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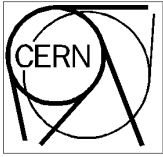
Invitation to Tender

Technical Specification for The Superconducting Cable for the Next European Dipole (NED)

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Terms and Definitions

Term	Definition
AMT	Advancements on accelerator Magnet Technology
CARE	Coordinated Accelerator Research in Europe
CD	Conductor Development
CMM	Cable Measuring Machine
ECFA	European Committee for Future Accelerators
ESGARD	European Steering Group for Accelerator R&D
EU	European Union
HEHIHB	High Energy High Intensity Hadron Beams
HEP	High Energy Physics
IA	Integrated Activity
IDI	Insulation Development and Implementation
IR	Interaction Region
ITD	Internal Tin Diffusion
JRA	Joint Research Activity
Nb-X	Niobium alloy
NED	Next European Dipole
PIT	Powder In Tube
TSQP	Thermal Studies and Quench Protection

1. INTRODUCTION

1.1 Introduction to NED Joint Research Activity

In October 2002, the European Committee for Future Accelerators (ECFA) set up the European Steering Group for Accelerator R&D (ESGARD), with the mandate of preparing a coherent set of bids to apply for EU funding. The first outcome of ESGARD was the Coordinated Accelerator Research in Europe (CARE) proposal of Integrated Activities (IA), which was submitted to the EU on April 15, 2003. The proposal was accepted in July 2003 after reviewing and ranking by a panel of experts across the fields of science. The Contract with EU has been signed in January 2004 after revision of the proposals to meet the funding profiles.

The CARE project integrates all High Energy Physics (HEP)-related accelerator R&D in Europe and is supported by more than 100 institutes. It is made up of 3 Network Activities (linear colliders, neutrino beams and High Energy High Intensity Hadron Beams or HEHIHB) and 4 Joint Research Activities (JRA's) aimed at developing specific hardware pieces or systems. The HEHIHB network includes a work package entitled Advancements on accelerator Magnet Technology (AMT), while one of the JRA's, called NED (for Next European Dipole), will focus on high-field accelerator magnet R&D.

The initial NED JRA proposal had five main objectives: (1) to revisit magnetic and mechanical designs of accelerator magnet coils made from brittle materials, (2) to address coil cooling issue under high beam losses, (3) to promote high-performance Nb₃Sn strand development in collaboration with European industry, (4) to improve mechanical robustness and radiation hardness of Nb₃Sn conductor insulation, and (5) to put into practice all of the above in a high field (up to 15 T on the conductor), large aperture (up to 88 mm) dipole magnet model that would push the technology well beyond LHC limits. The proposed dipole magnet model will serve two purposes: (1) assessing the feasibility of such a magnet in view of possible LHC luminosity upgrade scenarios with radically different Interaction Regions (IR) optics and (2) upgrading the CERN/FRESCA cable test facility presently limited to 10 T.

At the EU request, the initial NED proposal has been divided up into two Phases: Phase I (representing about 25% of the initial program), covers conductor development and includes some limited studies on conductor insulation while Phase II is devoted to the detailed design, manufacturing and testing of the dipole magnet model. The funding of Phase I, which is foreseen to last ~3 years, is fully secured, while that of Phase II is still under discussion.

Six institutes have agreed to collaborate in the NED JRA: CCLRC-RAL (UK), CEA/DSM-Saclay (France), CERN/AT (International), INFN-Milano/LASA and INFN-Genova (Italy), University of Twente (The Netherlands) and Technical University of Wroclaw (Poland).

1.2 Generalities on the Nb₃Sn Conductor Development

The Phase I of NED is based on three main work packages: (1) Thermal Studies and Quench Protection (TSQP), (2) Conductor Development (CD) and (3) Insulation Development and Implementation (IDI).

The CD work package is coordinated by CERN and includes the preliminary design of a large-aperture (up to 88 mm) and high-field (up to 15 T conductor quenching field) Nb₃Sn dipole magnet in order to derive meaningful conductor specifications. The core of the activity

will be devoted to strand and cable development. Among the various processes to produce Nb₃Sn conductors, the bronze route, which enables the achievement of fine filaments, was deemed inadequate to reach the desired high critical current densities. Within the limited funding available, it was then decided to concentrate the efforts on two routes: (1) Powder In Tube (PIT) and (2) enhanced Internal Tin Diffusion (ITD). It is worth mentioning that high current densities in the 15 T range represent a new technical challenge for the European superconductor industry, which will invest in this ambitious program. The program aim will be the industrial production of high-current density Nb₃Sn strands, with diameters in the 1.15- to-1.3-mm range and piece lengths superior to 1 km.

The strands will be characterized by performing critical current measurements at CEA/DSM-Saclay, INFN-Milano/LASA and University of Twente (following a standardized protocol) and magnetization measurements at INFN-Genova. The cable critical currents will be measured at University of Twente.

The initial dipole coils consisted of two layers that should be wound with a different type of cable for an optimum use of the superconducting material. Due to budget limitations, the present specification concerns only one type of cable, which will be used in both layers of the dipole coils. The layers use a Rutherford-type cable made of up to 40 Nb₃Sn composite strands of 1.25 mm in diameter. The strands consist of Nb₃Sn filaments with a maximal effective diameter of 50 μm, embedded in a copper matrix. The strands may be coated prior to cabling or cabled around a central metallic core. The strands will be of very high and uniform quality. The present specification is based on a critical current density in the non-copper part of 1500 A/mm² at 15 T and 4.2 K. This current density would constitute a big step in the technology of Nb₃Sn strands.

The technology chosen for the magnet construction is “wind and react” due to the small bending radius of the cable in the coil ends and to the brittleness of reacted Nb₃Sn conductors. This means that the cable will be delivered to CERN before the final heat treatment leading to the superconducting Nb₃Sn phase formation. After winding the insulated cables to form a coil, the coil will be heat-treated following the precise instructions to be given by the supplier. A reference strand will be heat-treated in the same oven at the same time for final electrical characterization. The ramping time of the temperature will be dominated by the coil mass to be heated; the duration and temperature of the various plateaus will strictly follow the supplier instructions.

The supply to CERN of superconducting cables will be asked from two strand manufacturers (hereafter individually and collectively referred to as, respectively, "the Contractor" and "the Contractors"). It will be spread over a period of 3 years, starting in 2004, the final cable being delivered by the end of 2006.

Due to the crucial role of the Nb₃Sn superconducting cable development, it is essential that the Contractors ensure the traceability of all materials and equipment involved by means of a consistent documentation of test results, in accordance with a quality assurance program.

The development will be considered as successful if:

- It makes it possible to produce cables of accelerator magnet quality (high critical current density, low magnetization, ...),

- It makes it possible to produce long lengths of cable with a consistently high performance,
- It demonstrates how to proceed to larger scale production,
- It explains and remedies quality and production problems encountered during the development work.

CERN reserves the right to make minor modifications to the present specification prior to the Contract being signed.

2. TENDER PROCEDURE

2.1 Pre-Tender discussions

Bidders are encouraged to contact CERN to discuss the present specification in detail before preparing their Tenders, so as to avoid any misinterpretation of the requirements set out in the present specification.

2.2 Technical Questionnaire

Bidders shall fill in the Technical Questionnaire attached to the present specification and send it to CERN together with the Tender Form. The submission of an incorrect and/or incomplete Technical Questionnaire may lead to rejection of the Tender by CERN.

3. SCOPE AND CONDITIONS OF SUPPLY

3.1 Quantity of supply and delivery schedule

Various dipole magnet designs are under consideration by NED collaborators. All designs use 1.25 mm diameter strands assembled in a Rutherford-type keystone cable consisting of up to 40 strands. Depending on the dipole configuration the final decision on the cable dimensions will be taken before the start of cabling. The total quantity of Nb₃Sn cable to be supplied to CERN shall be about 1160 m for a 40 strand trapezoidal Rutherford-type cable which represents about 500 kg of final material. The minimum unit length of Nb₃Sn cable shall be 145 m. The minimum strand continuous length shall be greater than 1 km.

The total supply of cable shall be shared between two Contractors in a proportion to be determined by CERN when placing the Contracts. CERN shall place two contracts for a total of two dipoles using a different Nb₃Sn technology. The cable delivery quantity per dipole is 580 m, accounting for the risks inherent in dipole construction. The minimum cable quantity to be contracted is 435 m.

Since the aim of this development program is to have an industrial process, it is required that final multi billets of at least 50 kg will be manufactured.

It is understood that the supply is a part of a difficult development program and that the Contract is made for the development of a cable with a final deliverable to be used in a magnet. The Contractors shall develop and deliver Nb₃Sn strand and cable according to the following general schedule:

Step	Date	Description	Milestone
	July 2004		Contract signature
	December 2004		Progress report
1	June 2005	Qualification of initial strand designs	Fabrication/tests of at least 10 kg of strand and relevant cabling tests Progress report
2	December 2005	Qualification of final strand design	Fabrication/tests of at least 10 kg of strand and relevant cabling tests Progress report
3	June 2006	Total strand production	Fabrication/tests of total strand quantity and cabling tests Progress report
4	December 2006	Total cable fabrication	Total cable quantity delivery Final report

The proposed schedule assumes that, as a first step and by June 2005, the Contractor will fabricate several small billets to test an initial billet design and some variants. According to the results, as a second step, the Contractor can still modify the billet design, fabricate strand and then qualify the final process before the final strand production.

The Bidders will describe the various steps they will follow to reach the final technical goal and the final delivery. At the dates mentioned in the general schedule, the

Contractor has to fabricate a significant quantity of strand, to test it and to perform some relevant cabling tests to demonstrate that the strand does not degrade at cabling. The Contractor will submit official reports on the status and the technical progress or difficulties in the development of the product.

The detailed quantities to be fabricated at the milestones will be clarified in the Contract in agreement between CERN and the Contractors following the decision tree of the program. It is important that the status of the product at the milestones will be described precisely from the technical and fabrication point of view. At the end of the Contract, even if, although unlikely, the ambitious goal is not obtained at 100%, the Contractor must know and explain the reasons for discrepancies and should provide a detailed plan for remedies. At the Contract mid-term, the potentiality of the billet design and of its industrialization must be known and understood.

The payments will be related to the various steps of the program. The documented reports linked to substantial and proven technical results will be audited by the European Union.

However, in case a Contractor does not fulfill the requirements of the present Specification, CERN, at its sole discretion, is entitled to cancel the totality or a part of the Contract, without any payment or compensation being due by CERN in connection with the quantity of cable still to be delivered by that Contractor.

Moreover, CERN, at its sole discretion, is entitled to cancel the Contract altogether in case a contractual requirement is delayed for a period of longer than ten weeks in any calendar year, without any payment or compensation being due by CERN in connection therewith.

The Contractor shall refund to CERN any payment made by CERN for any supply subsequently cancelled by CERN to the Contractor in the circumstances described above.

The remedies described above do not apply in case of force majeure, excluding strikes and labor unrest at the Contractor and non-performance of his sub-Contractor(s), in which cases the mechanism described in section 7 of the Tender Form applies.

In case of cancellation by CERN of one or a part of a Contract, CERN is entitled to demand that the quantity of cable to be supplied to CERN by the other Contractor shall be increased accordingly or given to a third supplier, at CERN's sole discretion.

3.2 Testing of Nb₃Sn strand and cable

Unless stated otherwise in the present specification, the Contractors shall perform all chemical, metallurgical, electrical, mechanical, dimensional and surface tests and measurements described in the present specification. The Contractors shall provide the necessary equipment for such tests and measurements.

3.3 Sub-Contractors

If a bidder intends to sub-Contract a part of the work, he shall state this in the Tender Form, specifying the sub-contracted work, the percentage value thereof and the name(s) of the sub-Contractor(s). Main sub-Contractors shall be agreed by CERN. The Contractors shall not engage other sub-Contractors than those stated in the Tender Form without prior written approval by CERN, which it may give or withhold at its sole discretion.

Notwithstanding any sub-contracting, the Contractors shall remain fully responsible for the proper execution of the Contracts, including but not limited to ensuring that the strand and cable are conform to the present specification.

3.4 Contract management, procurement and manufacturing schedules, progress reports

Prior to the Contract being signed, the Bidder will supply to CERN a document detailing a provisional procurement and manufacturing schedule.

The Contractor shall nominate a contract manager who shall represent the Contractor throughout the execution of the Contract.

Every three months throughout the execution of the Contract, the Contractor shall submit to CERN written status reports (the format of which will be agreed by CERN and the Contractor prior to the Contract being signed) on the development and manufacturing of the strands and of the cable, including the manufacturing schedule for the next three months, the results of all tests performed in accordance with the present specification, the quantity and identification numbers of the billets which have passed the Contractor's quality control checks, and the quantity and identification numbers of the strands and cable manufactured.

Every six months, the Contractor shall submit to CERN a progress report indicating the status of the materials and work for the past and define the work and the production schedule for the next six months' period. Within one month thereafter, the Contractor shall submit to CERN an up-to-date procurement and manufacturing schedule for the final delivery. The 6-month report will be transmitted to EU.

3.5 Access to the Contractor's premises

Representatives of CERN shall be entitled during working hours to visit the Contractor's facilities and those of his sub-Contractors, to inspect the manufacturing progress and to monitor any testing. CERN's presence at these facilities does not release the Contractor of any of his responsibilities under the Contract.

3.6 Packing and Transport

The Contractor shall arrange for the safe and efficient packing, transport and delivery to CERN of cable. No shipment shall be carried out without prior written approval by CERN.

3.7 Provisional Acceptance

After delivery to CERN of cable, including all test certificates and a certificate of conformity to the present specification, and after the satisfactory performance of all reception measurements by CERN, CERN shall declare the provisional acceptance of that cable.

3.8 Responsibility

The Contractor shall be solely responsible and liable for all layouts, drawings, designs, specifications, reports, protocols, calculations and other documentation or information produced or prepared by him, whether or not based upon data, information or documentation provided by CERN or by any third party. Where the Contractor seeks or is obliged to seek CERN's approval or agreement, the giving or confirming of the same by CERN shall not in any way derogate from the Contractor's duties, obligations or liabilities under the Contract, nor diminish any liability on his part in respect thereof.

4. QUALITY ASSURANCE AND MANUFACTURING PLAN

Prior to the Contract being signed, the Contractor shall submit to CERN, for its approval, a documented Quality Assurance program, which fulfils all requirements described in the present specification.

Prior to the Contract being signed, the Contractor shall furthermore submit to CERN, for its approval, a detailed description of the test procedures and the model test certificates that he proposes to use. He shall submit the model test certificates for the strands and the proposed strand map at least two weeks prior to the commencement of the manufacturing of cable.

The Contractor shall document all chemical, metallurgical, electrical, mechanical, dimensional and surface measurements and shall keep the full documentation and samples at his facilities until 2010.

Prior to the cable being shipped to CERN, the Contractor shall submit to CERN, for its approval, copies of all test certificates and a certificate of conformity in respect of that cable. No shipment shall be effected without prior written approval by CERN.

4.1 Sampling and test requirements

The Contractor shall prepare the samples and perform the measurements that are required to demonstrate that the chemical, metallurgical, electrical, mechanical, dimensional and surface properties of cable are conform to the present specification. The Contractor shall notify CERN ten working days in advance of any test being performed.

The Contractor shall label all samples used for tests and shall identify their position within the strand and the cable length from which they were taken. CERN is entitled to demand that the Contractor prepares additional samples and may reject any cable that does not conform to the present specification.

4.2 Manufacturing plan

Prior to the Contract being signed, the Contractor shall establish and make available to CERN, for its information, a manufacturing plan describing the complete manufacturing process and all tooling, machines and equipment, including a flow chart, diagram and narrative. If the plan includes proprietary information, the Contractor shall take all necessary measures to allow it to disclose that information to CERN. If need be, CERN is prepared to enter into a non-disclosure agreement. The implementation of any changes to the

manufacturing plan after the commencement of the manufacturing is subject to prior written approval by CERN.

4.3 Quality assurance program

Part of the quality assurance programme shall be a programme, appropriate for the development and manufacturing process. It will incorporate a clear decision tree showing the steps followed to reach the target and the milestone dates and results for the proper decisions.

5. STRANDS

The strands are a composite of Nb₃Sn filaments in a high quality copper matrix. Their fabrication starts from the assembly, called a billet, consisting of Nb-X rods in copper tubes or Nb-X tubes and copper keys in a copper can. The strands produced from a billet will be in variable lengths as a result of breakages or by purpose. A continuous length of unbroken strand, without welds, is called a strand piece length.

5.1 Main characteristics of the strands

The main characteristics of the strands are summarized in Table I and subsequent paragraphs. The Contractor shall ensure that the chemical, metallurgical, electrical, mechanical, dimensional and surface characteristics of the strands are conform to the present specification.

Table I - Main characteristics of the Nb₃Sn superconducting strands for cable

Strand diameter	1.250 ± 0.004 mm
Effective Filament diameter according to billet design	< 50.0 µm
Copper to non-copper volume ratio	1.25 ± 0.10
Filament twist pitch after cabling	30 ± 3 mm
Filament twist direction	right-handed screw
Minimum critical current at 4.222 K	1636 A at 12 T 818 A at 15 T
RRR (after full reaction)	> 200
n-value @ 15 T and 4.2 K	> 30

The critical current values are based on a non-copper critical current density of 1500 A/mm² at 15 T and 3000 A/mm² at 12 T and 4.2 K. These specified minimum critical current values are the aimed values, measured after the twisting and the final reaction heat treatment as defined by the Contractor. The Bidder will choose a design and a fabrication process

leading to an homogenous Nb₃Sn phase containing close to 25% Sn. The Bidder can propose a strand diameter between 1.15 and 1.3 mm if he thinks and explains that the proposed dimension is more suitable to reach the high critical current density. In such a case, the minimum critical current will be adapted consequently.

5.2 Strand material

The Contractor shall record for each billet the identification numbers of the Nb-X alloy rods or tubes and of the barrier sheets used in it. It would be wise that the Nb-X alloy rods/tubes incorporated in the same billet shall come from the same lot of raw material; likewise, if used, all the barrier sheets incorporated in the same billet shall come from the same lot of barrier sheets. The notion of "lot" is defined as all material of a single process and casting, heat-treated and processed in the same charge in a batch type furnace. The Contractor shall preserve the identification numbers of each lot of raw material to allow all manufacturing, test and inspection records for finished strands to be traced back to the original lot of raw material.

5.2.1 Nb-X alloy

The Contractor will provide CERN with the specification, all the certificates and test protocols of the Nb-X alloy rods or tubes used in the strands. The Bidder shall specify in the Technical Questionnaire the type of alloy he intends to use for the present specification. The Contractor shall submit to CERN copies of the certificates and test protocols all with the mention "read and approved" and signed by the Contractor for each Nb-X alloy rod/tube entering the manufacturing process.

5.2.2 Barrier sheets

Some processes use a barrier to stop the Sn diffusion in the copper and avoid pollution of the protective copper material. Any Contractor using such a barrier will provide CERN with the specification, all the certificates and test protocols of the sheet material if used in the strands. The Bidder shall mention the type of barrier he intends to use for the present specification. The Contractor shall submit to CERN copies of the certificates and test protocols all with the mention "read and approved" and signed by the Contractor for each barrier entering the manufacturing process.

The chosen thickness of the anti-diffusion barrier shall be adequate to guarantee no breakage of the barrier during cabling and full reaction heat treatment. It shall pass the sharp bend test. The barrier should not create flares on the strand surface after cabling and full reaction heat treatment.

The Bidder shall indicate the barrier type and the thickness. He will show by his past experience how he guarantees the absence of barrier breakage during cabling and heat treatments. The Contractor shall submit to CERN copies of the certificates of conformity and the test protocols all with the mention "read and approved" and signed by the Contractor, for each barrier sheet entering the manufacturing process.

Some processes use Nb-X tubes. A part of the wall thickness is reacted whereas the rest acts as a barrier. The chosen thickness of the tube shall be adequate to guarantee no breakage of the tube during cabling and shall pass the sharp bend test. The Bidder shall indicate the tube thickness, the part that is reacted to create the Nb₃Sn phase and the part serving as anti-diffusion of Sn. He will show by his experience how he guarantees the absence of tube breakage during cabling and final reaction heat treatment.

5.2.3 *Copper material*

The copper used for the billet shall be wrought. The copper will be chosen to fulfil the quality requirements of the final strand and cable described in section 5.3.5. The Contractor shall provide CERN with the chemical analysis, the copper resistivity at room temperature (293 K) and the residual resistance ratio $[R(293K) / R(10K)]$ (see section 5.3.5) of the copper incorporated in the billet before manufacturing commences. The value of the residual resistance ratio shall be greater than 250.

5.3 **Strand design**

5.3.1 *Number of filaments*

The number of filaments in the ITD process or the number of tubes in the PIT process shall be such that the overall specified current in the strand (with a copper to non copper of 1.25) will be obtained assuming an area and a Sn percentage of the reacted Nb₃Sn phase. These values shall be based on the Contractor's experience or on the metallographic studies made with the prototype billets. In the ITD process, as an example, the number of Nb filaments of 1 µm in the strand will be approximately 300,000 with a designed value of copper to non-copper ratio of 1.25. In the PIT process, the number of tubes will be between 280 and 500 depending on the real thickness and quality of the Nb₃Sn phase. CERN and the Contractor shall agree on the nominal number of filaments or tubes based on the proven experience of the manufacturer.

5.3.2 *Nominal filament diameter, barrier, filament array and spacing*

Before the assembly of the billet and before any manufacturing begins, the Contractor shall submit to CERN for its approval the design of the overall arrangement of filaments inside the billet. The rods or tubes used to assemble the multifilament billet shall have a regular and symmetrical cross-section. The central part (at least 2 %) of the cross-section area of the billet shall contain no superconducting filaments.

In the PIT process, the nominal filament diameter and filament spacing is determined by the billet design taking into account the volumetric expansion of the filaments at reaction. In order to ensure that the filaments are electrically decoupled, the outer part of the tubes shall stay resistive above 1 T and will not break during manufacturing and cabling.

In the case of the ITD process, the design will be such that the filaments shall not touch each other after reaction. A barrier having a diameter not greater than 50 µm will define the effective diameter of the superconducting zone. In order to ensure that the filamentary zones are electrically decoupled, the barrier shall be resistive above 1 T and will not break during the manufacturing and the cabling.

The tubes and barriers shall be regularly disposed in the billet design and surrounded by a copper sheath as thick as possible to protect mechanically the superconducting areas.

Before strand manufacturing begins, the Contractor shall submit to CERN for its approval a drawing showing the dimensions within the billet and the billet assembly. The Contractor shall demonstrate to CERN that the nominal filament diameter and spacing shall be obtained between tubes or between barriers at the final strand size. The Contractor shall document the number of the Nb rods or tubes assembled in each billet. If a multiple stacking procedure is used for the strand manufacturing, the filament spacing inside a bundle of Nb₃Sn

filament and the barrier spacing will be documented. The average diameter of the filamentary zone and its variation shall be measured by image analysis on strands sampled from the production. The micro-photos shall show the spacing between the non-copper zones and the spacing between the reacted filaments for the ITD process. Metallographic analysis shall indicate the reacted elements and the Sn concentration variation in the Nb₃Sn phase.

5.3.3 Bonding between the elements

The bonding between the elements of the strands is essential for a low degradation at cabling. The Contractor shall establish a billet design and a fabrication process to ensure a good bonding between the constituents of the billets. The Bidder shall indicate how the bonding between the elements will be maintained based on his own manufacturing experience, the billet design and the development program.

5.3.4 Strand annealing

Annealing is a heat treatment at moderate temperature (~ 200 °C) for relaxing the internal stresses in the copper before cabling. It should reduce the cable thermal expansion and provide a more regular variation during the coil thermal cycle. The strand will be annealed before coating (if any) and cabling. The annealing will occur after twisting and at the final dimension of the bare strand. After annealing, the strand shall have a homogenous diameter. The state of annealing of the copper matrix shall be measured by a residual resistance ratio (RRR) check. The Bidder will indicate whether the low temperature annealing around 200 °C will have a negative impact on the strand quality.

5.3.5 Strand Residual Resistance Ratio (RRR)

The strand electrical resistance per unit length shall be determined at room temperature (293 K) and just above the transition temperature of Nb-X (10 K). These two quantities are designated as R(293 K) and R(10 K). The ratio R(293 K)/R(10 K), defined as the residual resistance ratio (RRR), shall be measured on three samples taken from different strand piece lengths of each billet before and after reaction. The residual resistance ratio shall be measured with an accuracy of 5%. The RRR value shall be larger than 120 for annealed strands and be at least 70 for strands in the cable before the latter is submitted to any final heat treatment for reaction (see section 6.6.). The strand samples shall be taken from the ends of each continuous length of cable.

When RRR measurements are performed after the final heat treatment, the low temperature electrical resistance shall be R(20 K). The high RRR value requested in Table I for the strand after the final reaction (greater than 200) would indicate the fair quality of the anti-diffusion barriers. The final value will be agreed between CERN and the Contractor before signing the Contract.

5.3.6 Copper to non-copper volume ratio

The strands shall have a copper to non-copper ratio meeting the value specified in Table I. The copper content shall be determined by weighing the different components on strand samples taken from each billet after having measured with accuracy the diameter and the length of the sample.

In the strand length, at the point where the copper to non-copper volume ratio is stable (stationary region), the Contractor shall determine an average value of the copper to non-copper volume ratio by measuring at least three samples taken on different strand piece lengths.

Transition lengths, which occur at the start and end of the extrusion billet, shall be removed. To identify the transition lengths, a continuous electrical resistance measurement during the strand manufacturing is required to record the copper to non-copper volume ratio with an uncertainty of less than 2 %.

As an alternative to electrical copper to non-copper volume ratio measurements, CERN accepts copper to non-copper volume ratio measurements, which are to be performed by weighing the components on strand samples cut from both ends of the billet after the extrusion in the course of the manufacturing programme until the stationary region is reached. In any case, the Bidders shall describe in the Technical Questionnaire the method proposed for removing the transition regions. The final method shall be agreed between CERN and the Contractor prior to the Contract being signed.

5.3.7 Twist pitch

All the strands shall be twisted so that the filaments follow the same rotation as a right-handed screw thread. The presence, the value and the direction of the filament twisting must be verified on each strand piece length.

5.3.8 Effective filament diameter and magnetization

The effective filament diameter, given in Table I, is the geometrical equivalent diameter provided by the projected size of the barrier impeding the Sn diffusion within the copper at the billet design.

The magnetization of a strand is related to the critical current density at low field and to the filamentary zone diameter. The fabrication processes shall be tightly controlled, to reduce the variations on strand critical current and filament diameter or copper to non-copper volume ratio and critical current density. The NED collaboration will perform magnetization measurements at 4.2 K on one strand sample of each billet. The magnetization will be measured using the standard pick-up coil method or the squid method. The hysteresis behaviour of the sample magnetization will be recorded for a field perpendicular to the strand axis and varying between 0 and 4 T. The width of the magnetization loop of the annealed strands at 2 T and 4.2 K shall be less than 300 mT. No flux jump, which could induce a quench in a magnet environment, shall be observed during these measurements.

5.3.9 Minimum length of strands

Minimum length requirements are imposed to assure a high quality of the strand, of its manufacturing process and to show that the process has potentiality for industrialization. The minimum length is 1000 m. Strand length shall be determined after all lead and end defects have been removed. Before the manufacturing of cable begins, the Contractor shall submit to CERN a continuous compilation of all strand piece length measurements. The homogeneity of the production shall be demonstrated by metallographic photos. In case of

breakages, the Contractor shall supply to CERN a technical report explaining the reasons of the breakages and propose remedies.

5.4 Surface condition and coating of the strands

The strand surface before coating shall be free of any surface defects, slivers, folds, laminations or inclusions. No Nb or barrier material shall be visible.

It is not yet decided to have a cable with coated strands or a cored cable. The individual strands could be coated with a material having a maximum thickness of 1 μm , specified according to the norm DIN 40500(V2). If coated, the coating material is not yet decided. For the present tendering, a Ni coating will be assumed. The surface of the finished strand must be smooth and clean. The coating process shall be maintained under a tight control in order to guarantee the inter-strand cross contact resistance after the cable heat treatment in the magnet. Depending on calculations and measurements of the final inter-strand resistance, the type of coating can be modified until the cabling starts. The Bidder shall provide evidence that the coating process he intends to use, either at its premises or at its sub-Contractors', can be consistently controlled. The Bidder will indicate separately the costs for the coating as specified.

5.5 Heat Treatment Cycle for Nb₃Sn phase reaction

The Contractor will supply all the precise information (the various cycles, temperature, duration) concerning the required reaction heat treatment cycle coming from the optimization. He will keep in mind that the temperature rise time will be governed by the mass of the coils (> 500 kg). The rise time shall not be then a crucial parameter for the electrical characteristics of the final strand and cable.

5.6 Frequency of strand sample testing

The required frequency of strand sample testing by the Contractor is summarized in Appendix D. The method of transmission of the test data to CERN is stipulated in section 7.5. The Contractor shall deliver to CERN one 10 m long strand test sample, which shall be taken adjacent to each strand used by the Contractor for the electrical characterisation.

5.7 Mechanical and geometrical tests

5.7.1 Sharp bend test

In order to ensure that the strands are well suited for cabling, the Contractor shall subject the strands, after coating (if any), to a sharp bend test, as described in Appendix A. The sharp bend test shall be performed on three adjacent samples. Before etching, no deterioration of the bond between the superconducting filaments and the copper matrix and no sign of cracking at the outer diameter of the sharp bend shall be visible under a magnification of at least 50. After etching, the bent sample shall be inspected for broken barrier or filaments. A critical current measurement and a RRR measurement will be performed after the sharp bend

test has been made at 10 locations with 1 m long samples followed by the reaction heat treatment cycle after sample re-alignment.

5.7.2 Spring back test

The spring back test must be performed on three adjacent samples taken after coating (if any). The test procedure is described in Appendix B. The maximum acceptable value of unwinding of the spring for any strand of cable is 3 turns.

5.7.3 Eddy current test

Each strand shall be checked continuously on its overall length by an eddy current method to detect inclusions, voids, cracks and barrier defects.

5.7.4 Strand diameter

The Contractor shall verify the strand diameter by means of a calibrated laser micrometer. All the strands that have been manufactured shall be checked on line before coating and after coating (if any) with a two-axis laser micrometer. The Contractor shall provide statistical analysis of the laser micrometer measurements. The strand diameter, after coating, shall be within the control limits of $\pm 4 \mu\text{m}$ compared to the nominal diameter of 1.25 mm over the full length. The ovality of the strands before coating, defined as the difference between the diameters measured for the two axes, shall be less than $5 \mu\text{m}$.

5.7.5 Measurements after strand deformation

The strand will be submitted to a diameter deformation varying between 5 to 50 % by passing through rollers. A metallographic analysis will demonstrate the integrity of the strand and the barriers. After a reaction heat treatment, critical current measurements will be performed to deduce the degradation due to deformation.

5.8 Critical current in the strand

5.8.1 Definition of the critical current and quality index

The voltage (U) and current (I) of a reacted strand are recorded as a function of increasing current until an irreversible transition or quench occurs. This measurement is carried out for several specified external fields applied normal to the strand axis and at the measured temperature of a liquid helium bath. For currents below the quench current, the relation between voltage and current is reversible. The critical current in the strand is defined as the current measured at an electric field of $10 \mu\text{V/m}$. Data points are taken up to a voltage corresponding to an electrical field of at least $100 \mu\text{V/m}$ and at a current ramping rate not larger than 20 A/s. The n-value or quality index is defined as the slope of the $\log(U)$ versus $\log(I)$ curve for all data points measured upwards and downwards in the reversible part of the voltage versus current curve. The n-value will be recorded and will be constant for all the billets.

The voltage (U) of a reacted strand at a fixed current can also be recorded as a function of increasing field until a transition occurs. The voltage variations will be recorded in view of measuring the flux jumps if any. The Bidder shall indicate if his measuring set-up allows this procedure.

5.8.2 Critical current measurements

The Bidder shall indicate the fields and current available at his test facility. The Contractor shall describe the sample arrangement on its holder and all the equipment to record the U-I curve. The exact protocol of short sample measurements is to be agreed between CERN and the Contractor and will depend on the arrangement of the short sample on its holder in the critical current measurement set-up. A working group has been settled to describe the strand short sample measurement set-up and procedures, which will be applied in the various laboratories (INFN-Milano, CEA/DSM-Saclay and University of Twente). The idea is to have the strand to be measured as reacted on the final sample holder. The strand has to make ~ 2 turns on a copper ring for current transfer.

5.8.3 Electrical acceptance criteria

The minimum specified critical current at 4.222 K, 15 T is 818 A or 1636 A at 12 T as measured by the NED collaboration. The Contractor shall perform the critical current measurements of the strands on a minimum of three samples coming from different strand piece lengths of each billet having a copper to non-copper ratio meeting the requirements given in section 5.3.6, twisted and having received the final reaction heat treatment. The final heat treatment will be precisely recorded. The critical current will be measured at 10, 11, 12, 13, 14, 15 T if possible and corrected to the reference temperature 4.222 K using the formula given in Appendix C. If all the samples of a billet have a critical current greater than 1636 A at 12 T, 4.222 K for strand (values fixed as explained in section 5.1), the strands of the billet may be used in the cable manufacturing, provided that all other requirements of the present specification are fulfilled as well. If one strand piece length has a critical current value below 1636 A at 12 T, 4.222 K, all strand piece lengths from the same billet have to be tested. The ratio of the critical currents at 12 and 13 T or 12 and 15 T will be recorded.

The existence and the number of quenches happening before reaching the reversible resistance build-up part of the U-I curve shall be noted and recorded. Any strand that has more than ten quenches shall be rejected.

The n-value shall be determined in the range from 10 $\mu\text{V}/\text{m}$ to 100 $\mu\text{V}/\text{m}$ at each applied field and shall be recorded and stay nearly constant for all the billets.

Samples adjacent to the ones used by the Contractor for short sample measurements must be delivered to CERN. The NED collaboration will perform critical current measurements on these samples at 11, 12, 13, 14 and 15 T and 4.222 K.

6. CABLES

The strands shall be cabled on a high quality, fully controlled cabling machine. The Bidders shall provide evidence that the cabling machine they propose to use is capable of fulfilling the stringent quality requirements of the NED cable in the interest of efficiency and of a consistent quality control.

The required characteristics of the cable are given in Table II.

6.1 Table II: Main characteristics of Nb₃Sn cable

The values given in the following tables are indicative. The final specifications on cable dimensions will be decided before June 2006 and after cabling tests. The cable critical currents assume a cable degradation of 10 %. Following the results of the cabling tests, the specified values of the cable critical values can be revised. The tables refer to two types of cables related to the two potential magnet designs. They use the same strand type. If a cored cable is decided, the dimensions will be revised according to the experience.

Cable 40 strands (Reference design)

This cable is for a 88mm bore dipole magnet with a two-layer coil configuration.

Cable width	26 mm
Cable mid-thickness at 50 MPa	2.275mm
Keystone angle	0.22 degrees
Cable thin edge thickness	2.175 mm
Cable thick edge thickness	2.375 mm
Cable transposition pitch	~180 mm
Number of superconducting strands	40
Critical current at 4.222 K, with field normal to broad face	29440 A at 15 T 58880 A at 12 T
Minimum critical current at 4.222 K of extracted strand	736 A at 15 T 1472 A at 12 T
n-value @ 15 T and 4.222 K	> 20
Residual resistance ratio before reaction	≥ 70
after reaction	≥ 120
Cable transposition direction	left-handed screw thread
Minimum unit length	145 m

Cable 24 strands (variant design)

This cable is for a 88mm bore dipole magnet with a block motor coil configuration

Cable width	15.6 mm
Cable mid-thickness at 50 MPa	2.175 mm
Rectangular cable	
Cable transposition pitch	~110 mm
Number of superconducting strands	24
Critical current at 4.222 K, with field normal to broad face	17660 A at 15 T 35320 A at 12 T
Minimum critical current at 4.222 K of extracted strand	736 A at 15 T 1472 A at 12 T
n-value @ 15 T and 4.222 K	> 20
Residual resistance ratio before reaction	≥ 70
after reaction	≥ 120
Cable transposition direction	left-handed screw thread
Minimum unit length	255 m

6.2 Geometrical characteristics

6.2.1 Dimensions

The cable dimensions given in the previous tables are to be obtained after reaction. Before reaction, at the cabling, the dimensions and the packing factor will be different to take into account the volumetric expansion at reaction. It is assumed that the thicknesses will be the same if an adequate packing factor will be chosen for cabling. The cable mid-thickness values given in Table II for a transversal pressure of 50 MPa is the nominal value of the cable mid-thickness. The cable mid-thickness at a pressure of 50 MPa is verified by measuring the height of 10 samples (15 cm long) of unreacted cable stacked with alternated positions in a ten-stack measuring fixture, which will be provided by CERN to the Contractor. The ten-stack measurements will be performed at the beginning of each cabling run to adjust the cable mid-thickness on the cabling machine. The cable width, the keystone angle and the mid-thickness shall be measured at 20 MPa during manufacturing and recorded at least every 3 m by a cable measuring machine, (hereafter referred to as "CMM"). Further resizing of the cable shall not be accepted by CERN. The ten-stack measurements shall be correlated to the values measured on the CMM during the cable manufacturing.

The cable width, the keystone angle and the mid-thickness will be measured by and at CERN on the overall length of unit lengths of cable. Previous experience has shown that the dimensional measurements performed with the CERN measuring equipment and with the CMM during cabling are well correlated. The tension on the strands and on the cable during cabling shall be measured and kept constant over the fabrication. The exact protocol for on-

line dimensional measurements and their reporting shall be agreed between CERN and the Contractor before the Contract is signed. Appendix E describes the calibration procedure currently foreseen for the measurement of the cable dimensions.

6.2.2 Cable transposition direction

The transposition direction of the strands is opposite to the twist direction of the filaments in the strands in order to reduce the amount of residual twist in the cable. The cable shall be transposed counter clockwise following the rotation of a left-hand screw thread.

6.2.3 Continuous length and unit length of cable

A continuous length of cable contains 40 continuous lengths of strand that are unbroken and without welds and that conform to the present specification and have been manufactured in the same cabling run.

The cable must be delivered in continuous lengths equal to the minimum unit length or to a multiple of it. The minimum unit length is 145 m for the cable (see section 6.1). Fractions of a unit length shall not be accepted.

6.3 Quality of cable

6.3.1 Cable surface condition

The surface of the cable shall be delivered in a clean condition free from oil, metallic particles or other residues. To avoid damage to the electrical insulation, which shall be wrapped around it, the edge of the cable shall be smooth and free of roughness, sharp edges, slivers or burrs. To demonstrate the absence of sharp edges the Contractor shall take a photograph, with a magnification of 50, of the cable thin edge at the beginning of any cabling run. This photo will be part of the quality control documentation and be archived. The lubricant used during cabling shall not deteriorate the inter-strand cross contact resistance of the cable. Its use is subject to prior written approval by CERN prior to cabling. Any use of cleaning solvents is subject to prior written approval by CERN. The Contractor shall propose the cleaning method to CERN for its approval.

6.3.2 Cable residual twist

The residual twist of the cable in the unloaded condition shall be as small as possible and less than 1.5 turns on any 10 m length.

6.3.3 Welds and cross-overs

No broken or repaired strands, no welds and no cross-overs of strands are acceptable in any unit length of cable.

6.3.4 Cable expansion

The cable is expected not to expand longitudinally more than 1 % at ambient temperature after full reaction. The Contractor will perform the contraction measurements on 1 m long cable sampled from the production. It is assumed here that the volumetric expansion at reaction is 3 % and that the strand diameter will grow by ~ 2 %. One expects that the filling factor of the cable would change without any substantial modification in cable transverse dimensions.

6.4 Selection and identification of strands for cable

6.4.1 Identification of the strands

All the strands, which are incorporated into the cable, shall be taken from billets incorporating raw material originating from the same raw material lot. Each strand shall be identified by a unique code number and shall be traceable to the billet code number. At each step of the cable manufacturing process, the strand shall be traceable to the original code number.

6.4.2 Cable strand map

Prior to each cabling run, the Contractor shall submit to CERN for its written approval a strand map for each unit length giving the foreseen position of the selected strands in the cable, their code number, their calculated critical current, their copper to non-copper ratio and the sum of the critical currents for the strands to be incorporated in the cable. The calculated strand critical current is obtained by multiplying the average critical current density of all strand samples coming from one billet by the non-copper cross section of the selected strand, taking into account the average value of the copper to non-copper volume ratio of the billet (as defined in section 5.3.6). The Contractor shall select the strands to be incorporated in the cable such that the variation of the sum of the calculated strand critical currents in a cable shall remain within control limits of $\pm 2\%$ from the target average value.

6.4.3 Welds in a cabling run

On the cabling machine, lengths of strands corresponding to a cable unit length can be joined, if necessary, by welds in order to improve the cabling process efficiency. After cabling the well-identified weld regions will be removed with care, stored and kept at CERN's disposal. The Contractor's quality assurance programme shall address the removal of welds from the cable and clearly demonstrate the absence of welds in each cable length delivered to CERN. The detailed procedure for the traceability of the weld shall be established in agreement with CERN.

6.5 Cable with a metallic core

The cabling machine shall be able to cable the strands around a central metallic foil made of stainless steel (for example). The thickness of the core could vary from 25 μm to 100 μm . The final dimensions will be adapted after experience if this approach is decided before the start of the cabling. The Bidder shall quote the cost of cabling with a core.

6.6 Pre-reaction on the finished cable

The finished cable shall be submitted to a heat treatment in an Ar (A 99.97) atmosphere at max 220 °C. The duration of this heat treatment of pre-reaction at a temperature below melting of the Sn compound will be decided by the Contractor in conjunction with the subsequent heat treatments for the final reaction in the magnet. The Bidder shall describe the proposed method. If sintering between strands occurs during this pre-reaction heat treatment, the cable will be un-spooled and re-spooled passing through dedicated rollers to open the cable without destroying the mechanical stability. A 10-stack measurement will be performed after

the low temperature heat treatment. The Bidder shall indicate the possible gain (if any) of the pre-heat treatment on the total reaction time duration.

6.7 Cable bend test and mechanical stability

The purpose of this test is to check the mechanical stability of the cable and the absence of cracks and fractures after bending in order to ensure that the cable is suitable for coil winding. A cable sample of 200 mm long is bent over a 12 mm diameter rod while applying a 30 kg tensile load. The cables shall keep their coherence after bending, proving their mechanical stability.

The bent cable will be examined under a microscope with a magnification of at least 50 to determine if any strands are cracked or fractured near the cable edges. Subsequently, the bent area of the sample will be etched in nitric acid and examined for possible filament damage. Cables showing broken filaments or broken barriers will not be accepted. The bending test of the cable shall be performed on one sample for each continuous length of cable to be delivered to CERN.

6.8 Cabling tests

The Bidder shall incorporate in his development programme cabling tests with the mechanical, dimensional and electrical characterization in view of the final adaptation of the specification. The cabling tests will allow the deduction of the cabling degradation in connection with the billet design. They will allow performing winding tests for the coil ends. The Bidder will indicate his capabilities of making short lengths of cable with various packing factors. He will indicate the costs of the cabling tests and the material required.

6.9 Overall critical current in the cable

6.9.1 Cable critical current

The critical current in the finished cable is defined as the current measured at an electrical field of 10 $\mu\text{V/m}$. The specified minimum critical current at 4.222 K is 29440 A at 15T or 58880 A at 12 T for the cable of 40 strands and is 17660 A at 15 T and 35320 A at 12 T for the 24 strand cable.

The defined magnetic field is perpendicular to the broad face of the cable. The field taken into consideration is the maximum magnetic field seen by any strands of the cable in the measuring set-up, taking into account the effect of the self-field, averaged on the strand cross-section.

6.9.2 Degradation during cabling

Before sending the cable to CERN, the Contractor shall measure, for each cabling run, the critical currents of extracted strands and compare them with the measured critical currents of the same strands before cabling. The degradation shall not exceed 10 % for any strand. The degradation value can be revised after the cabling tests. To have a sufficient number of measurements for statistics, CERN requires that critical current measurements be made on at least five extracted strands and five virgin strands selected in such a way that each billet entering in the cable manufacturing is tested. Short samples will be taken from one end of each cabling run, directly on the cabling machine where the identification is still possible.

The degradation during cabling will be checked by making critical current measurements at 12 and 15 T and corrected to the reference temperature of 4.222 K as described in Appendix C. The above data shall be reported to CERN.

6.9.3 *Electrical acceptance tests at Contractor's premises*

Before sending the cable to CERN, the performance of the manufactured cable shall be checked by the Contractor by critical current measurements on 5 extracted strands randomly taken from samples cut from one end of each continuous length of cable. The cable will be refused if the critical current of any extracted strand does not reach, at 4.222 K and 12 T, the minimum current of 1472 A. Depending of the critical current value achieved during the cable tests, the minimum critical current of extracted strand at 4.222 K and 12 T will be reviewed. The average measured value of the 5 extracted strands will be multiplied by the number of strands to define the critical current of the cable. The calculated cable critical currents values at 4.222 K shall be reported to CERN with the proposed strand map.

6.9.4 *Electrical acceptance tests and criteria at the NED collaboration*

The NED collaboration will perform the acceptance test of the cable in the following manner. The performance of the manufactured cable will be monitored by critical current measurements on 5 extracted strands randomly taken from samples cut from one end of each continuous length of the cable. Heat treatments as specified by the Contractor will be performed on the measuring holder. The cable may be refused if the critical current on each extracted strand does not reach the minimum current specified in Table II, namely 736 A at 15 T or 1472 A at 12 T and 4.222 K. These values can be adapted after the results of the cabling tests. Any unit length, which does not reach the minimum critical current specified, will be rejected.

6.10 *Critical current measurements under pressure*

Reacted cables will be assembled and impregnated in a fixture in order to measure the cable critical current under a pressure perpendicular to the broad cable face and varying from 50 to 180 MPa to study the critical current degradation under the mechanical forces. These measurements will be performed on the test cables and on the final cables.

6.11 *Frequency of cable sample testing*

The frequency of cable sample testing by the Contractor is summarised in Appendix F. The transmission of the data to CERN will be as specified in section 7.5. One 5 m long cable sample, taken from one end of each delivered length of cable, shall be delivered to CERN, as required in section 7.1.

7. PREPARATION FOR DELIVERY AND TRANSPORT

7.1 *Test specimen submission*

Before shipping the spools of cable to CERN, the Contractor shall deliver to CERN a 5 m long sample of cable taken from one end of every continuous length of cable. Sample identification shall include the mention "pre-shipment test specimen" and the data defined in

section 7.6. These samples shall be marked with the cable identification number and delivered to CERN as soon as possible after the manufacture of the cable and before the cable shipment. The cable samples shall be accompanied by the results of the mechanical measurements made during the cabling operation and by a copy of the cable strand map (see section 6.4.2.). These samples will be used by CERN to verify the mechanical and electrical characteristics of the cable before the approval for the delivery of the cable spools.

7.2 Spools

The cable shall be wound on the spools in such a way that there are no cross-overs of the cable. A protection sheet shall be placed between cable layers to prevent damage of one layer by another. The starting end of the cabling length will be marked with blue paint. The finishing end of the cabling run will be marked with a red colour. Starting and finishing here refer to the order during the cable manufacturing. The spools shall be designed and constructed to prevent damage to the cable properties during spooling and un-spooling.

7.3 Packing

Spools of cable shall be boxed or strapped to a pallet to prevent damage during transport. They shall be stacked with the spool flanges vertical in order to prevent the cable from settling on the spool. Each spool shall be marked with the cable identification code.

7.4 Inspection, test results and protocols

The Contractor shall provide written reports of the tests required by the present specification as outlined in Appendix G, together with a copy of any and all test certificates. Appendix G gives a non-exhaustive summary of the data to be reported. The inspection and test results shall also be written into a database in a computer form compatible for an IBM PC (or compatible computer). The details of this database will be discussed between CERN and the Contractor and an acceptable format will be agreed between by CERN and the Contractor before manufacturing begins.

7.5 Transmission of data

A means for electronic or remote computer readable transfer via a network link shall be established between CERN and the Contractor before the Contract is signed.

7.6 Marking and identification requirements

Spools and exterior packaging shall be identified with the following information:

- "cable Nb₃Sn",
- specification no.,
- name of manufacturer,
- date of manufacturing,
- CERN order no.,
- cable identification no.,
- strand map no.,

- length (in m),
- weight (in kg).

8. CERN CONTACT PERSONS

Persons to be contacted for technical matters:

Name/Division/Group	Tel-Fax	Email
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	Fax: +41 22 767 7450	

Annex A: Sharp bend procedure

The purpose of the sharp bend test is to simulate the deformation of the superconducting strand that may occur during cabling. The sharp bend test fixture is shown in fig. A1.

1. Bend the strand sample in half over a rod 1.3 mm diameter for the strand of cable.
2. Remove the rod and place the bent sample in the slot of an appropriate fixture; squeeze the sample to the value of two strand diameters in order to get a hairpin.

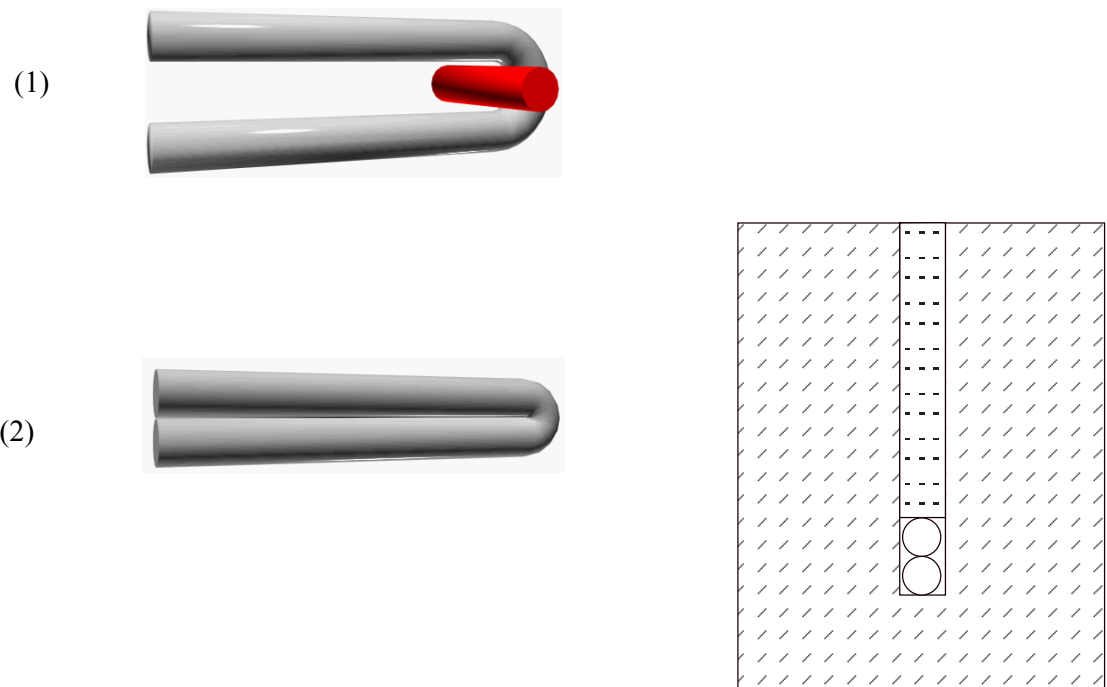


Figure A1.

3. Examine the bend under a microscope with a magnification of at least 50 to determine if the surface of the strand is cracked or deformed in a way to inhibit cabling.
4. Etch the sharp bend sample in nitric acid and examine the sample again under the microscope to determine possible filament damage.
5. Repeat the test three times on different samples taken from each strand length. Fill in the inspection report (see appendix G).

Annex B: Spring back test procedure

This test method, introduced to standardise the measurements of the spring back of superconducting strands, determines the amount of spring back accepted for cabling.

The test is performed on three 1m long undeformed straight strands taken from each strand length. The equipment to be used is shown in fig. B1.

Test procedure :

1. The strand test sample is bent on one end by 90 degree over a length of 15 mm to be fixed through a hole in the 10 mm diameter shaft. The other end of the sample is fixed to the 2 kg weight.
2. Perform 10 complete turns with the spring winder, keeping the strand clamp and the locking pin loose. This produces a 10-turn coil spring of superconducting strand.
3. Block the locking pin and strand clamp, then gently open the locking pin, after which the spring winder will start unwinding.
4. Note and record the number of turns over which the spring unwinds. Once the spring has been taken off the fixture without further unwinding, measure and record the mean inner diameter of the spring. All three samples shall be labelled and stored.

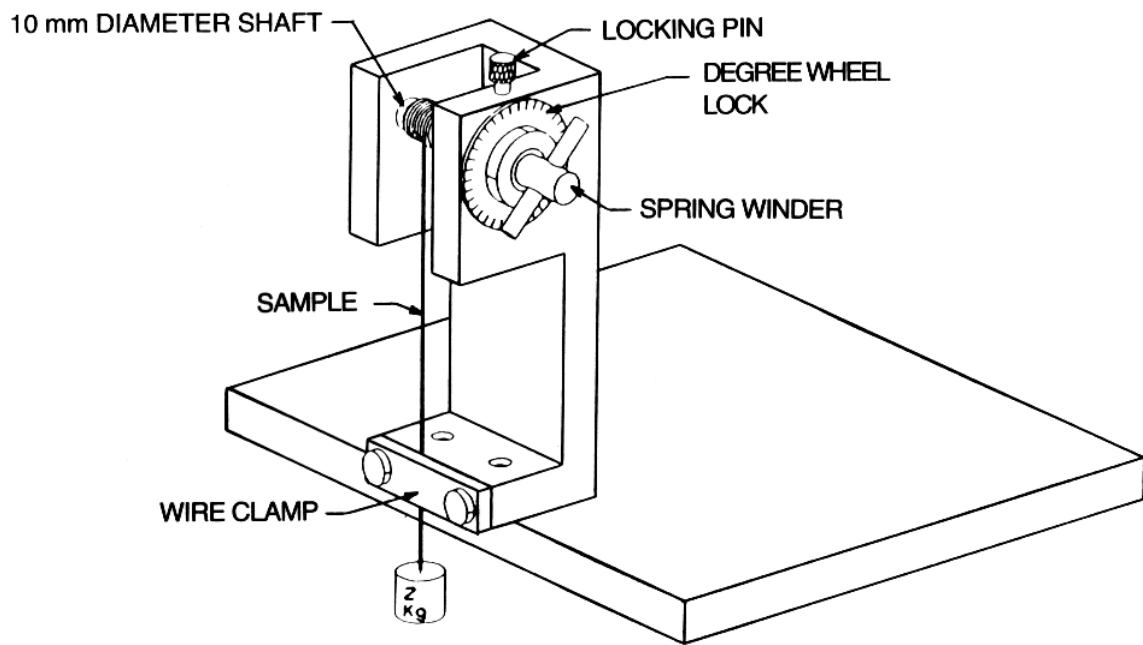


Figure B1: Spring back test fixture

Annex C: Precision required for the critical current measurements

1. Correction for bath temperature

The specification temperature is 4.222 K, that of boiling helium at standard atmospheric pressure. The bath temperature shall be recorded with an accuracy of 10 mK. For a measured temperature different from 4.222 K, a linear temperature relation should be assumed to correct the measured critical current to that at the specification temperature:

$$I_c/I_m = (T_c - 4.222)/(T_c - T_m) \quad \text{for } T_m < 4.2 \pm 0.2 \text{ K}$$

with T_c = critical temperature at the specified magnetic field
 I_c = critical current at the specification temperature
 I_m = measured critical current at temperature T_m
 T_m = measured temperature of the liquid helium bath

2. Magnetic Field

- The magnetic field shall be uniform to 0.5 % over the sample length.
- The direction between field and strand axis shall be $90^\circ \pm 6^\circ$.

The magnet field value measurement system shall have a resolution better than 20 mT and an absolute accuracy better than 1%. The field setting shall have a repeatability better than 0.5 %.

3. Current

The current shall be measured with a resolution better than 0.1 A and an absolute accuracy better than 0.5%.

The resolution is defined as the smallest portion of the signal that can be observed.

The absolute accuracy is the difference between the result of the measurement and the real value of the measured parameter.

Annex D: Frequency of strand sample testing

Table I - Strand dimensional and mechanical requirements.

<u>Requirement</u>	<u>Test Frequency</u>
Number of filaments, number of barriers or Nb-X tubes.	Contractor Quality Control Plan
Nominal effective filament diameter and spacing between barriers and filaments.	Demonstration from billet design
Metallographic analysis of the Nb ₃ Sn phases	Image and metallographic analysis
Average filament diameter	
Strand diameter	Continuous laser micrometer measurements
Strand twist direction	A sample of each strand piece length
Strand twist pitch	Value verified after the setting of the twisting machine and on minimum 3 samples per billet
Strand sharp bend test after coating	Minimum three samples per billet selected from widely separated strand piece lengths or 25% of the number of strand piece lengths, whichever is greater
Strand spring back test after coating	Minimum three samples per billet selected from widely separated strand piece lengths or 25% of the number of strand piece lengths, whichever is greater
Strand surface condition	Contractor Quality Control Plan
Strand eddy current test	Continuous test on each strand piece length

Table II - Strand electrical requirements

Note: a 10 m long strand test sample , which is adjacent to strand used by the Contractor for the electrical characterization, shall be delivered to CERN.

<u>Requirement</u>	<u>Test Frequency</u>
Strand critical current	Minimum 3 after the final heat treated samples from each billet, selected from widely separated strand piece lengths and one additional sample for each breakage
Copper to non-copper ratio	By the weighing method and in the case where a continuous electrical resistance measurement method is implemented: minimum on both ends of each billet and on 3 samples taken on different strand piece lengths By the weighing method and in the case where a continuous electrical method is not implemented: minimum on both ends of each strand piece length or 5 samples from each billet, whichever is greater
Strand minimum residual resistance ratio	Minimum 3 samples from each billet taken from different strand piece lengths

Annex E: Calibration Procedure for Measurement of Cable Dimensions

1. Cable Dimensions

The Turkshead adjustments to produce cable with the specified mid-thickness, have to be made taking the result of the 10-stack measurement at 50 MPa as the reference. The cable mid-thickness values measured by the CMM shall be considered as relative measurements to maintain the cable mid-thickness within the required tolerances.

The initial measurements of the cable width and keystone angle shall be made with the CMM calibrated using a certified reference standard gauge before each cable manufacturing run.

2. Calibration of the Cable Measuring Machine and gauge checks

At the beginning of each cable manufacturing run, the CMM is to be calibrated using a certified, flat, reference gauge. This initial calibration is further checked using a keystone angle gauge certified by CERN. The following test sequence is required to check the CMM calibration:

- make a minimum of two measurements with the flat reference gauge
- make a minimum of five measurements with the keystone angle gauge.

The angular measurements given by the CMM are expected to be within $\pm 0.01^\circ$ of the keystone angle gauge.

3. Cable checks at the beginning of the run

At the beginning of each cable run the cable mid-thickness value at 50 MPa is to be measured using the 10-stack fixture. Cable samples used for off-line tests of the cable dimensional and mechanical requirement, are to be taken just after having made the final Turkshead adjustments, giving cable within specified dimensional tolerance limits. At the start of production of the 2 m “hub” cable sample for the 10-stack measurements the CMM mid-thickness measurements are to be made at intervals of 30 cm. The average value of these measurements will be correlated to the mid-thickness value determined on the “hub” cable sample with the 10-stack. Before starting the cabling run, a photo of the small edge of the cable with a magnification of 50 shall be taken and inspected to ensure the absence of sharp edges.

4. Cable checks at the end of the run

Normally, at the end of the cabling run, the cable mid-thickness should be stable within 2 μm . The Contractor should ensure that this is the case. The cable mid-thickness value is to be checked, off-line, by a 10-stack measurement. During production of the 2 m cable sample at the end of cable manufacturing the CMM measurements are to be taken at intervals of 30 cm. The average value of these measurements will be correlated to the mid-thickness value determined with the 10-stack. At the end of the cable manufacturing run the CMM calibration is to be checked by carrying out a minimum of two measurements against the flat reference gauge.

Annex F: Frequency of cable sample testing**Table I – Cable dimensional and mechanical requirements**

<u>Requirement</u>	<u>Test Frequency</u>
Cable mid-thickness, width and keystone angle	Continuous measurement with a CMM at 20 MPa. Off-line check of mid-thickness with a ten-stacked measuring fixture every continuous length of cable.
Cable transposition direction and pitch	Contractor Quality Control Plan
Strand twist pitch in cable	Contractor Quality Control Plan
Cable surface condition	Contractor Quality Control Plan
Cable residual twist	Every continuous length of cable
Cable bend test	Every continuous length of cable
Cable filament condition	Every continuous length of cable
Inter-strand cross contact resistance	Cable sampling

Table II - Cable electrical requirements

<u>Requirement</u>	<u>Test Frequency</u>
Critical current measurements on extracted strands	5 extracted strand samples will be taken from each continuous length of cable
Degradation due to cabling	Every cabling run: 5 extracted strand samples taken from the end of the cabling run and 5 virgin strand samples
Residual resistivity ratio	5 strand samples extracted from one end of each continuous length of cable

Annex G: Nb₃Sn superconducting strand test results

NED Project		Contractor				Certification date		
Specification No.					Contractor quality			
CERN Order No.					Representative			
Billet Identification No.								
Production unit								
HT cycle								
Remarks								
Test Item		Unit	Sample No.					
Strand Diameter average/strand ovality		mm						
Copper to non copper Ratio		-						
Number of superconducting zones surrounded by barriers.		-						
Photo of the filamentary zone								
Filament Twist Pitch		mm						
Filament Twist Direction		-						
Twist OK ? (Y/N)		-						
Resistance	R(293 K)	$\mu\Omega/m$						
	R(20 K)	$\mu\Omega/m$						
	RRR	-						
Sharp Bend Test	No. of cracks	-						
	No. of broken filaments	-						
Spring back Test	No. of Turns	-						
	Inner diameter	mm						
Eddy Current Test OK ?		-						
I _c	Test Field	T						
	Test Temperature	K						
	Measured I _c	A						
	Corrected I _c at 4.222 K	A						
	n-value	-						

Nb₃Sn cable test results

NED Project		Contractor	Certification date			
Specification No.			Contractor quality			
CERN Order No.			Representative			
Cable Identification No.			Spool No.			
Strand map No.			Date of manufacturing			
HT cycle						
Remarks						
Test Item		Unit	Sample No.			
Cable length		m				
Cable mid-thickness		mm				
Cable width		mm				
Keystone angle		deg				
Cable Transposition Pitch		mm				
Cable Transposition Direction		-				
Tension during cabling		N				
Residual twist of the cable		deg./m				
Surface condition		-				
Cable Bend	No. of cracks	-				
Test	No. of broken filaments	-				
Cable Integrity (no broken strands, no cross-overs, no repaired strands, no welds) (Y/N)		-				
Virgin strands						
I _c	Test Field	T				
	Test Temperature	K				
	Measured I _c	A				
	I _c at 4.222 K	A				
	n-value	-				
Extracted strands						
I _c	Test Field	T				
	Test Temperature	K				
	Measured I _c	A				
	I _c at 4.222 K	A				
	n-value	-				
RRR		-				