex E2. A turn-to-turn short circuit test is then performed by measuring the damping of an oscillating current in the coil. The acceptance is given by the comparison with the reference coil. Full details are given in Annex B10.

6.3 Collars

The collars clamp together four poles (each consisting of a pair of inner and outer layers) to form a twin dipole. The collars are described in Annex C6. Collars of the following types will be delivered to the Contractor:

- Collars “type A”, divided into “subtypes A1 and A2”, covering the straight region of the coils,
- Collars “type B”, divided into “subtypes B1 and B2”, covering the end regions of the coils over a length of about 190 mm,
- Collars “type C”, divided into “subtypes C1 and C2”, covering a length of about 300 mm in the layer jump and splice region.

Short packs of about 30 mm length are formed with collars of the subtypes 1 and 2 respectively, placed in alternate positions and fixed by four short stainless steel rods to facilitate the subsequent collaring process.

An alternative technique consists in coupling subtypes 1 and 2 collars in pairs.

The axial position and adequate helium flow between collars are ensured by the embossed surface of the subtype 2 collar.

6.4 Coils/Collars assembly

6.4.1 Assembly of poles, quench heaters, ground insulation of the coils, shims

The four poles (each one assembled as describe in Section 6.2.6) will be assembled in couples around the cold bore tubes using the same bench utilised later for the positioning of the ground insulation, coil protection sheets and collars. The outer layers of each assembled pole will be equipped with quench heaters according to drawing LHCMB__A0021. Their basic assembly consists of thin heating strips as active elements, sandwiched between two wider polyimide films according to Annex B14 and drawings LHCMB__A0025, LHCMB__A0026 (these drawings will be updated with the delivery of the quench heaters technical specification for the series production attached in Annex G2) . The quench heaters will be of uniform width, with the correct size for utilisation along the straight part of the coil.

At the coil extremities, the Contractor shall adapt the ground insulation in the region of the quench heaters in order to guarantee the mandatory layout of insulation layers. Along the straight part of the coil, the quench heaters shall be creased, by the Contractor, with about a 90 ° bend. For creasing, a hot process is recommended by the quench heaters supplier in order to avoid microcracks. The Contractor is free to suggest an alternative method that guarantees the sharpness and long-term integrity of the crease; the final process shall be agreed with CERN. The Contractor shall provide all necessary tools, heaters and moulds for the cutting and creasing processes.

The electrical terminals of the quench heaters on the connection side shall be located in grooves machined into the end spacers of the outer layer. On the non-connection side the wires bridging the quench heaters will be housed inside grooves machined in EP-GC-22 pieces (see drawing LHCMB__A0043).

Electrical insulation between the poles and collars is provided by four sheets manufactured from 125-µm thick polyimide film according to drawing LHCMB__A0021 and Annex C10. This polyimide film will be supplied by CERN. The ground insulation sheets shall be cut to size as well as pre-formed and creased by the Contractor, who shall provide all necessary tools, heaters and moulds as above. The sheets shall be arranged such that at any location there are at least 3 insulating barriers between the poles and ground.

Details of the insulation at the coil heads and coil terminals are shown in drawing LHCMB__A0020, LHCMB__A0024.

Pairs of overlapping coil protection sheets made of austenitic steel (see Annex B14) prevent damage to the coil ground insulation at the outer interface with the collars. In preparation for collaring, surfaces shall be coated with an antifriction agent whose composition shall be approved by CERN.

Special attention shall be paid to the execution and checking of the ground insulation around the layer jump, the splice joining the two layers and the coil ends.

6.4.1.1 Collaring shims

The inner layer shims are placed inside the shim retainers positioned at the inner layer pole edge. The outer layer shims are positioned at the outer layer pole edge. Shim configurations at the coil ends and at the layer jump differ from those in the straight part. The Contractor shall provide written procedures for the determination of the shims thickness.

The collaring shim thickness is likely to be used for the fine-tuning of the magnetic field quality of the collared coils. The collaring shim calculation and choice shall be done, by the Contractor, following the instruction given in the Annex B17.

6.4.2 Collaring

Pre-assembled packs of collars or pairs of collars are placed around the two insulated single coils, starting at the layer jump. The assembly operation is performed carefully in order not to damage the ground insulation. At the “return” end of the straight part, the length of the collar blocks is adapted to the actual length of the coils. After all the collars have been placed around the coils, the electrical insulation between upper and lower poles, between poles and ground and between coils and quench heaters shall be verified in accordance with Annex B10. At this stage, the collars are not closed owing to the oversized dimensions of the coils that are not yet under compression.

The coil/collar assembly is introduced into a collaring press in which precise mechanical references will ensure the vertical alignment of the upper and lower collars during the collaring and the horizontal alignment of the whole.

The collaring shall be performed in several steps, starting with a pre-stress phase when the collars are only partially closed and increasing up to a pressure where temporary locking rods of reduced diameter can be inserted into the stack. A phase of pressure cycles (as agreed between the Contractor and CERN for the pre-series production) will then take place until the introduction of the final nominal rods (see details in Annex B16).

Metallic expandable mandrels may be inserted inside the cold bore tubes during the collaring, in order to avoid excessive deformation of the tubes in the layer jump region.

Before and after completion of the collaring operation, the Contractor shall check the inside diameter of the cold bore tube along its entire length with “go” plug gauges in order to measure the diameter of the bore. At any location along the entire length of the cold bore tubes, the inner diameter shall be larger than or equal to 49.65 mm.

The insulated cold bore tube is described in Annex C7.

Full closure of the collars is achieved in one operation where the thinner locking rods are subsequently replaced by the definitive ones as detailed in Annex B16.

A dedicated set of collaring tools is required to transmit the forces between the collaring press and specific points of the collars at each step of the procedure.

During the increase of the collaring pressure, the displacements of the upper beam, with respect to the lower beam, shall be measured and recorded for at least 6 points along the beams, and low-voltage tests of interturn and ground insulation performed together with inductance measurement

In case of re-collaring (owing to possible faults or repairs) the quench heaters, ground insulation, coil protecting sheets and shim retainers shall be changed. The fore mentioned parts shall not be reused after a failed collaring.

End plates shall be screwed on the assembly after the collaring operation is completed. The orientation of the apertures shall be marked on these end plates (see drawing LHCMB__A0009).

The finished collared coils assembly is shown in drawing LHCMB__A0001.

6.4.3 Tests after collaring

Electrical and mechanical tests as detailed below shall be performed after collaring and their results documented in adequate protocols.

6.4.3.1 Electrical tests

The following electrical parameters shall be measured according to Annex B10, with the acceptance criteria mentioned in brackets [].

- coil DC resistance [comparison with reference coils],
- coil impedance at several frequencies [comparison with reference coils],
- capacitance of quench heaters to ground and to coils [acceptance value],
- isolation resistances [acceptance values],
- leakage currents under high voltage [acceptance value],
- pulse responses (interturn insulation test) [comparison with reference coils].

6.4.3.2 Dimensional measurements

The following dimensions shall be measured according to Annex B9:

- deformation of the collars, measured in the horizontal and vertical planes. The nominal increase of the dimensions 3-3 and 7-7 in Figure B9.1 of Annex B9 (corresponding to the pre-stress given in Annex B17) is Δ 3-3 and Δ 7-7 = 0.25 mm. These Δ 3-3 and Δ 7-7 are the difference between the size at the requested pre-stress and the size at zero pre-stress. The tolerance on these values is ± 0.05 mm,
- length of the collared coil,
- "go" gauge in cold bore tubes (inner diameter ≥ 49.65 mm, see Annex C7).

Full details are found in Annex B9.

6.4.3.3 Warm magnetic measurements

Considerations about field quality and the admissible figures are given in Annex B1. The magnetic field properties of the collared coils shall be measured at ambient temperature and low current, using test equipment provided by CERN. The Contractor shall provide adequate infrastructure and construct the necessary non-magnetic support (see Annex E3).

The warm magnetic measurements as detailed in Annex B18 shall be fully performed by Contractor's personnel, after an initial training by CERN staff.

6.4.4 Additional measurements by CERN personnel

CERN reserves the right to measure, at the Contractor's premises, additional electrical/magnetic/mechanical properties of the collared coils or parts thereof, as deemed necessary within the scope of the Contract.

7. TECHNICAL REQUIREMENTS FOR THE COLD MASS ASSEMBLY

7.1 General description

Assembling the cold mass begins with a set of collared coils; i.e. two dipole coils clamped in non-magnetic collars. Each dipole aperture is equipped with its own cold bore tube.

During the operations that constitute the cold mass assembling, all parts, either sub-assemblies or single components (e.g. collared coils, austenic stainless steels half-cylinders, end plates, end covers, helium heat exchanger tube) are fitted together following particular procedures and requirements as described in the following sections. Mandatory electrical checks and inspections during the different assembly steps are described in Annex B22.

First, all the cold mass sub-assemblies have to be prepared and checked on appropriate workstations in view of their final integration into the cold mass assembly. These sub-assemblies are the collared coils, the half-yokes and the yoke insert packs. The half-yokes and the yoke insert packs are assembled as described in Annexes B20 and B21. The corrector magnets and the busbars will be provided by CERN in the form of sub-assemblies ready for mounting and for electrical connection. The cold mass assembly is equipped with three families of busbars, including:

- the dipole busbars,
- the quadrupole busbars,
- the auxiliary busbars.

There are two types of dipole busbars and two types of quadrupole busbars. These different types of busbars are defined in Annex C10.

Following the cold mass manufacturing process flow diagram (as presented in Annex B34), end plates shall be fitted and temporarily fixed on the collared coil ends. At this stage, the electrical connections can be shaped and some can be soldered as described in Section 3 of Annex B28. At another workstation, the defocusing quadrupole busbars are fitted in the slot of the lower half-yoke and the assembly is covered with the lower half-cylinder before being turned upside down (the half-cylinders shall be previously prepared as described in Annex B24). The assembly, so obtained, is transferred to the intermediate beam of the welding press, in the lower cradles. By using a special lifting jig, the collared coils are placed together with the yoke inserts in the lower half-yoke. The upper half-yoke is then lowered around the collared coils. The focusing quadrupole busbars and the dipole busbars are installed in the upper half-yoke slots. Finally, the upper half-cylinder is placed over the upper half-yoke.

Following these operations (described in Annex B25), which will be referred hereafter to as “yoking”, the “active part” is obtained. The intermediate beam and the active part assembly are moved into the welding press for the longitudinal welding of the two half-cylinders under load. Before the welding, the active part is pushed against a curved jig (top cradles and thickness wedges attached to the upper beam of the welding press), so that the nominal horizontal curvature and sagitta are obtained after welding. The procedure is described in Annex B26.

The active part “as welded” is then moved to another workstation where the instrumentation is installed, the remaining electric connections made, and the corrector magnets fitted and aligned according to the requirements of Annex B28, Section 6. For the performance of the cold tests at CERN, (see Section 9.2), the two dipole busbars, i.e. the right and the left ones, shall be short-circuited at their extremity on the connection side. The end covers shall be positioned and welded according to the requirements of Annex B29. The cold bore tubes are also aligned and welded to the end covers.

Finally, all the ancillary parts shall be fixed on the shrinking cylinder and on the end covers. These include: the cold mass support bases, the supports for the auxiliary busbars tube (“line N”), the interconnection bellows, the instrumentation wiring carried out through the Instrumentation Feedthrough System (see Annex B30), the diode stack in its container with the welded cover (see Annex B31), thus closing the cold mass envelope, ready for the final leak and pressure tests.

An inspection and test plan is necessary to ensure that the main parameters, defined in Section 7.2, are correctly controlled during the various stages of the manufacture.

CERN reserves the right to require the Contractor to modify the various assembly and inspection procedures (see Section 4.2.10), in order to improve or optimise them. This concerns in particular the inspection procedure of the active part geometry as well as the alignment operations, which are performed when the cold mass is completed.

7.1.1 Cleanliness requirements

Contamination of the cold mass (e.g. by projections of filler metal, pickling products, chips and swarf from mechanical operations necessary on the magnet extremities, debris of ground insulation like polyimide that might be trapped inside the assembly, etc.) shall be avoided by all possible means.

7.2 The main parameters

The main parameters governing the correct assembly of the cold mass are presented here. These parameters can be classified in two categories, the structural aspects (see Section 7.2.1) and the geometrical aspects (see Section 7.2.2.). A more detailed description of how these parameters are involved in the assembly process is given in the corresponding procedures and attached documents of Annex B.

The main parameter defining the correct assembly of the half-yoke is the stacking factor defined in Section 7.2.4.

The 1.9 K operating temperature of the LHC machine implies that the cold mass is filled with a static bath of pressurised superfluid helium and is surrounded by an insulating vacuum. Therefore, the cold mass envelope shall be leak-tight. The relevant requirements are defined in Section 7.4.

7.2.1 Structural parameters

7.2.1.1 Yoke-gap

The nominal sizes of the yoke laminations and collared coils are such that during the assembly, the yoke-halves are separated in the vertical plane by a gap. The nominal value of this gap varies linearly from the innermost point in contact with the separate inserts, where it is 0.24 mm, to the outermost point in contact with the shrinking cylinder, where it is 0.46 mm. These gap values occur provided that there is no strain in the unloaded assembly, i.e. before loading and welding the half cylinders.

After the longitudinal welding of the half cylinders, this gap shall be completely closed. A minimum mating force of 0.1 to 0.2 MN/m [4] will be induced in the area of the inner contact surface (below the hole of the heat exchange tube) and of 0.2 to 0.3 MN/m in the area of the outer contact surface (above the hole of the heat exchange tube).

7.2.1.2 Pre-stress in the shrinking cylinder

The half-cylinders shall be longitudinally welded around the yoke so that the final average circumferential pre-stress, after welding, is at least 150 MPa (for a shrinking cylinder with the nominal wall thickness, i.e. 10 mm). For safety reasons, the maximum values of the pre-stress in the region close to the weld shall be limited to 250 MPa. The leading parameters (press load, half-circumference of the shrinking cylinders, etc.) making it possible to obtain the right pre-stress shall be those determined during the manufacture of the pre-series cold masses.

7.2.2 Geometry

In order to provide the largest possible mechanical aperture for the LHC beam inside the cold bore tubes, the cold mass geometry, and more precisely the active part geometry, shall be controlled with great care. The arc dipole magnets shall be curved in the horizontal plane of the machine. The small aperture of the dipole coils (∅ 56 mm) and the resulting inner diameter of the cold bore tube (∅ 50 mm) imply an accurate control of the cold mass bending radius and vertical straightness in order to minimise the possible loss of aperture.

Only the portion of the active part whose length corresponds to the magnetic-length of the coils shall be curved with the nominal bending radius. The two apertures, i.e. the two coils, shall have the same bending radius. Therefore, the theoretical geometric axis of each aperture is to be curved along an arc-length that equals the magnetic-length [5] of the coils, i.e. 14343 mm at room temperature. This central region will be referred hereafter to as the “arc”. Beyond this arc, the theoretical geometric axis of each aperture is prolonged along the local tangent to the arc. These extremities will be also referred hereafter to as the “straight ends”.

The end covers, which belong to the straight ends shall be aligned with respect to the straight ends of the theoretical geometric axes so that the reference planes “C” and “L” (see Drawing LHCMB__S0001) of two adjacent magnets are strictly parallel. It will thus be possible to make straight junctions in the interconnection region between adjacent magnets. In particular, the cold bore tube extremities, i.e. the sections that are butt-welded to the interconnection bellows, shall be positioned with their axis at the nominal separation of 194.52 mm.

7.2.2.1 Reference co-ordinate system

It is assumed that the axes of the cold bore tubes represent the beam trajectories which is equivalent to assuming that the cold bore tubes axes and the magnetic axes [6] are identical. Owing to manufacturing tolerances and assembly clearances (the radial clearance between the cold bore tube and coils for instance), this may not be the case.

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[4] MN/m denotes the unit for the mating force per magnet length

[5] The magnetic-length of a dipole is defined as follows: Lm = $\frac{\int_{-\infty}^{+\infty} B(s).ds}{B_0}$, where Bo is the main field in the central part.

[6] The magnetic axis of the dipole magnet is determined by a Quadrupole Configurated Dipole (QCD) measurement as mentioned in Annex B27, Section 3.

Therefore, the actual geometric axes of the cold bore tubes will differ to some extent from the trajectory imposed by the magnetic field. The correlation between the magnetic and the geometric axes will be determined by CERN from the beginning of the cold mass production and it is expected that only geometric parameters will be considered for the alignment procedures described in Section 7.2.3.

The cold mass geometry has to be measured in a rectangular Cartesian co-ordinate system. These measurements shall include the vertical straightness and the horizontal curvature of the active part as well as the final positioning of the corrector magnets, of the end covers, of the cold bore tubes, of the cold mass support bases and of the supports of the N line. CERN has provided the Contractor with an optical device (a Laser Tracking System, see Annex E5) for making the requested measurements. A mechanical probe (supplied by CERN) centred inside the cold bore tube and equipped with a reflector allows the Cartesian co-ordinates of the cold bore tube centre to be picked up. More details about the measuring procedure are given in Annex B27.

7.2.2.2 The concept of "global tolerance range"

The theoretical figure that represents the nominal geometry of the active part (prolonged by the cold bore tubes' extremities) is constituted by the theoretical geometric axes of the two coils as illustrated in the reference drawing LHCMB__S0001. These theoretical geometric axes lie in a perfect plane, which will be referred hereafter to as the datum plane of the cold mass or simply the plane V1-V2.

The "global tolerance range" denotes the shape tolerance requested on the cold mass geometry, as built. It shall include any defect of the cold mass shape, which may arise from defects in its vertical straightness, horizontal curvature and/or sagitta. The global tolerance range is defined by a set of 2 toroidal sectors of circular section and of 4 straight cylinders, which are all centred on the theoretical geometric axes.

In the arc, each toroidal sector is generated by the displacement of a circle along a circumference with a radius of 2812.36 m (at 293 K). The radius of the generating circle is 1 mm. In the straight ends, straight cylinders oriented along the local tangent to the arc extend the toroidal sectors. The radius of these straight cylinders equals 1 mm as in the curved section. The combination of a toroidal sector and two end cylinders gives the tolerance range for the geometric axis of an aperture. The tolerance ranges of the two apertures are not independent. The axes of the two tolerance ranges as defined here above shall be taken to lie in the datum plane of the cold mass, 194.52 mm apart (293 K value).

7.2.2.3 Vertical straightness

The term "vertical straightness" denotes the straightness of each cold bore tube in the vertical plane. Any defect of straightness may result from a defect of the half-cylinders "as built" but there will always be a deflection of the cold mass due to its own weight. The vertical straightness shall be controlled so that the geometric axes of the cold bore tubes are included in the global tolerance range.

7.2.2.4 Radius of curvature

The parameter "R" denotes the radius of curvature in the horizontal plane of each coil (Dipole I for Aperture I, which is the outermost one and Dipole II for Aperture II, which is the innermost one, see drawing LHCMB__S0001). The radius "R" of each aperture equals 2812360 mm (measured at 293 K). The centres of curvature of each aperture are 194.52 mm apart (at 293 K).

The apical angle of the arc, which includes the curved part of the active part, equals 5.099988 mrad. The apical angles of the two apertures are identical (this angle does not change with the variation of the cold mass temperature).

The global curvature of the cold mass, i.e. the global curvature of the active part “as built” from the longitudinal welding in the welding-press shall be such that the actual geometric axes of the cold bore tubes are within the global tolerance range.

7.2.2.5 Sagitta

The sagitta is a consequence of the above mentioned definitions of the bending radius and apical angle. It denotes the middle deflection of each aperture in the horizontal plane. The sagitta that corresponds to the theoretical magnetic length is equal to 9.14 mm. As a consequence of the definition of the Global Tolerance Range, the tolerance on the sagitta value shall be ± 10 %. (A similar relative tolerance was achieved on the dipole magnets for the RHIC project at BNL).

7.2.2.6 Twist

After the completion of the cold mass assembly and welding, the geometric axes of the two cold bore tubes may not lie in a perfect plane. At any point along the arcs and the straight ends of the cold mass, the local twist [7] shall be within ± 3 mrad relative to the plane containing the theoretical geometric axes V1 and V2. The average tilt shall stay inside ± 1 mrad.

7.2.3 Alignment

7.2.3.1 Corrector magnets alignment

The corrector magnets, both the sextupoles on the connection side and the octupoles/decapoles, when applicable, on the lyre side, shall be positioned with respect to the straight ends of the theoretical geometric axes to within ± 0.3 mm.

7.2.3.2 End cover alignment

The end covers shall be positioned and welded on the shrinking cylinder extremities so that the following conditions are simultaneously fulfilled:

- The reference plane “A” shall be localised within ± 0.5 mm with respect to the plane V1-V2. This requirement defines, implicitly, the parallelism of the plane “A” with respect to the datum plane V1-V2,
- The reference plane “C” on the connection side and “L” on the lyre side shall be perpendicular to the straight ends of the theoretical geometric axes V1 and V2, within ± 0.1 mm,
- The reference plane “B” shall be localised within ± 0.5 mm with respect to the symmetry axis of the cold mass, “W”.

Please also refer to the drawings LHCMBB_S0001, LHCMBB_S0002, LHCMBB_S0003, LHCMBB_S0004, LHCMBB_S0005 which illustrate the above-mentioned requirements for (as an example) the “full test configuration” of a “Type B” cold mass.

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[7] The local twist is calculated as follows: $T = \frac{Z_{II} - Z_I}{X_{II} - X_I}$, where ($X_I$;$Z_I$) and ($X_{II}$;$Z_{II}$) denote the Cartesian co-ordinates of aperture I and aperture II, respectively. The twist will be positive when the apertures twist counter-clockwise for an observer looking the cold mass from the connection side.

7.2.3.3 Cold bore tube alignment

The end section of each cold bore tube where it is welded to the interconnection bellows, shall be localised with respect to its nominal position, which shall be on the theoretical geometric axis, within 0.3 mm of radius.

Please also refer to the drawings LHCMBB_S0008 and LHCMBB_S0010 for (as an example) the “Full test configuration” “Type B” cold mass.

Special attention shall be paid to the procedures for welding the cold bores to the end covers in order to minimise the radial shrinkage in the section of the welding.

7.2.4 Stacking factor

Each cold mass shall contain a minimum volume of helium serving as heat transfer medium. This helium also acts as a thermal buffer when the magnet current is ramped up or down.

In order to optimise the helium content (for thermodynamic and hydraulic reasons), the yoke laminations are provided with passages of appropriate sizes and the yoke packs are made according to a stacking procedure allowing enough free space for helium between adjacent laminations.

In addition, the magnetic length at cold shall be controlled with a precision of ± 15 mm. Therefore, the magnetic length at 1.9 K should be 14300 mm ± 15 mm. The yoke itself contributes at the injection field for about 17 % of the field strength. Therefore, the length of the magnetic lamination assembly of the yoke, which is theoretically 13554 mm according to drawing LHCMB__A0003, shall be adjusted on the basis of the warm magnetic measurements in order to fine-tune the integrated field, i.e. the magnetic length. Please refer to Annex B19.

The above-mentioned requirements imply a stacking factor of 98.5 % ± 0.25 % (98.25 % ≤ stacking factor ≤ 98.75 %).

The “stacking factor” denotes the ratio between the mass of the half-yoke as fabricated and the mass of a solid half-yoke with the same external dimensions and material.

More details about the requirements concerning the manufacturing procedure of the yoke are given in Annexes B20 and B21 entitled respectively “Half-yoke assembly” and “Packing of the insert laminations”.

7.2.5 Cold mass warm magnetic measurements

The cold mass shall be subjected to warm magnetic measurements according to Annexes B18 and B1. These tests must be successfully passed for the acceptance of the cold mass.

7.3 Cold mass instrumentation and wiring

The standard instrumentation of the series cold masses consist of:

- voltage taps (14) on the cold masses type A (50 % of the total cold mass number) to detect quenches of dipole windings and make diagnostics of spool pieces (sextupole and decapole/octupole) and diode stack,
- voltage taps (10) on the cold masses type B (50 % of the total cold mass number) to detect quenches of dipole windings and make diagnostics of the spool pieces (sextupole) and diode stack,
- current taps (2) to test the protection diode stack with short current pulses. The installation of the diode stack current taps is part of the scope of the supply,

- current taps (2) to allow magnetic axis measurements (QCD configuration),
- temperature sensor (1) at the centre of each cold mass,
- cryogenic heater (1) at the bottom on the connection side end plate.

Their location is shown on drawings:

   – Voltage taps designation and location (see drawings LHCMBA_A0003 and LHCMBB_A0003),
   – Electric connection of voltage taps (see drawings LHCMBA_E0005 and LHCMBB_E0005),
   – Location and wiring of diagnostic equipment (see drawing LHCMB__A0156),
   – Cold mass: out going wires (see drawing LHCMB__A0155).

A more detailed description of the instrumentation, its wiring and instructions for its implementation and testing are given in Annexes B23 and C16.

7.3.1 Voltage and current taps

Voltage (or current) taps are located as follows:

- at the terminals of the two dipole coils (6),
- at terminal A of the spool pieces (one tap per spool piece, 6 for cold mass type A, 2 for cold mass type B),
- at the terminals of the protection diode stack (2 voltage taps),
- at the busbars interconnections (2 diode stack current taps),
- at the terminal of Dipole 1-upper coil and Dipole 2-lower coil to perform the QCD measurements (2).

Each voltage tap is equipped with a single connection wire.

CERN will supply the voltage and current taps for the cold masses.

7.3.2 Temperature sensors

The temperature sensors will be procured and calibrated individually by CERN. Their mounting instructions are given in Annex B23. Each temperature sensor requires four connecting wires.

7.3.3 Wiring

Wiring is required for the above mentioned instrumentation (Section 7.3) and for the 8 quench heaters (2 wires each). The wire cross-section, material and insulation depend on the application.

The number, type, characteristics of the wires and of their insulation are given in Annex C16; the wiring paths and details are shown in the drawings quoted above. CERN will supply these wires.

7.3.3.1 Instrumentation Feedthrough System

The Instrumentation Feedthrough System (IFS) is essentially an electrical communication path from the inside of the dipole cold mass envelope to the outside of the cryostat. The extension to the cold mass, hereafter referred to as the “IFS tube” consists of a stainless steel tube with specific end flanges through which run the 40 (dipole type A) or 36 (dipole type B) instrumentation wires.

The installation of the IFS tube has to be done during the cold mass manufacturing. A full description of the IFS (of which the components are under responsibility of the Contractor) is given in Annex B30.

7.3.4 Installation of the protection diode stack

After the welding of the end covers, during the final assembly and electrical connections, the protection diode stack shall be mounted in its casing which has been previously fixed on the cold mass envelope and then welded on the end cover (see Annex B31).

7.3.5 Modifications to instrumentation, its layout and wiring; final layout

CERN reserves the right to ask for modification of (or implementation of additional) instrumentation and wiring. The corresponding additional material and manpower costs will be determined in agreement with the Contractor.

7.4 Leak tightness

In operation, the cold mass envelope contains a static bath of pressurised He II, which, owing to its very low viscosity, may penetrate the smallest channels. The shrinking cylinder and end covers are thermally isolated from the ambient by the cryostat insulating vacuum (10-6 mbar) whilst the cold bore tubes separates the helium volume from the ultra-high-vacuum allowing the particle beam to circulate freely.

The cold mass envelope shall therefore be leak-tight with respect to ultra-high-vacuum. The leak tightness shall be checked at room temperature after completion of the cold mass assembling. This test shall be performed in conjunction with the final pressure test.

Acceptance criteria for the room temperature leak test performed at the Contractor's premises (as provisional acceptance leak test):

1) Cold mass to insulation vacuum $\leq 1{\cdot}10^{-10}$ Pa·m^3/s
2) Cold mass to beam vacuum $\leq 1{\cdot}10^{-11}$ Pa·m^3/s
3) Cold mass to heat exchanger $\leq 1{\cdot}10^{-6}$ Pa·m^3/s
4) Heat exchanger to insulation vacuum $\leq 1{\cdot}10^{-10}$ Pa·m^3/s

At the Contractor's premises, the "Cold mass to insulation vacuum" test shall be performed together with the pressure test that serves safety purposes. In this way simplified procedures and an improvement of the leak rate sensitivity are made possible.

The cold mass shall be introduced into a vacuum vessel and shall be pressurised with clean helium gas (purity of He $\geq$ 95 %) up to 26 bar (absolute pressure). The pressure test is then performed on the cold mass and measuring the global leak rate towards the vacuum vessel performs the leak test.

The Contractor shall decide whether it is convenient for its testing procedures to perform any of the other three above mentioned specified leak tests at the same time.

The Annex B32 "Room temperature vacuum leak testing", describes the cold mass leak test.

7.5 Safety requirements

This Section with the Annex B33 "Safety Tests", describes the safety aspects concerning the cold mass and its assembly.

CERN's status as an International Organisation allows the Organisation to establish, in the cases not covered by European or Host States regulations, its own safety rules and directly to review and approve the structural safety of the equipment to be installed. This means that the Contractor is not asked to obtain formal certification from his national authorities for matters pertaining to the safety aspects of the cold masses.

The set of structural safety requirements listed in this Technical Specification results from a thorough review of the structural reliability and safety of the dipole cold mass envelope.

The dipole cold mass can work, in certain circumstances, as a pressure vessel, although its operational conditions do not allow it to be considered as a conventional pressure vessel according to the European Directive 97/23/EC. The set of structural safety requirements listed in this Technical Specification have been established in order to guarantee that the dipole cold mass structure is sound in all operational conditions including those arising from its operation as a pressure vessel.

The Contractor shall on his own responsibility, undertake a series of inspections to ensure the necessary manufacturing standards. Such inspections are mainly concerned with the quality of the materials used and verification of the welding procedures. Non-destructive testing shall be conducted to verify the quality of the assembly work. Test pieces needed for destructive testing shall also be manufactured. These examinations shall be supplemented by a pressure test on the finished product.

A recognised inspection authority (third party) appointed by the Contractor and approved by CERN, shall be in charge of the inspection operations defined in the Annex B33.

In addition to the inspections and tests, the inspection body shall take part with CERN in:

- the qualification of the various welding procedure,
- the qualification of the welders and of the operators.

CERN reserves the right to modify at any time the number and type of inspections and tests related to safety matters, depending on the results obtained during the production and in case of doubt.

CERN reserves the right to intervene during the manufacturing process and have free access to the Contractor's equipment to undertake any inspections and checks as may be deemed necessary to guarantee compliance with safety requirements.

7.5.1 Definition and identification of the cold masses

Each cold mass assembly shall be equipped with a non-reusable identification plate indicating its relevant characteristics in English or in French and the identification information required by CERN.

This information shall include:

- the name and country of origin of the Contractor,
- the series number,
- the year of manufacture,
- the mass in kg,
- the nominal free volume V of the cold mass in l,
- the design pressure PD in bars,
- the test pressure PT applied in bars and the date,
- the operational temperature,
- the fluid contained,

– the supply voltage and current.

7.5.2 Design and safety codes

For experimental equipment to be used at CERN but designed and constructed outside CERN, the Codes and Standards of the EC shall be used as reference documents for equipment design, manufacture and testing.

A list of relevant Documents and Codes is presented in Section 5.

7.5.3 Welding process and welders' qualification

Although CERN provides (in Annex B) recommendations and detailed information about the welding process to be used for the main welds, the Contractor remains fully responsible for the welding operations he will carry out. The applicable standards and codes are listed in the Section 5.

CERN makes available the Welding Procedure Specifications (WPS) qualified for the welding activities on the prototypes and on the starting of the pre-series production. The Contractor shall conduct at his own expenses the required qualifications and approval tests in case he intends to modify the welding procedures respect to those applied for the pre-series production (see Section 1.2 of Annex B33 for further details).

7.5.4 Final pressure test

After completion of the cold mass assembly, the Contractor shall, prior to delivery, conduct a final pressure test according to the procedure presented in Annex B33.

8. QUALITY ASSURANCE PLAN

8.1 General

The Quality Assurance Plan shall include the requirements of the Contractor's Quality Assurance plan and those of the Quality Assurance Plan imposed by CERN for the execution of the present Technical Specification.

The Contractor shall plan, establish, implement and maintain a documented quality assurance program that fulfils all the requirements described in the cold mass Technical Specification and drawn up according to the Quality Assurance Plan for the LHC Project.

The principal documents of the LHC Quality Assurance Plan relevant to this Technical Specification are annexed (in the form of a CERN official CD-ROM) in Annex D.

8.2 Quality Assurance Programme requirements

The cold masses supplied in compliance with the present specification shall be produced under a system of control checks, which meets the requirements of this Section. The Contractor's Quality Assurance Programme shall be described in a written manual or plan and shall be subjected to review and approval by CERN before the start of work. The manual or plan shall cover at least the following requirements:

8.2.1 Organisation

The Contractor's organisational chart shall demonstrate that personnel responsible for quality assurance have sufficient authority and independence to identify problems, verify compliance, control non-compliance and satisfactorily resolve conflicts.

CERN's Quality Assurance is imposed for the following points to keep common reference between the different Contractors for traceability purposes:

- Drawing format,
- parts identification,
- Assembly Breakdown Structure,
- Process Workflow Diagram,
- Inspection and Test plan.

<u>Drawings format</u>: all drawings produced by CERN are in HPGL™ format (see also Annex A).

The Contractor shall send his manufacturing drawings to CERN for approbation in AUTOCAD™ format following the rules imposed by CERN (see Annex A).

<u>Parts identification</u>: parts shall be identified with a serial number and/or a batch number according to the CERN QA Plan for identification and traceability.

<u>The Assembly Breakdown Structure</u> given by CERN shall be the reference for the establishment of the electronic Traveller designed by CERN and to be completed by the Contractor.

Separate and detailed information on the Traveller will be give to the Contractor by CERN.

<u>The Process Workflow Diagram</u> produced by CERN shall be respected and any deviation shall be discussed and agreed with CERN. For traceability purpose, for any proposed deviation a change notice document shall be issued for submission to and approval by CERN.

The Inspection and Test Plan (see Annex B2) of this Technical Specification shall be applied and all tests described shall be respected. Any deviation in the order of execution or in the test execution procedure shall be agreed by CERN. For traceability purpose, for any proposed deviation a change notice document shall be issued for submission to and approval by CERN.

8.2.2 Design control

The Contractor's Quality Assurance Programme shall provide for control on design activities. The Contractor shall implement procedures which provide for review and approval of specifications, drawings and other significant engineering documents, as well as changes thereto, prior to their issue for use. The reviews shall be conducted to verify completeness, correctness and adequacy with respect to Contract requirements. The format of the drawings supplied shall meet the LHC Design Standards as described in Section 8.3 "Management of Engineering Drawings".

8.2.3 Document control

The Contractor's Quality Assurance programme shall provide for the distribution and control of approved engineering and procurement documents (including specifications, drawings, procedures, purchase orders, and other critical documents) as well as changes thereto. The programme shall provide for the control of superseded or void documents by such means as recall, clearly marking as "Void", or other effective means of assuring that superseded documents are not inadvertently used.

8.2.4 Procurement

The Contractor's Quality Assurance programme shall provide for the planning and execution of procurement in accordance with documented instructions and/or procedures.

A) Provision shall be made for defining the requirements for review of procurement documents and changes thereto, for technical requirements as well as inclusion of appropriate quality assurance requirements;

B) Provision shall be made for methods of evaluation and selection of supplier or subcontractor; bases for approval shall be documented;

C) The Contractor's Quality Assurance programme shall provide for checking the compliance of purchased items to procurement document requirements. Such verification may be in the form of receipt inspection for simple, non-critical items or in-plant surveillance at the sub-contractor's facilities in the case of complex and/or critical items.

8.2.5 Manufacturing and tooling inspection, installation and test.

The Contractor's Quality Assurance programme shall provide for manufacturing planning, material and process control, inspection and testing, non-conformance control and objective evidence (documentation) of the inspection function.

A) A system of process sheets, shop travellers, or equivalent means shall be used to define the sequence of manufacturing, inspection and test activities to be performed during the entire collared coils manufacturing and cold mass assembly activities. "Hold" or "Witness" points shall be designated on such flow sheets where required by the Contractor or CERN. Flow sheets, or the equivalent, shall provide for sign-off by designated inspection personnel at specified inspection and test points, to assure completion as well as the proper sequencing of required operation.

B) Material and equipment identification shall be maintained throughout the manufacturing/assembly process, either on the material or equipment or on records traceable to the material or equipment. The status of acceptability of materials and equipment with respect to inspections and tests shall be readily discernible through Contractor's use of tags, stamps, routing cards or other positive means.

C) Inspections and tests shall be performed in accordance with approved written procedures; such procedures shall include or refer to criteria for acceptance or rejection. Adequate records shall be maintained of all inspection or test results (accepted or rejected) and identification of the inspection or test personnel.

D) Inspection and testing shall be performed using properly calibrated measuring and test equipment. The Contractor's Quality Assurance Programme shall describe a system which provides for:

1) Calibration procedures, including frequency and proper environmental conditions,
2) Calibration status indicators on measuring and test equipment where physically possible,
3) Serialisation of measuring and test equipment,
4) Traceability to the accepted and adopted Standards,
5) Calibration records for all measuring and test equipment as well as reference and transfer Standards,
6) Qualification, calibration, inspection and maintenance of all the tooling (whether provided by the Contractor or supplied by CERN) utilised during the activities of the cold mass manufacturing.

E) The Contractor's Quality Assurance Program shall provide for the qualification of personnel and/or procedures for the performances of certain special processes such as welding, heat treatment, non-destructive examination, helium mass spectrometer leak check, or other as may be required by the Contract, CERN, or the nature of the process or product.

F) The Contractor shall enforce a system of documentation whereby objective evidence of required inspections, examinations and tests is systematically compiled. Such objective evidence includes material test reports, which shall be complete, legible and validated by responsible Contractor's personnel. Documentation shall be traceable to particular material or equipment.

8.2.6 Non-compliance control and procedures

A) The Contractor's Quality Assurance programme shall provide for prompt identification and control of non-complying items, i.e. those which do not satisfy the requirements of the engineering documents. Non-complying material or equipment shall be positively identified, and segregated where physically possible, to prevent use. The Contractor's system shall provide for timely resolution of non-compliance, including approval by CERN when required by Contract.

B) The Contractor shall maintain a record of all non-compliance, including the resolution of each case. The Contractor's system shall provide for the analysis of non- compliance, and provide appropriate corrective action in such cases.

8.2.7 Packing, shipping and storage

A) The Contractor's Quality Assurance programme shall provide for procedures that assure adequate protection of material and equipment and sub-assemblies during storage and shipment. Such protection shall include special environmental packaging requirements if specified.

B) Procedures for packaging and storage shall provide for adequate marking or labelling in order clearly and readily to identify the material or equipment.

C) The Contractor's Quality Assurance programme shall provide for adequate control and protection of in-house stores (raw material, parts or sub-components of the cold mass) in order to prevent damage, deterioration or unauthorised use.

8.2.8 Audits

The Contractor's Quality Assurance Programme shall provide for planned, periodic audits of the various aspects of the program by persons not directly responsible for implementation of the area being audited. Such audits have the purpose of determining compliance with programme requirements as well as determining need for modification of the programme.

A) CERN reserves the right to have the quality assurance programme set up for the Contract's execution audited, at its expense, by an independent inspection firm. The outcome of such audits will be discussed with the Contractor who will, at his expense, take corrective actions deemed necessary within 4 weeks.

8.3 Management of engineering drawings

Drawings supplied as part of the required documentation shall be compatible with the relevant part of the LHC Quality Assurance Plan, namely the LHC Design Standards. Please refer to Section 4.2.4, 4.2.5, Section A and D for details.

8.4 Traveller and traceability

Procurement of the raw materials, manufacturing of the components, assembly and testing of each cold mass covered by this specification shall be recorded and followed in a specific file, called a "Traveller", following the procedure of the LHC Quality Plan. Annex B34 gives details about the Traveller, its structure and how the information has to be provided and stored.

CERN requires two levels of traceability.

8.4.1 Cold mass component level

All components identified in the Assembly Breakdown Structure shall be recorded and shall be identified either by a serial number or by a batch number.

Any deviation on the quality criteria imposed by CERN shall result in a non-conformity report sent to CERN.

Part serial numbers and or batch numbers for each cold mass shall be recorded in the Traveller via the identification form (see Annex B34).

8.4.2 Test level

Test results shall be recorded in the EXCEL™ format imposed by CERN. These tests shall be sent to CERN via electronic mail (EMAIL) or File transfer (FTP) in due time (for example: after winding, after curing, after collaring, after the welding of the Cold mass and the final assembly). This time will be defined and agreed with the Contractor.

All non-conformities concerning tests procedures and tests results shall be recorded and transmitted to CERN for analysis. The non-conformity shall be resolved before execution of the next step as described in the Inspection and Test Plan.

8.4.3 Delivery to CERN

Before shipment of a cold mass to CERN, the Contractor shall send to CERN the copy (electronic and paper) of the full Traveller of the cold mass.

An identity document (see annexes) shall be produced and shall contain the cold mass components identification, all tests reference, all non-conformities discovered and closed, and all relevant change notices.

More practical and technical details concerning the traceability and test recordings shall be given in a detailed technical meeting with the Contractor.

8.5 CERN Database

In view of the large number of components and tests involved during the LHC construction and the necessary standardisation of the collected data, a central database using the Relational Database Management System ORACLE™ has been implemented at CERN.

Component characteristics, components identification and tests data shall be loaded into this database either at CERN or when possible at Contractor’s premises. All steps of assembly, especially of those where newly designed jigs/tools etc. are involved or where preliminary tests are needed to provide a specified result, shall be recorded in full detail, together with all data collected even if they are not the result of the prescribed intermediate tests. Essential information specific to each cold mass shall be laid down in the Traveller accompanying every item throughout the entire manufacturing process. CERN will supply all the electronic templates and software program necessary for this activity. The Contractor shall use at his premises and workshops the Microsoft Office 2000™ package.

9. PROVISIONAL ACCEPTANCE AT CERN

9.1 Acceptance tests at room temperature

The provisional acceptance at CERN may imply the repetition, at CERN's discretion and expense, of any of the tests performed at the Contractor's premises (e.g. electric, geometric, magnetic, leak and pressure tests). The acceptance criteria for the acceptance tests at room temperature performed at CERN will be the same specified for the final tests at the Contractor's premises as described in Section B.

In order to be entitled for the provisional acceptance at room temperature a cold mass shall be delivered to CERN with its Traveller document fully completed and proving the conformance of the cold mass to this Technical Specification.

In the case of a significant difference (even if the results are still within the acceptance ranges) between the Contractor's measurement, before shipment to CERN, and the repetition of the measurement at CERN reception, a special "Measurement non-conformity" will be automatically opened. Consequently, the Contractor and CERN shall check the integrity and calibration of their measurement equipment in order to identify the reasons for the presence of the measurement non-conformity.

The cold masses shall successfully pass all the tests at room temperature before the performance of the provisional reception tests at liquid helium temperatures.

9.2 Acceptance tests at liquid helium temperature

Provisional acceptance tests will be those performed with the cold mass in a helium bath at 1.9 K or 4.2 K and the coils in the superconducting state.

While CERN takes full responsibility for the design, the Contractor shall take full responsibility for possible manufacturing faults (e.g. improper use of components, deviations from agreed manufacture and assembly procedures), including hidden ones (e.g. the resistance at 1.9 K of the SC cable splices) which may be discovered during tests or operation of the cold masses.

Should any of the cold tests reveal any defect which can be traced back to manufacturing fault or damage during transport, CERN will be entitled to the repair or replacement of the faulty part(s) at the Contractor's cost.

Should any of the cold tests reveal any defect which can be traced back to CERN supplied components, the cost of possible corrective actions will be born by CERN.

The following reception tests will be made, which may be relevant for the Contractor's responsibility:

- cold leak tests,
- integrity and impedance measurements of instrumentation and power circuits,
- performance of the quench heaters,
- measurement of the transfer function linking integrated field strength ($\int Bds$) to current,

- ability of the magnet to reach nominal and ultimate field within a given, limited number of quenches,
- ability of the magnet to surpass nominal field without quenching after a thermal cycle, to be performed for magnets which have reached the ultimate field after no more than three quenches.

Note: the scope of the electrical checks and magnetic tests will be slightly different depending on the auxiliary busbars configuration type (“STANDARD test” or “FULL test”).

In addition to the above tests, CERN will carry out field quality measurements. The Contractor is not responsible for the results of these measurements.

Any cold mass shall pass the cold provisional acceptance tests after three thermal cycles between 293 K and 1.9 K and three complete test sequences.

Non-conformities that may appear in the course of the cold tests may or may not be the responsibility of the Contractor. It is not possible to give an exhaustive list of all conceivable problems in advance, but it is expected that it will be possible to trace all non-conformities to their source.

Examples of non-conformities that would be the responsibility of the Contractor may be as follows:

- cold mass leaks, e.g. because of faulty welding and/or faults in materials,
- lack of continuity or insufficient insulation level to ground of instrumentation wiring, e.g. because of inadequate assembly and test procedures,
- excessive resistance of any of the soldered superconducting cable splices made by the Contractor, e.g. because of inadequate manufacturing procedures,
- quench heater to pole layer electrical short circuits, e.g. because of inadequate assembly procedures,
- interturn short circuits or short circuits to ground under the full load of the electromagnetic forces, e.g. because of contamination of the electrical insulation,
- poor magnet training because of poor workmanship in coil manufacture, e.g. because of incorrect assembly of the superconducting cable ramp from the inner to the outer pole layers, presence of broken coil end spacers, incorrect shimming of coil ends.

It is to be noted that the cold tests carried out at CERN will allow the evaluation of the performance of the superconducting cable and that of the cold mass assembly separately. This is achieved by testing the dipole cold mass at several temperature levels comprised between 1.8 K and 4.2 K.

While it is necessary to be aware of the possibility of faults in the cold masses, it will be the goal of the Contractor and of CERN that all the cold masses be 100 % free of defects and that all the cold masses shipped to CERN will be acceptable for LHC operation. In particular, the comprehensive programme of intermediate tests and checks throughout the production should guarantee the interception of such possible defects early enough to be corrected.

The aim and acceptance criteria for these tests are detailed in the following.

These tests will be carried out with the cold mass fully immersed in superfluid He at 1.9 K. Although for the sake of clarity these tests are described in subsequent Sections, the actual test sequence will be optimised to cope with the production rate.

9.2.1 Leak test

The purpose of these tests is to verify the cold helium leak-tightness across separate volumes of the cold mass, with the following acceptance criteria:

1) Cold mass to insulation vacuum $\leq 1.10^{-8}$ Pa m^3s^{-1}
2) Cold mass to beam vacuum $\leq 1.10^{-11}$ Pa m^3s^{-1}
3) Heat exchanger to insulation vacuum $\leq 1.10^{-8}$ Pa m^3s^{-1}

Cold masses showing higher leak rates will be submitted to a detailed leak search, at CERN's expense. Should this search show that the cold leaks originate in welds and parts that are the responsibility of the Contractor, the latter will, at his expense, take appropriate corrective action. The Contractor shall describe in writing the proposed remedies and obtain CERN's written approval before any steps are taken.

9.2.2 Integrity and impedance of instrumentation and power circuits

After cool-down and before powering the magnet, a check will be made that the instrumentation necessary for its protection is in working order, cool-down and thermal contraction notwithstanding. Further it will be verified that the interturn and ground electrical insulation of the windings have maintained their integrity and that the electrical resistance of the seven soldered splices made by the Contractor between layers, poles and apertures is within the admissible value.

The list of the items to be tested, the tests to be carried out and their acceptance criteria are presented in the following Table 9.2.2:

Table 9.2.2: Electrical tests (in liquid helium) before powering the magnet

Item	*Aim of the test*	*Criteria*
Temperature sensor	Electrical continuity, resistance	I < 1 mA, R [mΩ] to calibration table
	Insulation resistance to ground	V = 20 V , R > 10 MΩ
Cryogenic Heater	Electrical continuity, resistance, integrity under nominal power	R = 100 Ω ± 5%, 40 W
	Insulation resistance to ground	V = 700 V R > 10 MΩ
Quench heaters	Electrical continuity, resistance, integrity under nominal powering	I = 0.1 A, R [mΩ] to nominal value *
	Insulation resistance to coils	V = 2.7 kV, 120 s I < 20 μA
	Insulation resistance to ground (together with coils, voltage taps)	V = 3.1 kV, 120 s I < 20 μA
Dipole voltage taps	Electrical continuity and localisation	1 A < I < 10 A V [mV] = f (T,I)
	Insulation resistance to ground (together with coils, quench heaters)	V = 3.1 kV, 120 s I < 20 μA
Dipole coils and busbars	Insulation resistance to ground (together with voltage taps, quench heaters)	V = 3.1 kV, 120 s I < 20 μA
Dipole coils	Interturn insulation	Complex impedance Z(ω) Impulse test as at 293 K in case of doubt
Cables splices	Electrical resistance: - internal splices - external splices - total resistance	I= 11'850 A R_{int} < 1.2 n Ω / splice R_{ext} < 0.6 n Ω / splice R_{tot}< 7 n Ω
Spool pieces voltage taps	Electrical continuity	0.1 A < I < 1 A V [mV] = f (T,I)
Spool pieces and voltage taps	Insulation resistance to ground (together with coils)	V = 1.3 kV, 30 s, (for MCS, MCD and MCO) V =1.5 kV, 30 s, I < 6.0 μA

* Discharge of a capacitor bank of total capacitance equal to 7.05 mF and charged to 900 V.

It is CERN experience since several years that correctly assembled cold masses pass the tests listed in the Table 9.2.2. Cold masses that do not withstand the above tests are therefore deemed to present faults due to poor workmanship and will be returned to the

Contractor at his expense for the implementation of corrective actions. The Contractor shall inform CERN of the outcome of any tests, inspections and reviews he might decide to undertake to ascertain the causes of failure and seek CERN's approval before undertaking any corrective action with a view to re-submitting the concerned cold mass to the cold acceptance tests.

9.2.3 Performance of the quench heaters

Before powering the dipole magnet to ultimate field, it must be ascertained that the protection system is in working order. To this end, the protection system is triggered at chosen field levels and the time delay between the trigger and the start of the quenches is recorded in the four poles by monitoring the voltages at the voltage taps.

These time delays and the coil temperature increase are a measure of the quench heaters efficiency, determined among other factors by the actual position of the quench heaters and by the thermal impedance between them and the pole layers.

Misplaced quench heaters may be detected by the measurement of anomalous values of the above parameters with regard to average values determined during the pre-series production.

Cold masses equipped with quench heaters showing anomalous performance will be returned to the Contractor at his expense for the implementation of corrective actions.

9.2.4 Quench performance tests

These tests qualify the magnet performance in terms of the number of training quenches necessary to reach nominal (8.3 T) and the ultimate (provisionally 9.0 T) field levels, and of the magnet property of keeping a "memory" of the training process after a thermal cycle.

These criteria are of fundamental importance for the commissioning and operation of the LHC.

To put in perspective the performance requirements detailed in this Section, Annex F2 presents the results obtained at CERN on the last generation of full-length cryo-dipole prototypes, assembled with the same coil cross-section as in this Technical Specification.

On the basis of the data given in Annex F2 and pending the outcome of the results which will be obtained on the pre-series cryo-dipoles, the following provisional acceptance criteria are established:

1) The cryo-dipole shall reach the ultimate field (provisionally 9.0 T) after no more than eight quenches. (For cryo-dipoles that reach the ultimate field after no more that two quenches, a bonus of 1 % of the unit cold mass price will be paid to the Contractor).

2) Cryo-dipoles that reach the ultimate field with a number of quenches between three and eight may be submitted to a thermal cycle after which they shall reach the field of 8.6 T without any quench.

N.B.: The results given in Annex F2, for the prototypes MBP2N2, O1, O2 and the first pre-series magnet prove that the cold mass design satisfies the above criteria. The case of MBP2A2 (35 quenches at the same location, ultimate field not reached) is an example of a localised manufacturing fault.

3) The provisional acceptance of cryo-dipoles which reach the ultimate field after more than eight quenches will be temporarily suspended by CERN. If their number is limited to few units, CERN will eventually declare their provisional acceptance, provided that they have satisfied the acceptance criterion 2).

4) Cryo-dipoles that do not satisfy the acceptance criteria 1), 2) and 3) for reasons which can be traced back to manufacturing faults or damages due to transport, shall be repaired or replaced within six months at the Contractor's cost.

10. PACKING AND TRANSPORT OF THE COLD MASSES

The Contractor shall arrange for the safe and efficient packing, transport and delivery of the assembled cold masses to CERN.

Packing shall be secure to protect the cold masses from any damage during handling and transport. In order to optimise the operation of loading and unloading of the cold masses, the loading on the transport vehicle (from the Contractor premises and CERN), shall be done with suitable lifting devices agreed by CERN.

The Bidder shall define and propose a supporting structure allowing the transport of the cold masses without impairing their geometry (as specified in Section 7.2.2) and assuring their mechanical and electrical integrity. This system shall be based on:

- the utilisation of a full-length rigid frame insensitive to the vehicle deformation,
- support of the cold mass on at least 7 points,
- presence of damping elements between the full-length rigid frame and the truck-bed.

Before transportation, the cold masses and the beam tubes shall be filled with dry nitrogen following a procedure defined in agreement with CERN.

Cold mass shipment shall be authorised by CERN only after the Contractor has provided CERN with the complete the Traveller document.

The cold masses shall be delivered according to the delivery schedule given in the Contract.

The Contractor shall give a five (working) days notice for shipment.

ANNEXES

ANNEX A: Tender Drawings

ANNEX B: Procurements, Procedures and Tests under the Responsibility of the Contractor

B1: *Magnetic field characteristics*
B2: *Inspection and Test Plan (ITP) for dipole cold mass*
B3: *Requirements for the clean area*
B4: *Requirements for the superconducting cable during electrical insulation*
B5: *Insulation of copper wedges*
B6: *Procurement and preparation of end spacers chips and wedge-tips*
B7: *Electrical tests during cable insulation, polyimide splicing and repair*
B8: *Surfacing of the layer ends*
B9: *Geometrical and mechanical measurements and tolerances of the layers, poles and collared coils*
B10: *Electrical tests of the layers, poles and collared coils*
B11: *Coil inter-layer procurement and assembly*
B12: *Procurement of stabilisers, layer–jump box, layer–jump filling pieces. Soldering of the layer-jump coil interconnection and end stabilisers*
B13: *Sorting of poles and collared coils*
B14: *Quench heaters, coil protection sheets and shim retainers*
B15: *Magnetic characteristics and tolerances for the rods and shims under the responsibility of the Contractor*
B16: *Collaring procedure*
B17: *Coil Pre-stress after collaring and collaring shims*
B18: *Warm magnetic measurements*
B19: *Fine tuning of the magnetic length*
B20: *Half-Yoke assembly*
B21: *Packing of the insert lamination*
B22: *Electrical tests during and after the cold mass assembly*
B23: *Implementation of the cold mass instrumentation*
B24: *Definition of the longitudinal bevelling of the half-cylinders*
B25: *Active part assembly*
B26: *Bending and longitudinal welding of the shrinking cylinder*
B27: *Inspection of the active part geometry*
B28: *Preparation of the magnet extremities*
B29: *Positioning and welding of the end covers and of the auxiliary busbars tube*
B30: *Instrumentation Feedthrough System (IFS) assembly*
B31: *Installing the protection diode stack*
B32: *Room temperature vacuum leak testing*
B33: *Safety tests*
B34: *Traceability, Traveller, QA documents*
B35: *Planning and scheduling requirements*

ANNEX C: Description of the CERN supplied components for the series cold masses manufacturing

- _C1: Superconducting cables (for inner & outer layers)_
- _C2: Polyimide tapes for cable and copper wedges insulation (two types)_
- _C3: Copper wedges (4 types)_
- _C4: Void_
- _C5: Polyimide (in rolls) for the coils ground insulation_
- _C6: Collars (6 types)_
- _C7: Insulated Cod Bore tubes_
- _C8: Low carbon steel half-yoke & insert laminations_
- _C9: Non-magnetic steel half-yoke & insert laminations_
- _C10: Busbar subassemblies_
- _C11: Shrinking half-cylinders_
- _C12: Spool pieces (sextupole and decapole/octupole correctors)_
- _C13: End covers_
- _C14: Helium heat exchanger tube_
- _C15: Interconnection bellows_
- _C16: Instrumentation for the Cold Mass_
- _C17: Protection diode stack_
- _C18: Tube for the auxiliary busbars line ("N-line")_

ANNEX D: Available Documents of Quality Assurance Plan (QAP) for the LHC Project

Please refers to the attached CD-ROM (CERNDOCS Version 2.0): "CERN Official Documents: quality assurance, safety, purchasing, etc…"

ANNEX E: CERN supplied Tooling and Measuring Equipment

(Tooling delivered for the Pre-series production and applicable to the Series production).

- _E1: Presses for E-modulus measurements_
- _E2: Instruments for electrical measurements_
- _E3: Equipment for magnetic measurements_
- _E4: Welding press_
- _E5: Equipment for geometrical measurement and alignment_

ANNEX F: General Documents available on performances and field quality for the LHC Main Dipole prototypes and "pre-series" cold masses.

- _F1: Field error naming conventions_
- _F2: Quench levels in 15-m long dipole prototypes and pre-series cold masses_
- _F3: Field Quality in 15-m long prototypes and pre-series cold masses_

ANNEX G: Technical Specifications released by CERN for the supplying of the cold mass components and tooling

G1: *LHC-MMS/98-198/G01*
Technical Specification for the Supply of Copper Wedges for the Cold Masses of the LHC Superconducting Dipole Magnets.

G2: *LHC-ICP/01-242/FRM*
Technical Specification for the Supply of Quench Heaters for the series LHC Superconducting Main Dipole Magnets. (NOT YET AVAILABLE)

G3: *LHC-MMS/98-198/G03*
Technical Specification for the Supply of Austenitic Steel Strips for the Collars for the Cold Masses of the LHC Superconducting Dipole Magnets.

G4: *LHC-MMS/98-198/G04*
Technical Specification for the Supply of Fine-Blanked Austenitic Steel Collars for the cold masses of the LHC Superconducting Dipole Magnets.

G5: *LHC-MMS/98-198/G05*
Technical Specification for the Supply of Cold Bore Tubes for the LHC Main Dipole and Quadrupole Superconducting Magnets.

G6: *LHC-MMS/98-198/G06*
Technical Specification for the Supply of Fine-Blanked Austenitic Steel Yoke Laminations for the Cold Masses of the LHC Superconducting Dipole Magnets.

G7: *LHC-MMS/98-198/G07*
Technical Specification for the Supply of Fine-Blanked Low-Carbon Steel Yoke Laminations for the Cold Masses of the LHC Superconducting Dipole Magnets.

G8: *LHC-MMS/98-198/G08*
Technical Specification for the Supply of Austenitic Stainless Steel Shells for the Cold Masses of the LHC Superconducting Dipole Magnets.

G9: *LHC-MMS/98-198/G09*
Technical Specification for the Supply of Austenitic Steel End Covers for the Cold Masses of the LHC Superconducting Dipole Magnets.

G10: *LHC-MMS/98-198/G10*
Technical Specification for the Supply of Oxygen-Free Copper Helium Heat Exchanger Tubes for the LHC Main Dipole and Quadrupole Magnets. (NOT YET AVAILABLE)

G11: *LHC-CRI/BS/cl/*
Technical Specification for the Supply of LHC Bellows Expansion Joints.

G12: *LHC-MMS/98-198/G12*
Technical Specification for the Supply of Austenitic Steel Strips for the non-magnetic Laminations of the Cold Masses of the LHC Superconducting Dipole Magnets.

G13: *LHC-MMS/98-198/G13*
Technical Specification for the Supply of Coil Inter-Layers for the Cold Masses of the LHC Superconducting Dipole Magnets.

G14: *LHC-MMS/99-202*
Technical Specification for the Supply of Polyimide Film for the Cable and Ground Insulation of the LHC Superconducting Magnets.

G15: *LHC-MMS/98-180*
Technical Specification for the Supply of Three Hydraulic Presses for Assembling and Welding the LHC Superconducting Dipole Magnets.

G16: *LHC-MMS/98-184*
Technical Specification for the Supply of Pole Measuring Machines for the LHC Superconducting Dipole Magnets.

G17: *LHC-MMS/99-199*
Technical Specification for the Supply of Portable 3-D Measuring Systems allowing the on-site Dimensional Inspection of the Cold Masses of the LHC Dipole Magnets.

G18: *LHC-MMS/99-209*
Technical Specification for the Supply of End Spacers sets of the LHC Dipole Magnets.

G19: *LHC-MMS/2001-229*
Technical Specification for the Supply of Helium filling pieces for the Cold Masses of the LHC Dipole Magnets. (NOT YET AVAILABLE)