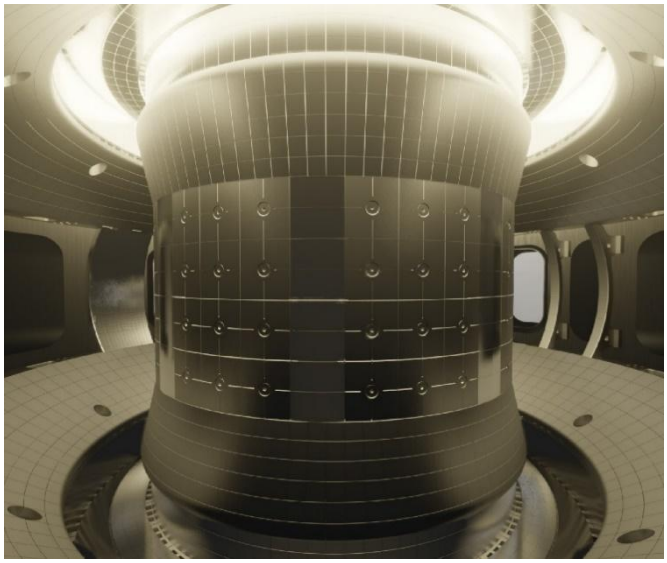
Technical specification

for

Poloidal Field Coils for COMPASS Upgrade tokamak

CU_CUPG-03_PTD_ Annex No. 1 - Technical Specification Poloidal Field Coils



IPP INSTITUTE OF PLASMA PHYSICS OF THE CZECH ACADEMY OF SCIENCES

MINISTRY OF EDUCATION, YOUTH AND SPORTS

Date: 10. 1. 2025

Version: 1.0

Table of content

1 Introduction

Disclaimer: The purpose of this chapter is to give a general overview and show the context of the tendered system – the Poloidal Field coils. The detailed description for manufacturing, defining the subject of the tender, is in chapter 5 and in the attached technical drawings.

There are several types of coils on the COMPASS-U tokamak with different function and geometry: Toroidal Field coils (TF) creating the toroidal magnetic field, Poloidal Field coils (PF) and Central Solenoid (CS) coils both creating the poloidal magnetic field and Correction coils distributed on the inner side of the tokamak vacuum vessel for control of the toroidal symmetry of the magnetic field. The scope of this particular Contract is the set of the PF coils.

There will be 10 poloidal field coils in total (five pairs) in the COMPASS-U tokamak. The five upper coils are named PF1aU, PF1bU, PF2U, PF3U and PF4U, detailed parameters are shown in Table 3-1, their counterparts are lower coils PF1aL, PF1bL, PF2L, PF3L and PF4L. Upper and lower coils form pairs, but are not exactly symmetrical, e.g. they differ in current feeders and coolant feeders placement. The winding pattern of the coils is optimized for error magnetic fields in the vacuum vessel and will be provided in drawings for each coil. Coils shall be wound from the hollow conductor to allow flow of cooling medium - gaseous helium. Each PF coil will have to accommodate multiple separate cooling circuits. Coolant inlet will be made of copper - stainless steel electrical break. PF coils current feeders are formed by parallel conductors. PF coils PF1-PF3 have additional wraps to help secure coils in the holding structure.

Each coil will be made of several separate conductors forming the individual cooling circuits. The advantage of the concept is that the joint of cooling channels can be done outside of the poorly accessible area inside the TF coils. The serial electrical connection of the separate coil windings creating these cooling circuits must be ensured.

A concise, but not fully complete, overview of the PF coils can be found in “Annex of technical specification No 5. – Overview presentation of the PF coils”.

Requirements are delineated in the following paragraphs.

1.1 Assembly and standard operation of the PF coils

PF coils will be placed in vacuum cryostat, therefore it is necessary that all materials and parts used for the coils manufacture shall be compatible with high vacuum operation - see the Annex of technical specification No. 1 - Vacuum compatibility. Moreover, special attention has to be paid to the quality of electrical insulation of the coils as one of major failure scenarios of the coils is electrical breakdown in case of leak in the cryostat. Especially, el. insulation in the area of coil feeders is of utmost importance. This is the reason why local Paschen tests are required for the chosen coil parts and full surface coverage Paschen test of coils can be optionally ordered by the Buyer. Nominal operating voltage of the PF coils is up to ±1 kV, with voltage spikes less than ±1.5 kV.

PF coils assembly will be a delicate and precise process. The coils will have to fit very precisely (in the order of few mm) in the stainless steel support structure. Any imprecisions in coil conductor circularity and its displacement and tilt with respect to the optimal position defined by the technical drawings will also lead to rise of error magnetic field in the tokamak vacuum vessel. This would seriously hamper the plasma performance and limit tokamak exploitation. It is therefore essential that the coil dimensional tolerances provided in this technical specification are fulfilled.

PF coils will be operated both at room temperature (initial operation at limited parameters) and at temperature of liquid nitrogen (77 K). Cryogenic coil operation will be standard, its aim being to reduce

coil resistances and allow higher currents and longer discharges. Maximum coil currents are ±25 kA (PF1a, PF1b, PF2, PF3) and ±30 kA (PF4). Typical tokamak discharge length will be 1-5 seconds and maximum allowed coils heat-up will be limited to ΔT = 80 K (i.e. up to 157 K). The coils will be cooled down using gaseous helium coolant flowing through internal cooling channel of the conductor. Nominal helium pressure will be 20 bar. It is essential that the manufactured coils will be able to operate in the whole range of used temperatures with low degradation caused by the temperature cycling. Busbars (not part of the delivery within "Poloidal Field Coils for COMPASS Upgrade tokamak" tender) interconnect PF coils terminals (ends of PF coils feeders) operated at cryogenic temperature with PF coils power supply cables, which are operated at room temperature and located at the tokamak cryostat.

PF coils are placed in an area of high poloidal and toroidal magnetic fields (up to 10 T) and associated electromagnetic forces acting on the coil conductor are very high (vertical forces up to ±2.5 MN, radial forces up to 8 MN). Corresponding high stresses in the conductor pose a significant challenge. For this reason, there are strict tolerances on conductor tensile yield strength. Moreover, conductor deformation and differential thermal expansion leads to high shear and tensile stresses in the insulation system.

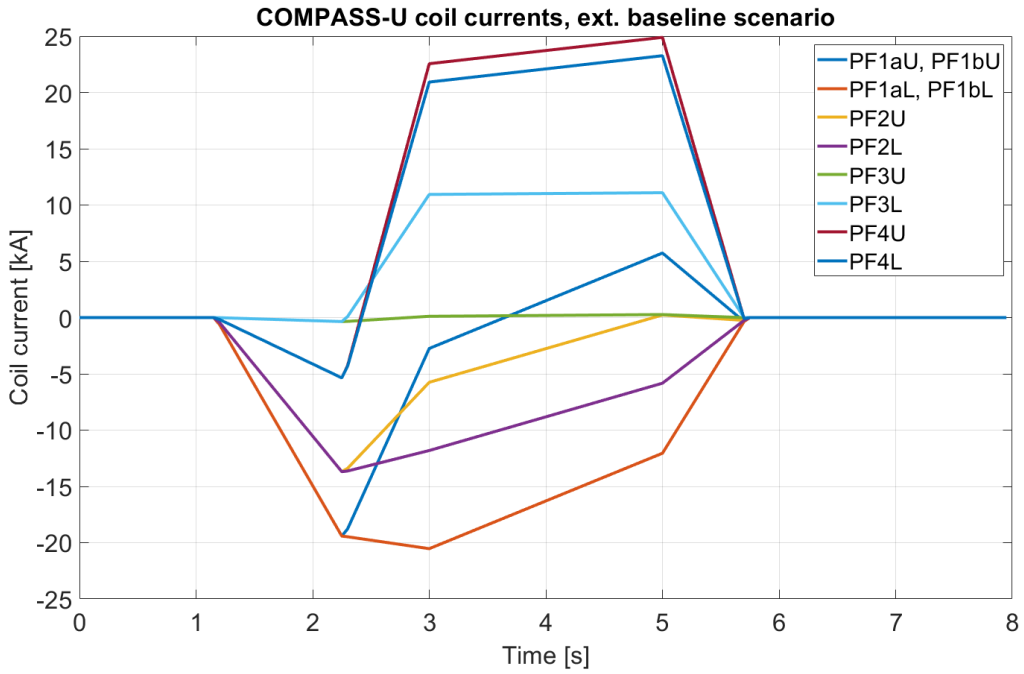


Figure 1-1 – Example of PF coil current waveforms during COMPASS-U scenario

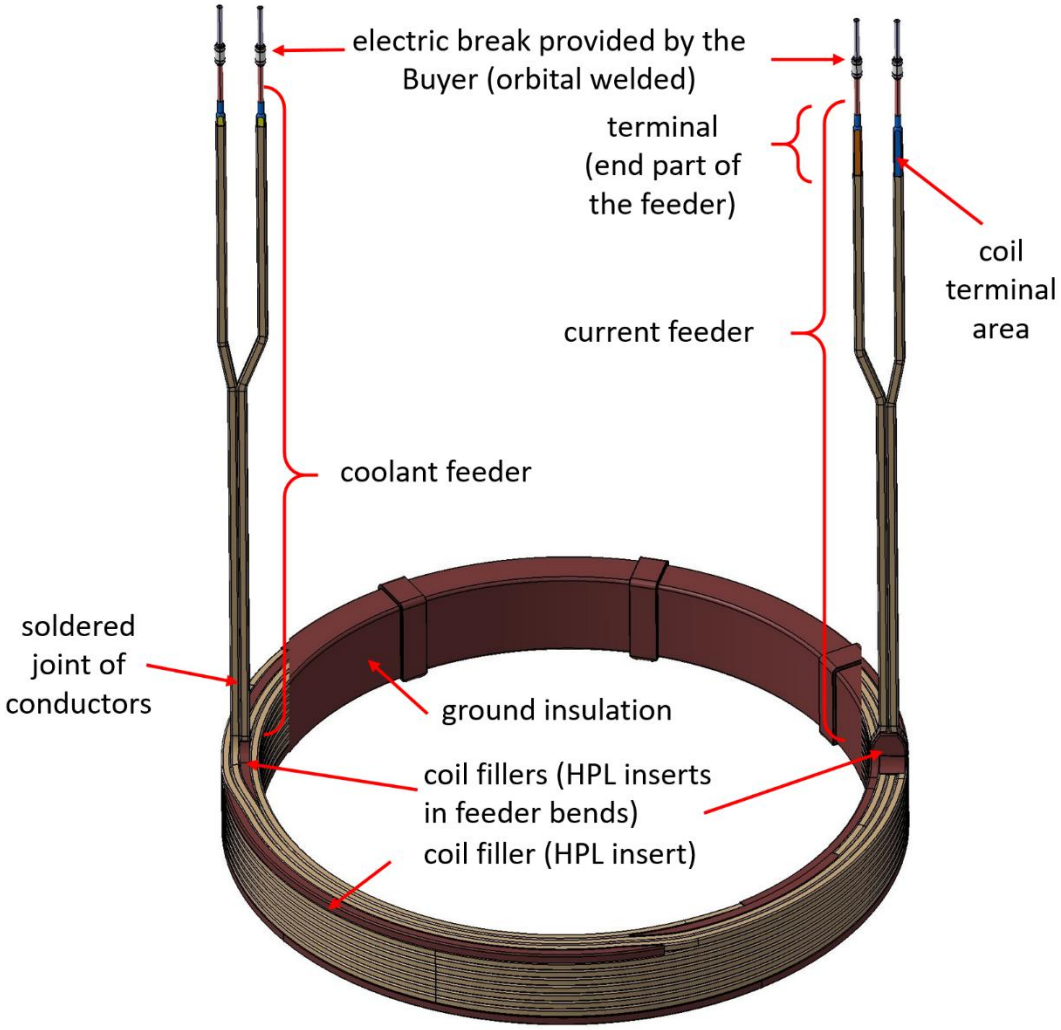


Figure 1-2 - Illustrative picture of one of the PF coils. Note that the ground insulation is not shown on part of the main body and on the feeders. Note that the turn-to-turn insulation is not shown around the terminals and close to the electric breaks.

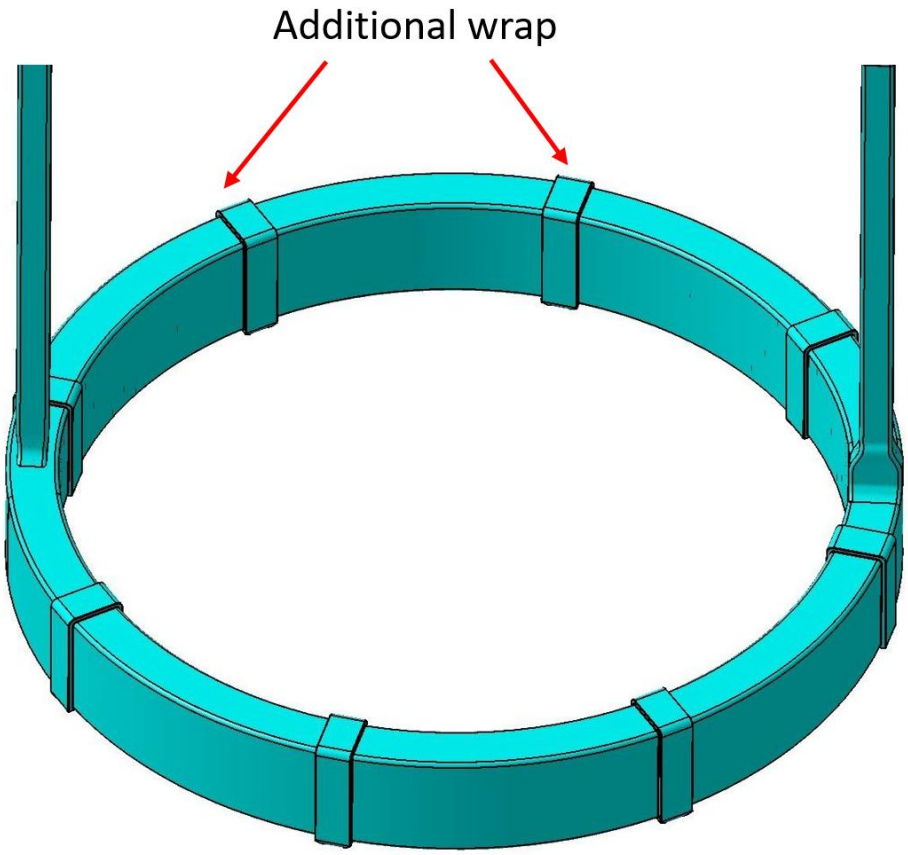


Figure 1-3 - Illustrative picture of one of the PF coils with “additional wraps” and “ground plane”.

2 Terminology, dictionary and abbreviations

Buyer	the contracting entity – Institute of Plasma Physics of the Czech Academy of Sciences; Contracting Authority (used in Tender Documentation)
Seller	the entity contracted to manufacture the PF coils, selected as a winner of the tender; Supplier (used in Tender Documentation)
COMPASS-U	tokamak under construction within the project "COMPASS-U: Tokamak for cutting-edge fusion research"
Contract	An activity of performing the duties agreed between the Buyer and the Seller in the Framework Purchase Agreement.
CS	Central Solenoid
PF	Poloidal Field
TF	Toroidal Field
GF	glass fibre
HPL	High Pressure Laminate (e.g. G-10)
T-T	turn-to-turn insulation
T-G	turn-to-ground insulation
Feeder	Part of the insulated coil conductor leading outside of the main coil body.
Current feeder	Coil feeder which electrically connects the coil to Busbars and, ultimately, Power Supply. On top of providing the electrical current, it also brings in and out conductor coolant.
Coolant feeder	Coil feeder which serves the sole purpose to lead conductor coolant in and out of the coil. Each PF coil thus consists of multiple coolant circuits (2-4).
Terminal, Terminal area	End part of the feeder. In case of current feeders, the terminal area is a dedicated space on the hollow conductor, which is without any insulation, and to which busbar or conductor can be connected. Feeder terminal ends are machined to circular shape and electric breaks are orbital welded there.
Additional wrap	Additional wraps are narrow "insulation rings" around the coil which are added on top of the ground insulation. Their purpose is to mechanically secure the coil against toroidal movement while allowing free radial coil expansion.
Coil filler	The "coil filler" fills large expected volumes between the insulated conductors inside the coils. It is a piece of High Pressure Laminate (HPL) machined according to the provided drawings.

Void filler	The “void filler” fills small volumes between the insulated conductors inside the coils (e.g. gap between the four adjacent turns caused by rounded edges of the turns). The drawings of the void fillers are not provided.; the material can be either High Pressure Laminate (HPL) or densely packed E-glass.
LN temperature	liquid nitrogen temperature (T = 77 K)
traveller	A traveller is the job paperwork carried along a work order’s lifespan.
MIT	Manufacturing, Inspection and Tests
BOM	Bill of Materials
FAT	Factory Acceptance Tests
SAT	Site Acceptance Tests
MIC	Manufacturing Interim Check – tests performed during the manufacturing process
PF1, PF2, PF3, PF4	abbreviation denoting all or any of the coils group, e.g. PF1 includes PF1aU, PF1aL, PF1bU, PF1bL
Basic Configuration	the set of deliverables which will be ordered together within the Contract (see “Annex No. 3 - Price Schedule and Deliverables”)
shall	means “must” or “mandatory”
PSS	Power Supply System
IPP	Institute of Plasma Physics (of the Czech Academy of Sciences). Equivalent to “the Buyer” or “the Buyer’s site”.

3 "Poloidal Field Coils for COMPASS Upgrade tokamak": Extent of delivery

The "Poloidal Field Coils for COMPASS Upgrade tokamak" Contract includes manufacture, development of tooling, purchase of materials, design of individual "non-critical" parts which are not prescribed by coil design, testing and transport to the Buyer's site.

The "Poloidal field coils for COMPASS-U tokamak" consists of these parts:

1) **Preparation of the MIT plan initial version (Manufacturing, Inspection and Tests)**

   The Seller shall submit the Manufacturing, Inspection and Test (MIT) plan in the initial version (see chapter 7.3) for the Buyer approval prior to the start of manufacture. The deadline for submission, evaluation and acceptance of the initial version of the MIT plan is specified in Annex No.3 of the Tender Documentation – Price Schedule and Deliverables.

2) **Manufacture and testing of mock-ups and samples**

   See chapter 5.2 - Coil insulation qualification program for information about the required insulation samples and 3x3 mock-up. See chapter 5.8.9 - Metal connection and its qualification program for requirements on samples (welding/soldering, …).

3) **Qualification of small radius conductor bends**

   The Seller shall, to the best of his ability, try to develop a technological process to perform small radius bends of the hollow conductor (i.e. 90° feeder bends) without compromising their integrity and material condition (i.e. the required minimum yield strength). Within the deadline specified in Table 3-4, the Seller shall try to qualify three bending processes by bending and inspection of hollow conductor samples (bending at room temperature, bending at cryogenic temperature, bending after local annealing). If these samples do not yield acceptable results, the responsibility to develop the technological process of bending will pass to the Buyer and the Seller's contract deadlines will be temporarily suspended. For more details, see chapter 6.2.1 - Integrity test of conductor bends and article 6.21 of the Framework Purchase Agreement.

4) **Manufacture and testing of a prototype coil PF1aU**

   The purpose of this part is to test the implemented solution and the Seller's technical ability to manufacture the coils of the requested quality. PF1aU coil is chosen as the prototype coil – it shall be made as an extra coil aside of the set of 10 PF coils described in point 4) below. Based on the experience with manufacture and subsequent tests, minor modifications of the specifications to improve the coils design and manufacturability are possible, see chapter 7.3.2. Please note that the Full surface coverage Paschen test (performed either in large vacuum chamber or as a series of overlapping local Paschen tests, see chapter 6.3.7 - Paschen test) is included in the required tests of the prototype coil.

5) **Manufacture of coils**

   Winding, insulation and impregnation of the set of 10 PF coils (incl. other manufacturing processes described in chapter 5). The basic PF coils parameters are summarized in the Table 3-1 below.

Table 3-1 Basic PF coils parameters

	coil	Conductor

Coil name	median radius [mm]	cross-section (incl. insulation**)		conductor mass [kg]	No. of turns	height [mm]	width [mm]	Cooling hole diam. [mm]	corner radius [mm]	length of conductor* [m]
		dR [mm]	dZ [mm]							
PF1aU, PF1aL	577.3	71.8	158	200	33	15	14.7	7	2	125
PF1bU, PF1bL	667.9	71.8	158	230	33	15	14.7	7	2	144
PF2U, PF2L	758.7	71.8	158	261	33	15	14.7	7	2	163
PF3U, PF3L	1052.8	105.2	124	404	37	15	14.7	7	2	253
PF4U, PF4L	1430.5	101	181	840	38	20	17	9	2	343

**Note: Dimensions in Table 3-1 are provided for information only. Refer to the drawings for precise and complete dimensions, including tolerances. Conductor mass and length values are approximate, given for the whole length of conductor (all cooling circuits together). Calculation of mass assumes conductor density of 8.9 g/cm^3. Lengths of conductor in individual cooling circuits of each coil are provided in* Table 5-3.

**Note: Without additional wraps

6) Coil accessories

a) Rigs/jigs (it can be only one universal rig/jig) for coil manipulation – the requirement is to be able to turn the coils upside down. Packaging for coil transportation. See chapters 5.7 and 8.2.

7) Testing and delivery (detailed list is in chapter 6, only overview is here)

a) Material acceptance tests (confirming required material properties)

b) Qualification and reference samples and their tests (e.g. insulation 3x3 mock-up; insulation samples; conductor bending and connection qualification, ...)

c) Size and shape inspection

d) Electrical testing (ground insulation, resistance, impedance, Paschen tests)

e) Cooling channels - leak testing and throughput

f) Delivery of manufactured PF coils to the Buyer's site (in the Czech Republic) within up to 4 transports (on Buyer's request) is part of the Contract. The rules are in the Framework Purchase Agreement, Article 4.7.

8) The Documentation (see chapter 3.2, chapter 7)

9) **Full surface coverage Paschen tests** – separately priced and ordered (i.e. the Buyer is not obliged to order these items) **items No. 2 and No. 3** in "Annex No. 3 - Price Schedule and Deliverables".

   a) Item No. 2 is a test of one of the "Group A" coils, which includes PF1-PF3 coils

   b) Item No. 3 is a test of one of the "Group B" coils, which includes PF4 coils

   Please note that the Full surface coverage Paschen tests can be performed (the selection is explicitly the Seller's decision – the Buyer has to accept this selection):

      a) either by placing the coil inside of a vacuum vessel and testing the entire surface concurrently,

      b) or the test can be performed as a series of local Paschen tests covering the entire surface of the tested coil with sufficient surface overlap between the individual local Paschen tests (this method does not require access to a vacuum vessel large enough to fit in the coils with their current and coolant feeders).

Note: The cost of all items listed in the points 1-8 shall be included in the cost of the "Basic configuration", as it is described in "Annex No. 3 - Price Schedule and Deliverables".

Throughout this document (Technical specification for Poloidal Field Coils for COMPASS Upgrade tokamak), the term "Poloidal Field Coils for COMPASS Upgrade tokamak" refers to the entire system, including all items of framework agreement. If it is not specifically stated otherwise, all technical specifications and requirements are valid for all items of the Contract.

3.1 Physical deliverables

The list of partial deliveries (Items or parts of the Object of Purchase), which are priced and form milestones in the Contract, is provided in document "Annex No. 3 - Price Schedule and Deliverables".

Alongside the prototype coil and the set of PF coils, the material acceptance tests, manufacturing qualification and interim tests imply delivery of samples, and also delivery of accessories and packaging necessary for the coil manipulation and transport (the costs of these samples, accessories and packaging are included in the price of the prototype coil and individual PF coils of the "Annex No. 3 – Price Schedule and Deliverables"). The list of physical deliveries is in Table 3-2.

Table 3-2 List of physical deliverables

Item	Chapter references
Prototype coil PF1aU (resp. all sections of the destructively tested coil)	5.3, 6.2.2
Coils PF1aU, PF1aL, PF1bU, PF1bL, PF2U, PF2L, PF3U, PF3L, PF4L and PF4U	5.4
Insulation qualification samples	5.2.1, Table 5-8
3x3 mock-up	5.2.2
Metal connection qualification samples	5.8.9

Bent conductor samples - metallographic cuts and tensile test residues	6.2.1
Hollow conductor samples for Buyer's bending tests	6.2.1
Raw material test samples	Table 6-5
Rigs and jigs for coil manipulation and transport	5.7
Packaging for transport	8.2

3.2 Deliverables of the Documentation

All documents shall be provided in digital format (e.g. PDF files, Microsoft Word or Microsoft Excel format, JPEG images, 3D models in STEP or CATIA files). Documents are listed in Table 3-3. More details about documentation are in chapter 7.

Table 3-3 - List of documentation deliverables.

	Deliverable item	**When required**	**Chapter references**
MIT plan (chapter 7.3)			
	MIT plan – initial version	Milestone M1; deadline specified in Annex No. 3 - Price Schedule and Deliverables; for IPP approval prior to the start of manufacture.	7.3
	updates to MIT plan	Prior to affected manufacturing, inspection, or test activities	7.3.2, 7.3.3
	Corrective actions and procedures	After non-conformance was found, prior to the corrective action	7.3.2, 7.3.3, 9.10
	Bill of Materials (BOM)	Part of milestone M1; Prior to procurement of materials and whenever their list is revised.	7.3.4
	QA Plan	Part of milestone M1; Prior to any manufacturing, inspection, or test activities specific to the scope of supply of this specification, including its further revisions.	7.3.5
	Manufacturing and tooling drawings	Part of milestone M1; updates prior to use.	7.3.6
Traveller (chapter 7.4)			
	Technical data sheets and certificates of conformity of all used materials	Prior to use of the particular material.	6.1, 7.4.1
	Inspection and test reports from conductor acceptance tests	Part of milestone M2. Without undue delay following each test/inspection. Prior to use of the	6.1, Table 6-4

		particular conductor batch.	
	Inspection report and acceptance protocol of Buyer-supplied material or components	Prior to use of the particular materials/components.	5.1.18
	Declaration of conformity with the directive 2011/65/EU	Prior to submittal of IPP Transport Permission.	8.4
	Fabrication process reports	Without undue delay following each fabrication step.	7.4.2
	Test reports of insulation samples FAT	Without undue delay following each test. Prior to prototype coil manufacture.	5.2.1, Table 6-1
	Inspection and test reports of 3x3 mock-up FAT	Without undue delay following each test/inspection. Prior to prototype coil manufacture.	5.2.2, Table 6-1
	Inspection and test reports of metal connection qualification samples	Prior to any particular metal connection operation	5.8.9, Table 6-1
	Reports of qualification of metal connection operators	Prior to any particular metal connection operation	5.8.9, Table 6-1
	Inspection and test reports of small radius conductor bends samples	Without undue delay following each test/inspection. Prior to prototype coil manufacture.	6.2.1, Table 6-1
	Inspection and test reports of conductor hardening process (if applicable)	Prior to prototype coil manufacture.	6.2.4, Table 6-1
	Inspection and test reports of prototype coil FAT	Milestone M3. Without undue delay following each test/inspection.	Table 6-2
	Inspection and test reports of each PF coil FAT	Milestone M4. Without undue delay following each test/inspection.	Table 6-3
	Inspection and test reports of each PF coil SAT	Without undue delay following each test/inspection.	Table 6-3
	Non-conformance reports	Without undue delay following detection of a non-conformance.	7.4.5, 8.3
	Video documentation plans	Prior to activities subject to video surveillance.	7.4.3
	Video documentation logs	Without undue delay following each activity subject to video surveillance.	7.4.3
	Time-lapse and other photo documentation	Photographs form part of the relevant inspection and test reports and fabrication process reports. For activities subject to video surveillance, time-lapse shall be delivered as soon as available.	7.4.3

3.3 Milestones and deadlines

The Milestones of the Contract are described in Framework Purchase Agreement in Article 4.2. An overview of deadlines for delivery of the partial deliveries and physical deliverables (as described "Annex No. 3 - Price Schedule and Deliverables" plus those listed in chapter 3.1) is in Table 3-4.

Table 3-4 - Deadlines for physical deliverables.

Item	**Part of milestone**	**Deadline definition** Note that the deadline may include time reserved for the Buyer for evaluation and acceptance	**Chapter references**
MIT plan initial version	M1	Specified in Annex No. 3 of the Tender Documentation – Price Schedule and Deliverables	7.3
75% of the conductor weight delivered to the Seller (based on accepted Bill of Materials)	M2	1 year after the Supplier´s acceptance of the Order issued by the Contracting Authority	5.1.1, 7.3.4
3x3 mock-up and insulation samples - FAT		9 months after the Supplier´s acceptance of the Order issued by the Contracting Authority	5.2, Table 6-1
3x3 mock-up and insulation samples - delivery to IPP		3 weeks after 3x3 mock-up FAT	
Small radius conductor bends - sample tests and inspection		12 months after the Supplier´s acceptance of the Order issued by the Contracting Authority	6.2.1
Prototype coil – FAT	M3	Specified in Annex No. 3 of the Tender Documentation – Price Schedule and Deliverables	5.3, 6.2, 6.5
Prototype coil - delivery of sections to the Buyer		3 weeks after the prototype coil FAT	6.2.2
PF1xx – PF4x coils (applies individually) - FAT	M4	not defined – shall be compatible with SAT deadline	6.5
selected coils PF1xx – PF4x – Full surface coverage Paschen test	M4	If the test is ordered, it becomes part of the respective coil's FAT. Deadline is not defined – shall be compatible	6.3.7

		with SAT deadline	
PF1xx – PF4x coils (applies individually) - SAT		Specified in Annex No. 3 of the Tender Documentation – Price Schedule and Deliverables	Table 6-3, 6.6
all other samples		As defined for each sample in the relevant chapter of this Technical Specification; in reasonable time after the sample was manufactured, otherwise at latest with the last SAT of the coils in the Basic Configuration applies	

4 Terms and conditions of the Seller's bid

The recommended structure of the Bid and formal requirements for the Bid are in the Tender Documentation in section 8.

4.1 Technical part of the Seller's Bid

This document (Technical specification for Poloidal Field Coils for COMPASS Upgrade tokamak) contains very detailed specifications and requirements, which must be followed and fulfilled by the Seller during the realization phase of the tender – i.e. during the detailed design and subsequent production of the PF coils. This chapter contains the minimal technical details, which must be included in the Seller's Bid.

The technical part of the Seller's Bid, which will be submitted within the public tender, **is required to provide**:

1) **A brief general overall description** of the offered Poloidal Field Coils (**four standard pages as a minimal extent**). It shall contain enough information to clarify the proposed manufacturing procedures and to convince the Buyer of the Seller's capability to fulfil the Contract with the required specifications and quality. Manufacturing drawings are not required at this point. It shall contain information about:
    - Procedure to achieve the required coil tolerances (see chapter 5.10 and coil drawings)
    - Procedure to achieve the required cleanliness during coil fabrication (see chapter 5.8.1)
    - Procedure to achieve the required insulation properties (see chapter 5.1.4 and chapter 5.2.1)
    - Chosen insulation materials (see chapter 5.1) (in case that the Seller intends to choose the insulation materials during realization of the Contract, the candidate insulation materials and the intended selection process shall be described)
    - Brief overview of proposed main coil fabrication steps - conductor cleaning and priming, winding and taping, VPI and curing (see chapter 5.8)
    - Procedure for Paschen testing of coils (see chapter 6.3.7)
2) **The minimal technical details and parameters**, as required by the Table 4-1. It is recommended to use the table as a template. The Seller shall confirm, that all these requirements will be fulfilled (i.e. the Seller shall fill in "YES" to the column "Seller's confirmation" at all lines).
3) **The specific statement that the bid and the final deliveries** within the Contract **fulfil all of the requirements contained in this Technical Specification**.

Table 4-1: Table of minimal technical details to be included in the Seller's Bid

No.	Name of the requirement	Description of the requirement	Seller´s confirmation
1	Cleanliness, housekeeping	In all steps of the PF coils fabrication the Seller shall provide clean environment and follow the safety procedures as prescribed in Chapter 5.8.1	

No.	Name of the requirement	Description of the requirement	Seller´s confirmation
2	Copper conductor properties	Procured copper conductors shall conform to the required chemical composition, mechanical and electrical properties as specified in Chapter 5.1.1	
3	Fabrication procedure	Material handling, preparatory works and coil fabrication procedures shall conform to the requirements described in Chapters 5.1 - Materials and 5.8 - Fabrication. Furthermore, the material handling, preparatory works and coil fabrication procedures shall be thoroughly specified in the MIT plan, which is a deliverable within the Contract (see chapter 3.2).	
4	General Insulation properties	Insulation of the manufactured coils shall conform to the properties specified in chapter 5.1.4 and requirements given in Table 5-4.	
5	DC resistances	DC resistances of PF coils at room temperature shall be equal or smaller than the maximal values specified for each coil in Table 6-7. Adjustment of the resistance values in Table 6-7 to correct for the as-built length of the wound coil is permissible.	
6	Insulation of current terminals	The insulation of current terminals is not specified in detail in the technical drawings. It is the responsibility of the Seller to propose a suitable insulation design of this part of the coils compatible with the general requirements of the insulation system. The proposed design has to be agreed by the Buyer before manufacture.	
7	Final conductor yield strength	Yield strength (0.2% proof stress) of coil conductors after the coil winding procedure shall be equal or greater than values prescribed in Table 5-2. The Seller shall specify (during the realization of the Contract) the procedure to achieve this requirement in the MIT plan initial version and propose specific tests to verify the conformance. More details in chapters 5.1.1, 6.2.1, 6.2.4 and 6.2.5.	
8	Vacuum and cryogenic compatibility	The Seller shall ensure that the fabricated coils conform to the vacuum and cryogenic requirements as specified in “Annex of technical specification No. 1 – Vacuum compatibility”. All coil fabrication steps shall follow the specific guidelines and procedures described in the annexed document.	
9	Dimensional tolerances	The Seller shall ensure that the fabricated coils conform to the required dimensional tolerances. The general dimensional tolerances are defined by Table 5-10.	

No.	Name of the requirement	Description of the requirement	Seller´s confirmation
		Tolerances of specific parts may be clarified in the technical drawings. The tolerances provided in technical drawings always take precedence.	
10	Photo and video documentation	The Seller shall ensure that crucial manufacturing steps are subject to video surveillance and time-lapse recording according to rules defined in chapter 7.4.3.	

5 Technical specifications and requirements

5.1 Materials

All supplied materials shall be inspected upon receipt and any discrepancies, deviations, or other defects shall be noted and communicated to the Buyer by the Seller as soon as possible. The excess materials are property of the Seller, the Buyer requires only samples from each production/delivery batch (as described in 6.1). The used materials shall be RoHS compliant (Directive 2011/65/EU) – more details in chapter 8.4.

Note that the use of the material as described in this chapter is one of the Critical activities, which are summarized in chapter 9.9. Chapter 9.9 further describes the consequences of the violation of the requirements on the material stated in this chapter.

5.1.1 Conductor

Basic applicable standards for the raw conductor material are defined by the norm **EN 13600**. However, **requirements of the Buyer on dimensional tolerances are stricter than as defined by the norm**. Dimensional tolerances of respective coil conductors are defined in the technical drawings. The Buyer has also **specific requirement on the mechanical properties of the conductor material** - see specifications for each of the coils conductors in the Table 5-1. The conductor material shall be CuAg0.10(OF) oxygen-free silver bearing copper according to EN CW019A or equivalent designation UNS C10700. Material supplier shall implement a QA system to meet the requirements of ISO 9001:2015 or equivalent.

Table 5-1 – Required conductor physical properties at 20 °C

	PF1a, PF1b, PF2, PF3 coil (upper and lower)	**PF4 coil** (upper and lower)
Material designation	CW019A	CW019A
Chemical composition		
Copper + silver content	min. 99.95%	min. 99.95%
Silver content	0.08-0.12%	0.08-0.12%
Mechanical properties		
Material condition	R290	R250
Yield strength (0.2% proof strength)	min. 250 MPa	min. 150 MPa
Ultimate tensile strength	min. 290 MPa	min. 250 MPa
Elongation at break	There is no specific requirement by the Buyer. However, the Seller shall pay close attention to this property in order to be able to wind the coils and especially the small radius conductor bends (see chapter 6.2.1 and coil drawings).	
Electrical properties		

Electrical conductivity (vol.)	min. 96.6% IACS	min. 98.3% IACS

Consistently with the conductor material requirements specified in Table 5-1, the Buyer requires **minimal yield strength of the conductor in completed coils** – see Table 5-2.

The Seller may recommend their preference to receive the conductor in a different condition than defined in Table 5-1 (i.e. fully annealed). In such a case, the Seller shall propose specific technological process in the MIT plan how to achieve the required minimal yield strength of the conductor in the completed coils (Table 5-2). The Seller shall also propose specific tests to prove the feasibility of the proposed process. These proposals are subject to approval by the Buyer.

Prior to use, the conductor shall be grit blasted, rinsed by appropriate alcohol cleaner and subsequently coated by a primer (see chapter 5.8.2.3) in order to ensure good adhesion of the resin to the conductor.

Table 5-2 - Minimal yield strength of the conductor in the completed coils at 20°C (applies to the whole volume of the coil conductor including feeders and small radius conductor bends).

Coils	**Minimal yield strength [MPa]** (0.2% proof strength)
PF1a	250
PF1b	250
PF2	250
PF3	250
PF4	150

PF coils consist of several (2-4) cooling circuits which are mechanically and electrically connected by soldered joints to form the full coil. It is the requirement of the Buyer that each of the cooling circuits is made of a single-length conductor without any joints. The Seller shall therefore make sure to procure conductor spools in sufficient lengths to fulfil this particular requirement. Lengths of the coils' individual cooling circuits are indicated in Table 5-3.

Table 5-3 - PF coils cooling circuit lengths

Coil	**Number of cooling circuits**	**Length* [m]**
PF1a	2	60.6
		64.4
PF1b	2	70.0
		73.8
PF2	2	80.3
		82.4
PF3	3	82.8
		83.9
		86.3
PF4	4	74.2
		89.7

		89.7
		89.7

**Note: Coil cooling circuit lengths in* Table 5-3 *are provided for information only. Refer to the drawings for precise and complete dimensions. Please note that conductor spools with surplus lengths than indicated in the table shall be procured as conductor samples have to be tested and provided to the Buyer.*

5.1.2 Cooling terminals

The cooling terminals shall be manufactured directly from the hollow conductor of the coil, i.e. from square/rectangular cross-section shape, machined to the circular cross-section, according to the drawings.

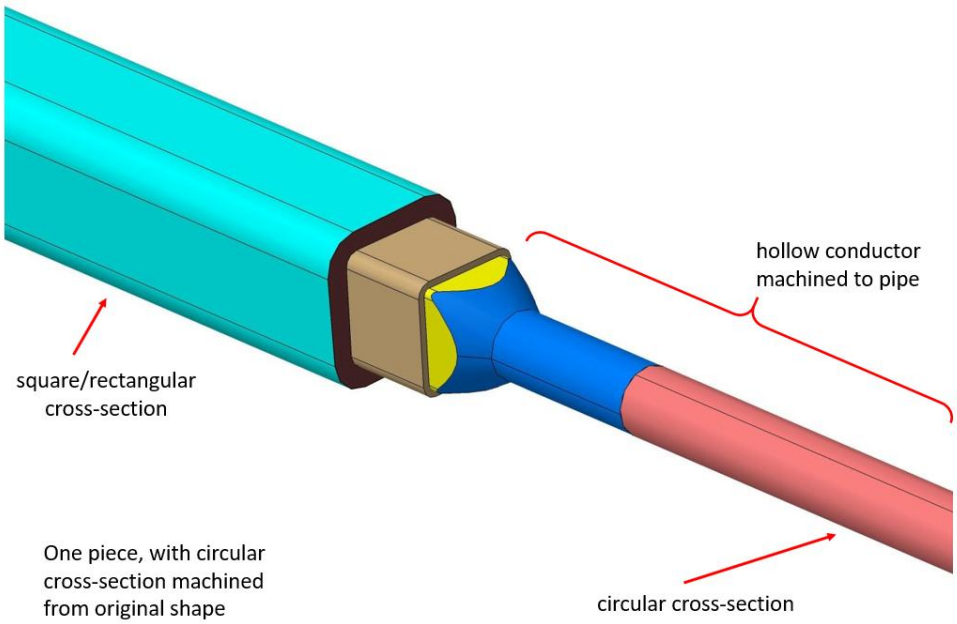


Figure 5-1 - Illustration of the square/rectangular shape of the hollow conductor machined to the pipe - circular cross-section shape.

5.1.3 Mandrel

The Seller is responsible for developing removable winding mandrel for production of “bare” coils.

5.1.4 General insulation properties

General requirements on the electrical insulation of PF coils are given in Table 5-4 below. The coils conductor shall be cleaned, primed, taped with a glass fibre (GF) tape (some GF layers interleaved by polyimide tape), vacuum pressure impregnated with resin and cured. The Seller can choose the recommended insulation material options (recommended primer, resin, polyimide tape etc. in this technical specification) or the Seller can choose suitable materials of their choosing while keeping all of the requirements in this technical specification and notably in Table 5-4 below.

There are few exceptions to the requirements denoted in Table 5-4: i/ **insulation thickness** in small radius bends of the conductor (see chapter 5.1.6), ii/**ground insulation thickness** on part of current and coolant feeders (see chapter 5.1.6.2), iii/ **ground insulation thickness** on top and bottom coil (PF1-PF3) surfaces (see chapter 5.10).

Conformance of the insulation materials and Seller's manufacturing procedures of insulation to these requirements will be established by successful passing of the coil insulation qualification program (insulation samples FAT and 3x3 mock-up FAT, see chapter 5.2 and Table 6-1) and prototype coil FAT (see Table 6-2). Wherever applicable, the Seller shall then use strictly the same insulation materials and manufacturing procedures which were successfully qualified (in the aforementioned samples, mock-up and prototype coil) when producing the PF1-PF4 coils.

Table 5-4 - General insulation requirements

Name and description of the requirement	Value / description
Insulation volumetric fibre glass ratio (to be confirmed by insulation qualification, see chapter 5.2.1 - Insulation samples)	40 ± 5 %
Turn-to-turn insulation nominal thickness (corresponds to the thickness of two conductor insulations facing each other)	2.0 ± 0.2 mm (see accompanying text for exceptions)
Ground insulation nominal thickness	2.5 ± 0.25 mm (see accompanying text for exceptions)
insulation resin rich area (in any direction)	Max. 0.5 mm
Insulation void gap (in any direction)	Max. 0.025 mm
Insulation void ratio	Max. 2.5 %
Primer thickness	As specified by primer manufacturer. (typically 7-25 µm)
Polyimide tape width	~80 % of the GF tape width
Through thickness tensile strength	Qualified by sample tests (chapter 5.2.1, Table 5-9)
Interlaminar shear strength	Qualified by sample tests (chapter 5.2.1, Table 5-9)

Additionally, general requirements on the insulation system shall respect the following rules:

1. Minimize void content.
2. Minimize resin rich areas.
3. Use materials with similar dielectric constants, preferably low.
4. Use materials with resistance to the long-term effects of partial discharges.
5. Use materials stable in the range of used temperatures and with low degradation caused by the cycling of the cooling down.
6. High mechanical strength over the range of operational temperatures.

5.1.5 Primer

The primer improves adhesion between the conductor and epoxy resin of the insulation. The thickness of the primer coating shall be maintained within the range specified by the manufacturer. The application procedure is prescribed by the manufacturer and shall be followed. Note that following of these requirements is considered of utmost importance by the Buyer and the procedure of priming of the coils is one of the so-called Witness Points, see chapter 9.8 - Witness/Hold Points and Notification of the Buyer in Advance.

Primer recommended by the Buyer is listed below. The Seller can propose an alternative product which conforms to the requirements denoted in this technical specification and notably in chapter 5.1.4. Regardless of using the recommended product or not, the Seller shall demonstrate the performance of the chosen product by successfully passing the insulation qualification program described in chapter 5.2. If a chosen alternative product does not pass the insulation qualification, the Buyer has the right to insist on the use of the recommended product below.

Recommended product name: CTD-450
Manufacturer: Composite Technology Development Inc. 1505 Coal Creek Drive Lafayette, Colorado 80026, (303) 664-0394

5.1.6 Insulation layout

This chapter describes the insulation layout requirements by the Buyer. An alternative layout can be proposed by the Seller, while keeping the requirements defined by Table 5-4 - General insulation requirements. **If an alternative layout is proposed by the Seller, it requires an approval from the Buyer**.

Table 5-5 Working voltage and frequency of power supplies for PF coils.

coils	Operation voltage [kV]	Switching frequency [kHz]
All PF coils	1	0.5 - 2

The tolerances on insulation thickness are defined in Table 5-4. As a general rule, insulation layers shall be half-lapped. Permitted glass-fibre overlap range is 50 - 100%, but excessive overlap shall be avoided to ensure that the correct dimensions of insulation (and the coil overall) are maintained. Particular attention shall be paid to conductor bends where the overlap and insulation build may differ at the inner and outer bend radius. The Seller may use a locally tapered GF tape or propose another solution to overcome this issue.

In the area of small radius conductor bends (see 6.2.1), it is allowed to exceed the insulation thickness tolerance on the outer (greater) bend radius side. There, the minimum allowed insulation thickness is decreased to 0.75 mm for conductor insulation (i.e. 1.5 mm for turn-to-turn insulation) and 2 mm for ground insulation. However, the Buyer requires that the insulation thickness at the inner radius is kept within the tolerances defined in Table 5-4.

5.1.6.1 Conductor insulation

2 half-lapped layers of E-glass tape interleaved with polyimide tape and 1 half-lapped layer of E-glass tape without polyimide tape. Polyimide tape width shall be ~80% of E-glass tape width in order to allow good wetting of the glass fibres during VPI. Width, thickness and weight of the E-glass tape shall be proposed by the Seller, such as to fulfil the requirements provided in Table 5-4.

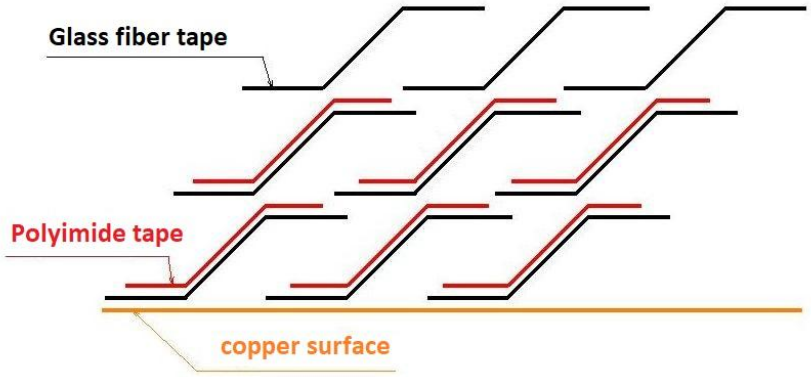


Figure 5-2 - Conductor insulation – sketch of glass fibre and polyimide tape layout.

Note: The thickness of turn-to-turn insulation, specified in Table 5-4, corresponds to the thickness of two conductor insulations facing each other between two neighbouring coil conductor turns.

5.1.6.2 Ground insulation

The required thickness of the ground insulation is defined in Table 5-4. The insulation layers shall be made of half-lapped E-glass tape. At least 5 half-lapped layers are required. Width, thickness and weight of the E-glass tape shall be proposed by the Seller, depending on the size of the winding pack/coil dimensions. Where possible, it is recommended to use a wider tape.

Parts of the current and coolant feeders have additional 0.5 mm ground insulation (i.e. 3 mm total thickness), which serve as a more robust mechanical protection. This applies for all coils and it is depicted in technical drawings.

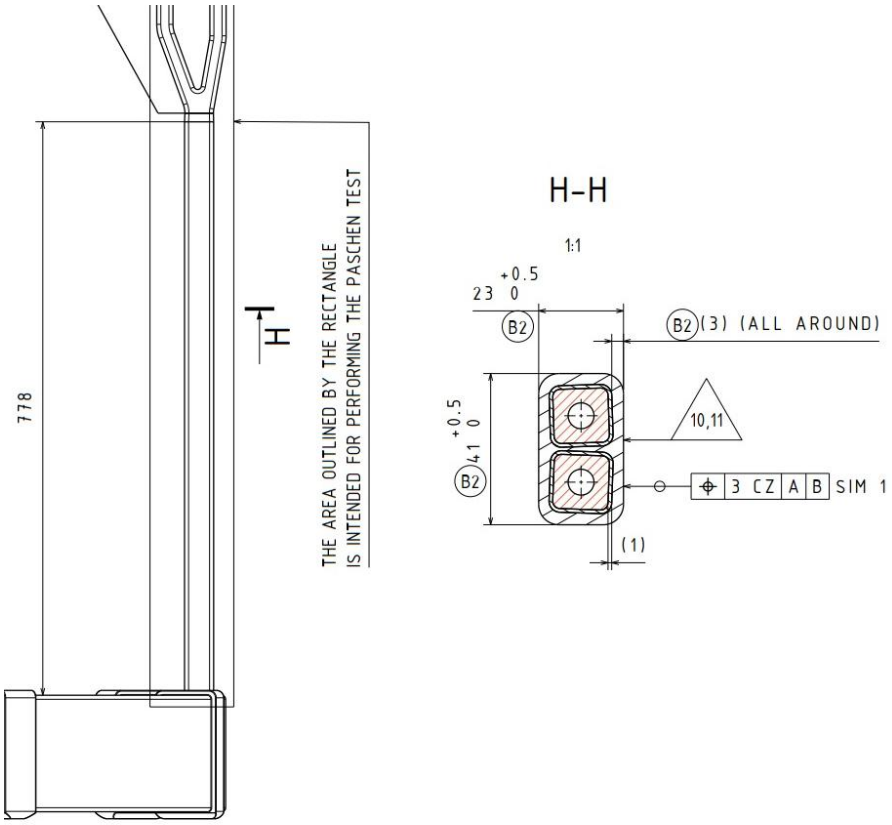


Figure 5-3 – Example of the additional ground insulation on a coolant feeder of coil PF1aL

Note: The conductors of the feeders in the CATIA models are rotated relative to each other, but they must be made parallel on the final coil.

5.1.6.3 Additional wrap

Additional wrap is a buildup of several layers of half-lapped E-glass tape on top of the ground insulation, toroidally localized at points specified in the technical drawings. The layers shall be vacuum impregnated (i.e. not necessarily vacuum pressure impregnated) with resin. This applies for coils PF1a, PF1b, PF2 and PF3 (there are no additional wraps for PF4 coils). Dimensions are in the technical drawings. Width, thickness and weight of the E-glass tape shall be proposed by the Seller.

The additional wraps shall be formed to a trapezoidal shape (machined or by other means) by the Seller at one coil side (top or bottom, according to the technical drawings). There, keystone elements will be attached (not part of the delivery, see Figure 5-4). The purpose of the additional wraps and keystone elements is purely mechanical. The keystones will fit into grooves in the stainless steel holder structure (not part of the delivery) of PF1-PF3 coils, allowing free radial coils expansion while securing the coils in toroidal direction. The strength of the bond of additional wraps to the coil ground insulation is of essential importance to the Buyer, so that it is resistant to peeling off by lateral/toroidal forces. It is also of essential importance that the insulation layers' build-up in the additional wraps is robust and resistant to toroidal shearing forces. FEM analysis done by the Buyer showed that peak frictional stress in the additional wrap reaches up to 35 MPa.

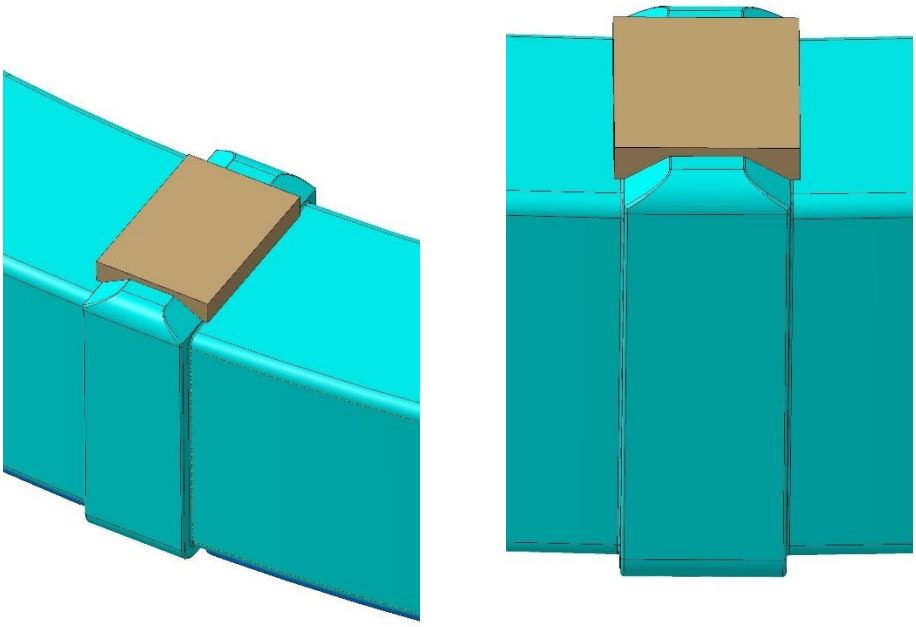


Figure 5-4 - Detail of the keystone elements (not part of the delivery; light brown)

The Seller is allowed to propose a modified design solution of additional wraps (e.g. using machined HPL blocks glued to the coil surface) if such a modification retains or improves their mechanical strength (resistance against peeling-off/de-bonding and toroidal shear). Such a modified design has to be vacuum and cryogenically compatible (notably the bond to the coil has to be compatible with the thermal cycling of the coil) and **it is subject to approval by the Buyer**.

The additional wraps have only one "functional" part, which is the one forming the trapezoidal shape

fitting to a keystone element. The other parts around the coil serve only to strengthen the bond to the coil and increase the resistance to toroidal peeling of the wrap from the coil. The Buyer requires strict compliance of the final product with the tolerances of the trapezoidal part of additional wraps. **The geometry of the "non-functional" parts of the wrap can be adjusted by the Seller** and the technical drawings of these parts can be understood as a space envelope available to accommodate the wraps. **The Seller is allowed to modify the shape of the "non-functional" parts** of the wrap or even not include them altogether (in case of using machined HPL blocks as described above). The requirement is to avoid sharp edges and ensure good adhesion of the wrap to the ground insulation of the coil.

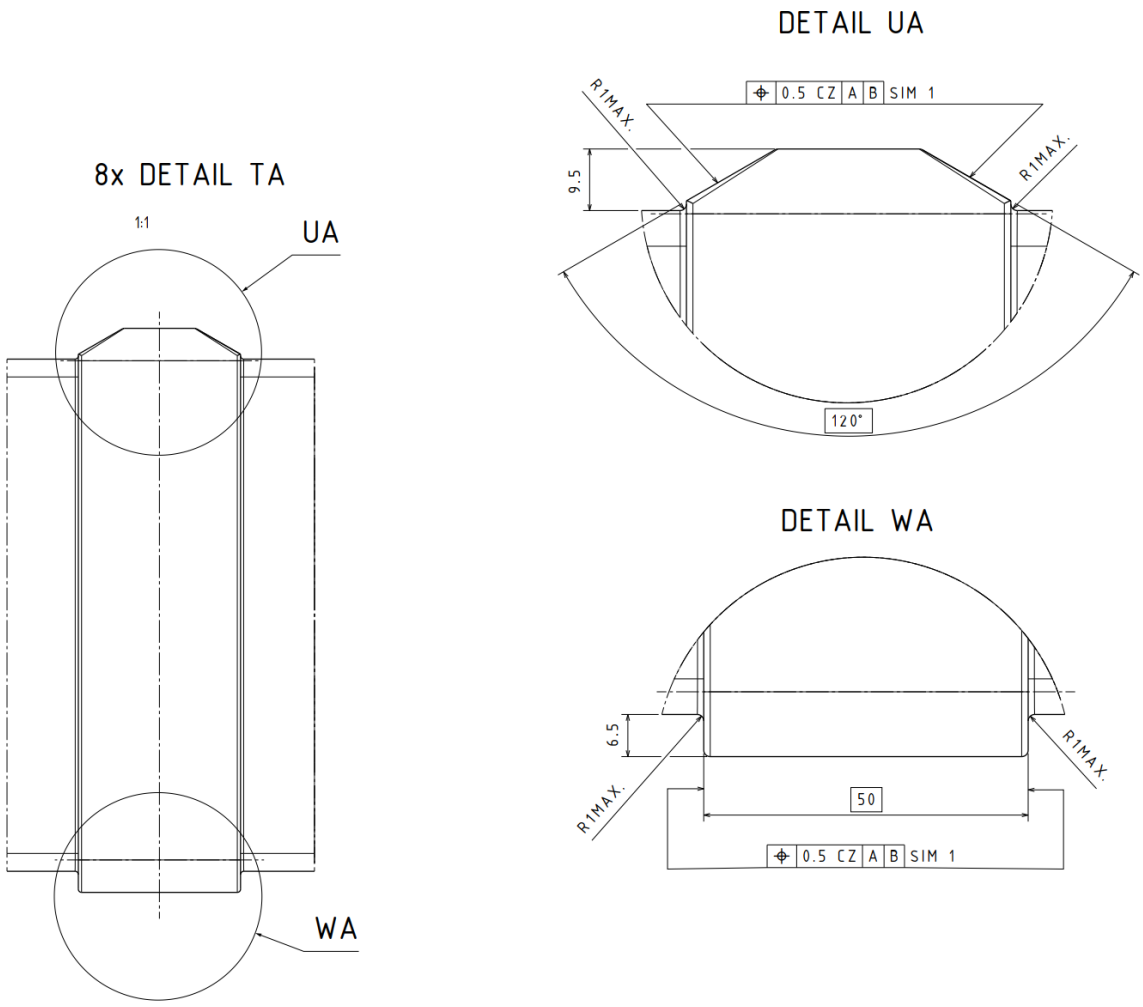


Figure 5-5 – Detail of additional wrap

5.1.6.4 *Ground plane*

After VPI of the coil and after successfully passing all required Paschen tests of the coil during FAT, an electrically conductive varnish shall be applied to the coil's surface, forming a ground plane of the coil. See description in the following bullets and technical drawings for individual coils.

- Coils PF1a, PF1b, PF2 and PF3:
  - The coils have full surface covered by conductive paint (including feeders), except of terminal area (without insulation).
  - We assume that the ground plane is applied for the entire surface of the additional

wraps but as alternative, ground plane can be applied first (before the additional wraps are manufactured) and then the additional wraps would be without ground plane. The adhesion between ground plane and additional wraps has to be trialled by the Seller and approved by the Buyer.

- Coil PF4:
    - The coil has conductive paint divided by 4 breaks (see Figure 5-6), the breaks are done with insulation barrier overlap. The Seller shall propose the method of creation of the insulation barrier (e.g. insulation paint or insulation tape). The proposal is subject to approval of the Buyer. See Figure 5-7 for geometrical constraints.

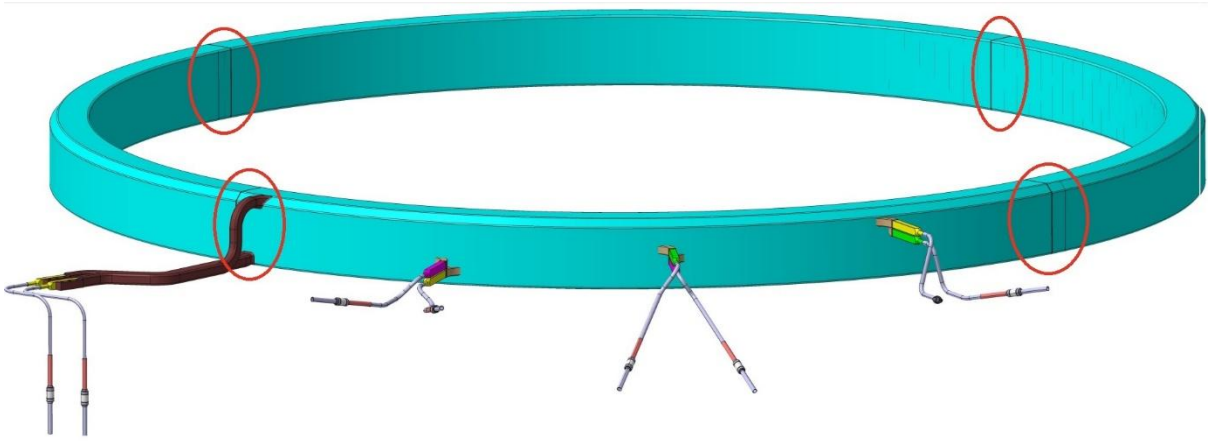


Figure 5-6 - Position of insulation barrier on the PF 4 coil. The insulation barrier is marked by red oval in the figure.

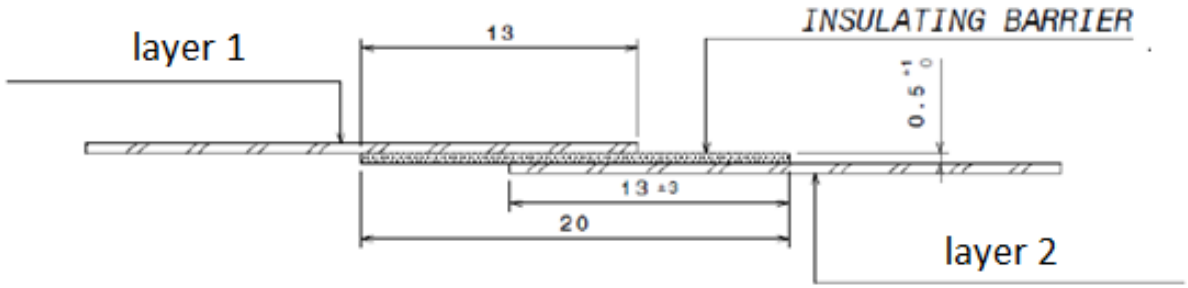


Figure 5-7 - Schema of the insulation overlap

- Dedicated grounding point - metallic copper sheet or copper wire without insulation – shall be incorporated on the surface of the ground insulation. Grounding points are specified in technical drawings and in Table 5-6.

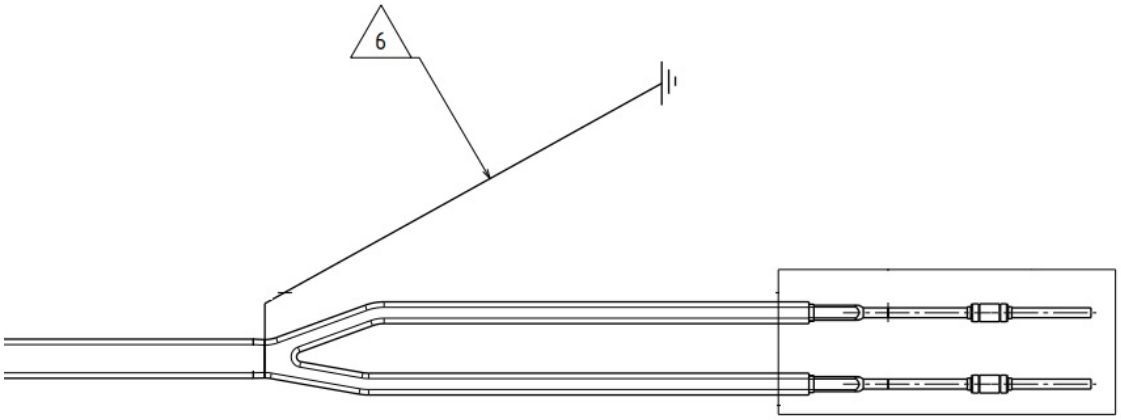


Figure 5-8 – Example of the grounding point location in technical drawings of the PF1aL coil

Table 5-6 Parameters of grounding connector

coil	**Sheet/wire length L**	**Connection hole at the end of the sheet/wire øD**	**conductive area S**	**numbers of grounding points**
	mm	mm	mm2	
PF1a	1000	7	5 ≤ S ≤ 6	2
PF1b	1000	7	5 ≤ S ≤ 6	2
PF2	1000	7	5 ≤ S ≤ 6	2
PF3	1000	7	5 ≤ S ≤ 6	3
PF4 (coils)	120	7	5 ≤ S ≤ 6	6
PF4 (feeders)	400	7	5 ≤ S ≤ 6	4

- The conductive varnish shall be vacuum compatible and cryogenic temperature compatible (for vacuum compatibility, see Annex of technical specification No. 1 – Vacuum compatibility).
- The Seller shall make conductive varnish sample (see Table 6-5).
- The varnish used by the Seller shall be approved by the Buyer.
- Resistivity of the conductive layer for all coils shall meet requirement (see chapter 6.3.9 - Ground plane resistance)
- The varnish shall be wear-resistant.

5.1.6.5 *Cooling terminal insulation*

Ground and conductor insulation ends behind the electric break (see the technical drawings).

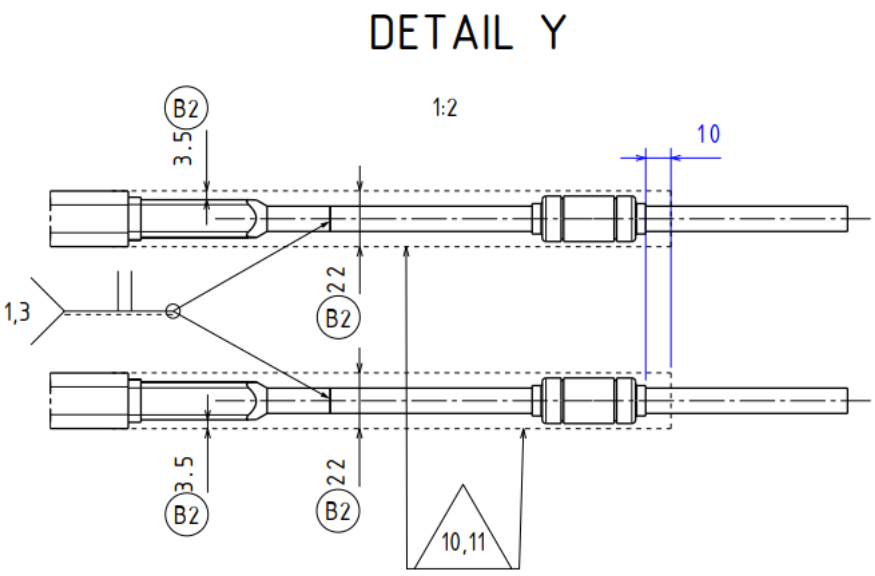


Figure 5-9 - Example of the location of the cooling terminal insulation of the PF1aL coil (excerpt from the drawing) – marked by dotted area, ends 10 mm behind the electric break.

5.1.6.6 *Current terminal area*

On the hollow conductor, there is a “terminal area” - dedicated space without any insulation to which busbar or conductor can be connected (marked in the drawings with text “bare copper”). Exact space is depicted in technical drawings and it is depicted in the Figure 5-10.

The design of current terminal insulation is the Seller´s responsibility and shall be designed with the same or superior insulation properties as the rest of the coil. This design is aimed primarily on a method of ending the insulation before the area without the insulation and starting the insulation behind the area without the insulation, where the coil conductor is machined (see chapter 5.1.2 - Cooling terminals) and transitions to the electric break. The design shall be approved by the Buyer. The area is identified in drawings.

These are points which the Seller shall take into the account:

- Insulation thickness shall be 3.5 mm (1 mm conductor insulation (i.e. insulation with polyimide tape, see chapter 5.1.6.1) + 2.5 mm ground insulation (i.e. insulation without polyimide tape, see chapter 5.1.6.2)).
- Insulation layout shall simulate conductor and ground insulation e. g. glass fibre and polyimide layout however alternative materials which are compatible with all requirement in this specification are allowed.
- Contact surface area on terminal shall stay clean or be cleaned - without any spoil which would negatively affect conductivity.

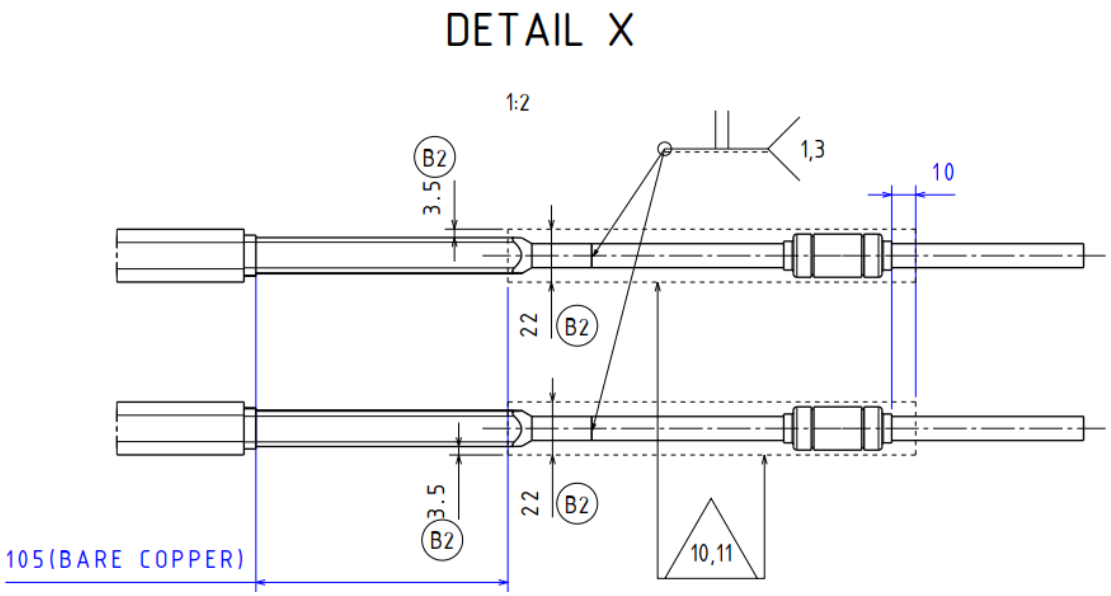


Figure 5-10 –Example of the location of the current terminal insulation of the PF1aL coil (excerpt from the drawing) – marked by dotted area, ends 10 mm behind the electric break.

5.1.6.7 Electrical break insulation

The insulation layout is the same as conductor insulation (see chapter 5.1.6.1) and ground insulation (see chapter 5.1.6.2) and it ends 10 mm behind the ceramic part of electric break. Both insulations are depicted in technical drawings (illustrative figures are Figure 5-9 and Figure 5-10).

Please note that the electric breaks are provided to the Seller by the Buyer (Institute of Plasma Physics) – see chapter 5.1.18 - Material provided by the Buyer.

Electric break insulation shall be impregnated with resin by VPI process.

5.1.7 Resin

The application procedure is prescribed by the manufacturer and shall be followed. Resin recommended by the Buyer is listed below. The Seller can propose an alternative product which conforms to the requirements denoted in this technical specification and notably in chapter 5.1.4. Regardless of using the recommended product or not, the Seller shall demonstrate the performance of the chosen product by successfully passing the insulation qualification program described in chapter 5.2. If a chosen alternative product does not pass the insulation qualification, the Buyer has the right to insist on the use of the recommended product below.

Recommended product name: Araldite® GY282

5.1.8 Polyimide tape

Polyimide tape recommended by the Buyer is listed below. The Seller can propose an alternative product which conforms to the requirements denoted in this technical specification and notably in chapter 5.1.4 and also in Table 5-7. Regardless of using the recommended product or not, the Seller shall demonstrate the performance of the chosen product by successfully passing the insulation qualification program described in chapter 5.2. If a chosen alternative product does not pass the insulation qualification, the Buyer has the right to insist on the use of the recommended product below.

Required thickness of the tape is 0.025 mm.

Recommended product name: DuPont™ Kapton® FPC

Table 5-7 Required properties of polyimide tape

Property at room temperature	Unit	Value	Test Method
Tensile Strength	MPa	≥230	ASTM D-882-91
Elongation	%	≥70	ASTM D-882-91
Adhesion	N/mm	≥1.6	IPC-TM-650 Method 2.4.9*
Dielectric Strength	kV/mm	≥300	ASTM D-149-91

**Acrylic adhesive to 28.35 g copper*

5.1.9 Glass fibre tape

All used glass fibre tapes must be E-glass woven from yarns made of continuous filaments with no more than 1% alkali E-glass (the Seller will prove this feature e.g. by technical datasheet). The filaments shall be amino-silane treated before weaving to improve wetting during resin infusion (the Seller will prove this feature e.g. by technical datasheet). The weave pattern of glass (satin / plain / twill / …) tapes shall be proposed by the Seller.

The glass fibre content of the insulation shall be 40% ± 5% volume (to be confirmed by insulation qualification, see chapter 5.2.1 - Insulation samples)**.**

Resin-rich areas are not permitted. Particular care shall be taken to ensure that the glass fibre content specified above is obtained in and around the end turns and formation of the tails. See also chapter 5.1.13.

5.1.10 Tooling

All tooling (including the VPI mould) shall be supplied by the Seller. The design of tooling used for fabricating the deliverable items of the Contract shall be reviewed and approved by the Buyer prior to use.

5.1.11 Solder materials

Suitable solder material will be supplied by the Seller. Soldering shall be done at room temperatures but solder material has to be suitable for cryogenic temperatures (down to LN temperature). All processing agents (e.g. flux, cleaner) shall be compatible with the coil insulation, to avoid its damage. All processing agents shall be compatible with high vacuum operation of the PF coils - see the Annex of technical specification No. 1 - Vacuum compatibility.

The Buyer recommends materials listed below. However, the Seller can propose alternatives with equivalent or superior properties. The areas to be soldered are explained in chapter 5.8.9.

For solder (coolant feeders, see Figure 5-13 in chapter 5.8.9):

- Minimum content of Pb ≥ 90% and Sn ≥ 5 % in the solder material (i. e. $Pb_{93.5}Sn_5Ag_{1.5}$ or $Pb_{90}Sn_{10}$)
- Melting temperature under 300°C
- Ultimate tensile strength greater than 30 MPa at 20°C
- Impact energy greater than 0.8 J at -200°C (solder must not brittle at cryogenic temperatures)

5.1.12 Coil fillers (machined HPL, drawings available)

The "coil filler" fills large expected (drawings are available) volumes between the insulated conductors inside the coils.

All required coil fillers (see drawings) shall be supplied by the Seller. The insulating coil fillers shall be constructed from High Pressure Laminate (HPL). Required HPL material is EP GC 201 according to IEC/DIN EN 60893-3 norm (G-10 according to NEMA norms). The Buyer would prefer to use a material with improved mechanical properties at cryogenic temperatures (i.e. G-10 CR).

Material certificates (chapter 6.1) are required. All machining of HPL must be done in a way to comply with its use in a high vacuum environment. The coil fillers shall be free of burrs and sharp edges. All HPL surfaces unless machined shall be grit blasted to remove any high gloss surface, to promote bonding of the epoxy to the coil fillers. The parts shall be cleaned with an appropriate solvent prior to use.

5.1.13 Void fillers (machined HPL or densely packed E-glass, without drawings)

The "void filler" fills small volumes between the insulated conductors inside the coils (e.g. gap between the four adjacent turns caused by rounded edges of the turns, where "glass lace" should be located). The drawings of the void fillers are not provided.

All regions within the winding volume not occupied by conductor or ground insulation shall be filled with certified (chapter 6.1) E-glass or HPL fillers to minimize resin rich areas. When using E-glass to fill voids, the glass shall be densely applied to avoid resin rich areas. Resin rich areas where there is no glass or HPL filler shall not exceed size defined in the Table 5-4 in parameter "insulation resin rich area". The edges of HPL shall be rounded (0.5 mm to 1.0 mm) to prevent damage to adjacent insulation. The HPL fillers shall not be in direct contact with other HPL components without intermediate layer of GF tape insulation. For description of HPL material see chapter 5.1.12.

5.1.14 Degreasing/cleaning solvents

All conductors, insulation blocks, and VPI mould parts shall be degreased/cleaned using a solvent that is able to dissolve grease, tar, wax, adhesives, oils and other soils, and is residue-free. Solvent selected by the Seller shall be approved by the Buyer prior to use. Recommended solvents are acetone and isopropyl alcohol, however only isopropyl alcohol is permitted for use on the primed copper.

5.1.15 VPI mould

The Seller shall supply the VPI mould. The design of the mould and sealing shall be submitted to the Buyer for review and approval as a part of the MIT plan (refer to chapter 7.3 - MIT plan).

5.1.16 Mould release

The Seller shall propose a mould release agent for use on the surfaces of mould parts that are to be removed after VPI. Mould release material have to be approved by the Buyer prior to use.

5.1.17 Other materials

All other materials not listed in chapter 5.1 or above required to fabricate, test, and ship the deliverable items shall be supplied by the Seller. Any other (i.e. not described in chapters 5.1.1 to 5.1.16) materials provided by the Seller shall be reviewed by the Buyer prior to purchase to verify compliance with this specification. All materials that become part of the coil must be certified (see chapter 7.4.1).

5.1.18 Material provided by the Buyer

The Buyer (Institute of Plasma Physics of the Czech Academy of Sciences) will provide to the Seller (company) the following material:

- Electrical breaks (for cooling feeders, see drawings)

The Buyer will lend the "holder for insulation qualification tests" (as described in "Annex of technical specification No. 2 – Insulation tests and results") to the Seller.

5.2 Coil insulation qualification program

5.2.1 Insulation samples

The insulation samples shall simulate part of a PF coil (turn-to-turn insulation), demonstrate the mechanical strength of the insulation and confirm the final insulation design (i.e. required volumetric fibre glass ratio, see Table 5-4).

It should be noted that the Buyer (IPP) performed their own qualification tests of insulation samples (see more in "Annex of technical specification No. 2 – Insulation tests and results"). The Buyer's test samples were made of insulated CuAg0.1(OF) base plates, primed by CTD 450 primer and wrapped by E-glass tape (satin weave, width 30 mm, thickness 0.15 mm). The insulation layout of samples mimicked PF coils turn-to-turn insulation, as described in chapter 5.1.6.1. The taping was done with 50% overlap, the layers which are interleaved by polyimide tape used 0.025 mm Kapton (~80% width of the E-glass tape) centred and co-wound with the E-glass tape. The samples were vacuum pressure impregnated using epoxy resin Araldite GY 282. **The volumetric fibre glass ratio (Vf) of the samples was approximately 50%**. Please note that the mentioned products CTD 450, Kapton and Araldite GY 282 are recommended products by the Buyer and alternative products may be used (see conditions and requirements in chapters 5.1.5, 5.1.8 and 5.1.7).

Through-thickness tensile strength and shear strength of the samples tested by IPP (both at room temperature and LN2 temperature) were found acceptable for PF coils. However, **it was later decided to lower the required insulation Vf to 40% due to better matching of the thermal expansion of insulation to the copper conductor at LN2 temperature**. The available literature (i.e. R.P. Reed et al.: *Short-beam shear testing of candidate magnet insulators*, Cryogenics. 32: 9 (1992)) shows that there is a dependence of shear strength of fibre glass reinforced epoxy composites on Vf. IPP found no literature on dependence of through-thickness tensile strength on Vf.

The aim of the coil insulation qualification program is therefore twofold:

- Firstly, the Seller has to prove that their chosen insulation materials and their quality of manufacturing of insulation is equal or superior (see exact criterion below) to the one qualified by the Buyer (IPP) in aforementioned sample tests.
- Secondly, the Seller will confirm the design choice of volumetric fibre glass ratio of insulation

by testing **3 sets of samples, each with different Vf (30 ± 5 %, 40 ± 5 % and 50 ± 5 %).** This confirmation is needed because the Buyer's decision to use Vf of 40% comes from extrapolation from known literature. The validity of this extrapolation needs to be confirmed by performing these tests. **Only then the final decision about the required value of insulation Vf will be made (either confirmation of 40% or change to other value, e.g. 45%)**.

The final PF coils (plus 3x3 mock-up and the prototype coil) insulation Vf will be confirmed by the Buyer together with evaluation/acceptance of FAT of insulation samples. Generally, the chosen design value of 40 ± 5 % of volumetric fibre glass ratio will be confirmed if the tested samples show that through-thickness tensile strength and shear strength don't decrease excessively when lowering Vf.

The **conformance of the Seller's chosen insulation materials and quality of insulation manufacture processes** will be successfully established by passing static through-thickness tensile strength tests and shear-compression tests of samples with 50% Vf (as these are comparable to the insulation samples tested by IPP). The tests are required both at room temperature and at LN2 temperature and **the samples shall pass by achieving at least 85% of strength of the samples tested by the Buyer** (IPP). The complete list of the required sample tests and their required values is provided in Table 5-9 below. The geometry of tensile and shear-compression test samples shall be prepared according to Annex of technical specification No. 2 – Insulation tests and results" and tested following the methodology described there.

The Buyer requires that the residues of the tested samples as well as 3 additional composite bars, each with a different value of Vf (30 ± 5 %, 40 ± 5 % and 50 ± 5 %), shall be delivered to the Buyer for their own tests. The samples which shall be delivered to the Buyer are specified and listed in Table 5-8.

Table 5-8 - Insulation qualification test samples to be delivered to the Buyer.

Sample description	**Quantity**
Composite bar (see technical drawing "CU_CUTT-03-102625_V01_DRW_A01_DRW" and "Annex of technical specification No. 2 – Insulation tests and results")	3 (each with a different value of Vf: 30 ± 5 %, 40 ± 5 % and 50 ± 5 %)
Tensile test samples (at RT)	residues from Seller's tests
Tensile test samples (at LN2 temperature)	residues from Seller's tests
Shear-compression test samples (at RT)	residues from Seller's tests
Shear-compression test samples (at LN2 temperature)	residues from Seller's tests

Table 5-9 – Insulation sample tests: Required values, samples and methodology

Test	**Minimum required values** (applies to samples with 50% Vf only)	**Samples** (per each Vf)	**Test methodology**

	Overall min. (MPa)	Min. average (MPa)		
Through-thickness tensile strength at RT	33.6	38.9	6	Chapter 4.1 (of Annex No. 2)
Through-thickness tensile strength at LN2	28.8	34.9	6	Chapter 4.2 (of Annex No. 2)
Shear-compression strength at RT – angle 30°	53.3	55.5	6	Chapter 5.1 (of Annex No. 2)
Shear-compression strength at RT – angle 45°	66.1	70.2	6	Chapter 5.1 (of Annex No. 2)
Shear-compression strength at LN2 – angle 30°	54.8	68.4	6	Chapter 5.2 (of Annex No. 2)
Shear-compression strength at LN2 – angle 45°	113.7	120.7	6	Chapter 5.2 (of Annex No. 2)

Note to Table 5-9: *The minimal requirements are related to the 50% Vf qualification samples, which shall achieve minimal strength in average of the tested samples and minimal strength of all the tested samples. Example: if 6 samples are measured, then average obtained from the 6 measurements shall be higher than "Min. average" and each of the 6 measurements shall be higher than "Overall min.".*

5.2.2 3x3 mock-up

The mock-up shall demonstrate the technology of insulation of the coils. 3x3 mock-up shall simulate part of PF1a coil. Specification:

- Minimal assembly of 3x3 hollow conductors (conductor specification in 5.1.1).
- Minimal length (l) of the mock-up 250 mm.
- Coated with primer (primer specification in 5.8.2.3, 5.8.4, 5.1.4).
- Wrapped with turn (marked T1 in the Figure 5-11) and ground insulation (marked T2 in the Figure 5-11), mimicking the insulation layers (insulation layout specification in 5.1.6)
- Use of void fillers (materials specification in 5.1.13)
- Vacuum pressure impregnation (VPI specification in 5.8.7 and 5.8.8.)
- The conductor insulation layer should be extended by approximately 10 mm beyond the conductor ends in order to prevent tracking discharge at the free ends during the turn-to-turn HV test. The exact procedure to achieve the sufficient electrical insulation of the conductor ends shall be proposed by the Seller and it is not subject to the approval by the Buyer.

- Ground plane conductive layer with the same properties as required for the PF coils (reference in 5.1.6.4) shall be applied.

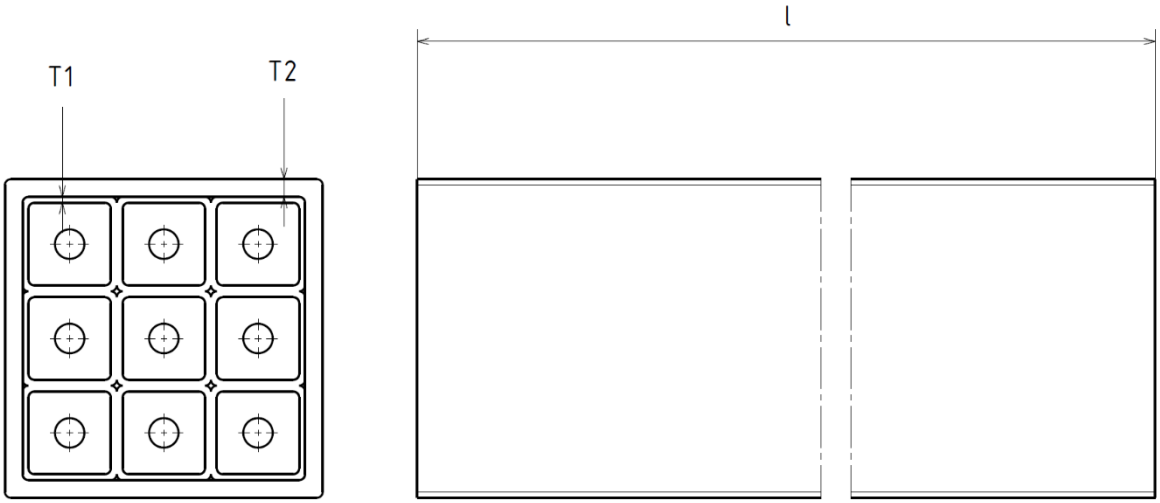


Figure 5-11 - Scheme of Mock-up sample.

The **3x3 mock-up shall be subjected to the FAT tests** required in the chapter 6 - Testing specification in the Table 6-1 and then it shall be delivered to the Buyer (see Table 3-4 - Deadlines for physical deliverables.).

5.3 Prototype coil

The prototype coil will be manufactured to demonstrate feasibility of the design. The prototype coil shall be the same as PF1aU.

The prototype coil will be tested in order to find any design flaws (see Table 6-2), including "destructive" tests for inspection of the conductor and insulation cross-section. The tests listed in the Table 6-2 constitute the FAT of the prototype coil and will be evaluated according chapter 6.5.6 - Evaluation of FAT.

The samples shall be provided to the Buyer, as described in the chapter 6.2.2.

5.4 Poloidal field coils

The poloidal field coils PF1aU, PF1aL, PF1bU, PF1bL, PF2U, PF2L, PF3U, PF3L, PF4L and PF4U are defined by the drawings. In the following chapters we describe only details which are not self-explanatory from the drawings.

The Seller shall note that the **top and bottom coils are not exactly symmetrical – there are important** (though physically small) **geometrical differences**.

5.5 Electrical breaks

The electrical breaks insulate the coil conductor from the cooling circuit piping, to avoid electrical current flow through the cooling system. The inlet part of the electrical break is made of copper, outlet is made from stainless steel and these parts are insulated from each other by a ceramic material. The drawings of the electrical breaks are provided in technical drawings of the individual PF coils (coils PF1-PF3 have one size of the electric breaks, PF4 has large electric break) and in the "Annex of technical specification No. 4 – Electrical break specifications and drawing".

Electrical breaks **shall be welded by orbital welding machine** to all cooling channels (as is shown in drawings) and all requirements for metal connection quality shall be met as specified in chapter 5.8.9. Electrical breaks shall be insulated with the same layout of glass fibre and polyimide tapes (see chapter 5.1.6) as PF coils and VPI-ed with resin (see chapter 5.1.6 and drawings). The endings shall be protected against intrusion of resin and clogging of the cooling channel and against contamination during manipulation and transportation as well.

The electrical breaks will be provided by the Buyer. The Buyer will provide pressure test and leak test protocols. The Seller shall propose reasonable acceptance inspection and tests and then the Seller will sign acceptance protocol, which confirms that Seller takes full responsibility for insulation ceramic breaks performance during subsequent fabrication and testing steps. The insulation and welding of the electrical breaks is responsibility of the Seller. Damaged or contaminated insulation ceramic break shall be photographed and documented in a non-conformance report.

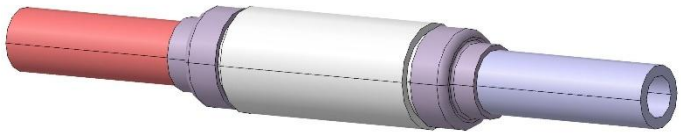


Figure 5-12 - Electrical break.

5.6 Soldered joint of hollow conductor

At a dedicated place of coolant feeders outside of the coil winding, there will be a soldered joint to create electrical connection to ensure the current can continue flowing uninterrupted through the coil turns. The end of the hollow conductor of coolant feeders is connected to the electrical breaks (see chapter 5.5). Solder joints are specified in chapters 5.8.9 (procedure, qualification, …) and by drawings (see chapter 5.8.9 for example of the drawing). See Figure 1-2 for illustration of the position of the soldered joint of conductor. See chapter “5.1.11 - Solder materials” for requirements on the soldering material (including ultimate tensile strength).

5.7 Coil accessories

The rigs/jigs for the coil manipulation and transportation shall allow safe operation. It shall allow to turn the coils upside down (transport, inspection, storage and installation). It is recommended to design universal rigs for the manipulation, e.g. one piece for the smaller coils (PF1, PF2, PF3) and one piece for the bigger coils (PF4).

5.8 Fabrication

5.8.1 Cleanliness/housekeeping

Cleanliness and housekeeping is an essential element to the success of the manufacturing of the PF coils. Cleanliness and housekeeping are one of the Critical activities, which are summarized in chapter 9.9. Chapter 9.9 describes further the consequences of the violation of the rules stated in this chapter. The following steps shall be taken during the fabrication of the PF coils to enforce this practice.

5.8.1.1 Clean environment

The final preparation of all insulating materials, the final preparation of the mould, the application of insulation, and the winding of the coil must be performed in a clean, humidity controlled environment that eliminates the risk of debris and dust particles such as metal chips, dirt, etc., from contaminating the coil insulation prior to VPI. The work environment shall be enclosed, shall include an intermediate entry area with double doors or other equivalent means of separation in which workers can put on

protective wear (chapter 5.8.1.3) and shall employ a positive pressure fan with a filter capturing a particle size of 1 micrometer or larger.

The winding line shall be covered during off-shifts to protect the material.

5.8.1.2 Step-Off pads

Step-off pads shall be used at the entrances to the work areas to minimize transport of foreign particles and dirt into the work area. Step-off pads shall be changed at least twice per a week.

5.8.1.3 Gloves and lab coats

Latex, vinyl, rubber or cotton lint-free gloves, hair covers, and lab coats shall be worn in the work areas during the handling of insulated conductor, insulation, HPL fillers or other components used in the construction of the PF coils. An alternative glove material may be proposed, but needs to be approved, in writing, by the Buyer prior to use. Lab coats and hair covers worn outside of the clean area, regardless of length of time, shall not be brought back into the clean area. No uncovered jewellery shall be permitted in the clean room. Prior to entering a clean room, eyeglasses shall be checked for loose screws and parts.

All materials shall be protected from contamination from skin oil, etc., both during storage by sufficient cover and during manufacturing by usage of the gloves, lab coats and hair covers.

5.8.1.4 Markers and Pencils

The use of electrically conductive pencils is prohibited in the fabrication stations due to electrical tracking concerns. Markers used on the conductor may affect adhesion of the insulation – compatible type of markers has to be discussed with the primer/epoxy manufacturer. Used brand and type of markers have to be approved by the Buyer.

5.8.1.5 Chips and filings

Filing, grinding, or any other operation that generates any kind of electrically conductive chips or metallic dust shall not be allowed in the clean area (chapter 5.8.1.1). Clamping and tooling design must preclude conductive debris from being generated. For example, any fixtures or clamps that could possibly abrade and form conductive chips are not allowed. If such an operation is not planned but is needed (e.g. removal of burrs on conductor) the protective measures to prevent contamination of insulation shall be reviewed and approved by the Buyer in advance of the work.

5.8.1.6 Material Protection

Material controls shall be addressed in the QA Plan (chapter 7.3.5) or MIT Plan (chapter 7.3). Copper conductor and all insulating materials shall be stored and processed in controlled areas free from metallic dust or other contaminants. Copper conductor and all insulating materials shall not be contaminated by metallic dust, normal dust or other contaminants in manufacturing activities performed between priming and finishing VPI.

5.8.2 Copper receipt, inspection and handling

5.8.2.1 Identification

The Seller-assigned identification number shall be carried through on all documentation and references for traceability during processing.

5.8.2.2 Receipt inspection

Upon arrival of each shipment of conductors, the Seller shall inspect the shipment for any visible

damage to the packaging and/or the conductor. Any discrepancies shall be immediately noted, photographed, documented on a Non-Conformance Report (NCR), and repaired in accordance with the Buyer-approved NCR disposition. Repairs shall be photographed. This receipt inspection step shall be delineated in the MIT plan.

5.8.2.3 Conductor preparation, handling and priming

All manipulation, like unwinding or rewinding of the conductor during the manufacturing process, shall be minimized and performed in the way to avoid damage of the conductor surface and inner structure (e.g. cracks), deformation of the conductor outer profile and inner cooling channel and change of the conductor mechanical properties in an unfavourable way (e.g. lowering yield strength). When the conductor is transferred and when it is fed into the winding line it shall be inspected and any surface defects shall be marked in non-conformance report and repaired. Immediately prior to application of the primer, the conductor shall be grit blasted and then rinsed with solvent (see chapter 5.1.14 - Degreasing/cleaning solvents) to remove excess oil, lubricant, grease or any other contaminant. Sufficient time shall be allowed for the alcohol to fully evaporate before turn insulation is applied. If the conductor is not going to be primed within 4 hours, it is required to place the cleaned conductor into a plastic sleeve and back fill with an inert gas such as Nitrogen or Argon into bag to minimize oxidation.

After the cleaning, the primer shall be applied, then the glass fibre tape with polyimide (layout specified in detail in chapter 5.1.6) shall be wound on the conductor. If the GF tape with polyimide is not applied immediately after conductor priming, the primed conductor shall be packed in a plastic sleeve to prevent dust collection and shall be cleaned before GF tape and polyimide application. The whole sequence of conductor cleaning, priming, primer curing, GF tape and polyimide application shall comply with the processing specifications defined by the primer and epoxy manufacturer.

During winding of primed conductors, the **method used to maintain conductor tension cannot use a friction method** that would damage the primer coating.

5.8.3 Conductor bending

Special attention shall be given to the small radius bends of the conductor (90-degree feeder bends). The bending process shall be qualified before the manufacturing. The procedure of the conductor bending must be the same as the procedure qualified and tested by the Seller on the bent conductor samples (more in chapter 6.2.1 - Integrity test of conductor bends).

5.8.4 Key winding steps

Key steps of the winding sequence are described in this chapter. The Seller shall include all winding steps in the MIT plan and sub-tier procedures referenced by the MIT plan.

5.8.4.1 Winding tooling and initial steps

Ensure that the winding tooling is cleaned, deburred and prepared for the commencement of winding. Precautions such as clamping and pinning of spacers in place must also be taken to ensure the spacers do not shift during winding. Planning and measurement is required to ensure the proper shim thickness is used on the lead start side of the mandrel to ensure the full complement of turns fits in the prescribed coil space.

5.8.4.2 Turn insulation

The turn insulation shall be applied to the conductor using an automated taping machine so that precise control of dimensions is achieved. If the Seller identifies critical locations, where automated taping is not possible, it must be agreed with the Buyer to use manual taping (with written approval).

Joints at the end of one roll of insulation and the start of another shall be carefully tailored to retain the number of overlapping layers of glass and polyimide and to avoid excess build. See chapter 5.1.6 for turn insulation details.

5.8.4.3 Dimensional control

Apply sufficient tension on the conductor feed and a force normal to the conductor to achieve the nominal compression of the insulation (to reach the required glass fibre volumetric content ratio) while retaining dimensional tolerances on the gap between turns, the radial build, and the axial build of the winding pack, with minimal wandering of the conductor from its nominal position. To avoid over-compression of the insulation, tension beyond the nominal required to seat the conductor and maintain dimensional control is to be avoided. The dimensional build shall be monitored during winding. Any indication that the build of the turns cannot be held to the tolerance on the drawings shall be recorded as a non-conformance and communicated to the Buyer before continuing with the winding process.

5.8.4.4 Start and finish leads

The insulation shall be tailored to ensure that the number of overlapping layers of glass fibre and polyimide tape on the turns is retained on the leads.

5.8.5 Handling of coil prior to VPI

Care shall be taken to avoid damage to the insulation in subsequent handling. Damaged or contaminated insulation shall be photographed, documented in a non-conformance report, and replaced with new insulation in accordance with a repair procedure that is reviewed by the Buyer before use.

5.8.6 Pre-VPI electrical tests

For details see chapter 6.

5.8.7 VPI preparations

5.8.7.1 Mould cleaning

The Seller shall thoroughly clean and degrease all surfaces of the mould prior to coil winding activities using the pre-approved solvent (see chapter 5.1.14).

5.8.7.2 Mould leak test

Before VPI the mould has to be leak tested – see details in 6.4.

5.8.8 VPI and curing

The VPI and curing process shall include the following steps. Parameters to be measured and recorded, along with acceptance criteria, shall be delineated in the MIT.

- Leak check and/or rate of pressure rise test
- Resin fill volume measurement (it is recommended to expand a pressurized volume of nitrogen into the evacuated VPI mould and perform delta pV calculation).
- Bakeout/de-gassing of the coil and resin delivery system.
- Weighing, mixing and degassing of the resin (to be de-gassed to a pressure less than the vacuum pressure during VPI)
- Filling process including fill rates at each inlet and soak times

- Milking process (reverse flow under positive pressure) after fill is complete.
- Determination of the quantity of resin that was used to impregnate the coil and comparison with expected fill volume based on fill volume measurement.
- Oven temperature ramp rates and hold times with each step annotated on the chart and MIT (beginning ramp up, end ramp up, etc.)

Details of the VPI and curing process shall be delineated in the MIT plan which shall include provision for entry of key data and parameters as well as the recording of time and temperature throughout the VPI and curing process.

For each coil and each material batch used in manufacturing the coil, after the coil is removed from the mould, a small sample of excess cured resin is to be supplied to the Buyer for analysis (see Table 6-5).

5.8.9 Metal connection and its qualification program

All technical norms cited in this chapter are required as minimum or they shall have adequate technical setup approved by the Buyer. During the process the temperature shall be monitored and recorded and it has to be made in a way that no other nearby materials/components are damaged. Monitoring points of temperature shall be documented.

5.8.9.1 Procedure

The Seller shall develop a metal connection procedure and inspection procedure in MIT plan for performing all connection operations. Procedure shall be reviewed and approved by the Buyer.

The materials for the connections are specified in chapter 5.1.11.

- soldering of coolant feeders (depicted in drawings)
    - Soldering temperature must be held below 300 °C to avoid annealing of the base material. Both ends (except of PF4 – only one cooled end is required because the other end is not suitable for cooling insert) shall be cooled.
    - Note: If the Seller proposes different permanent metal joining procedure that meets the requirements specified by the Buyer (e.g. laser welding, …), this procedure may be used instead of soft soldering. This procedure must be included in the MIT plan and approved by the Buyer.

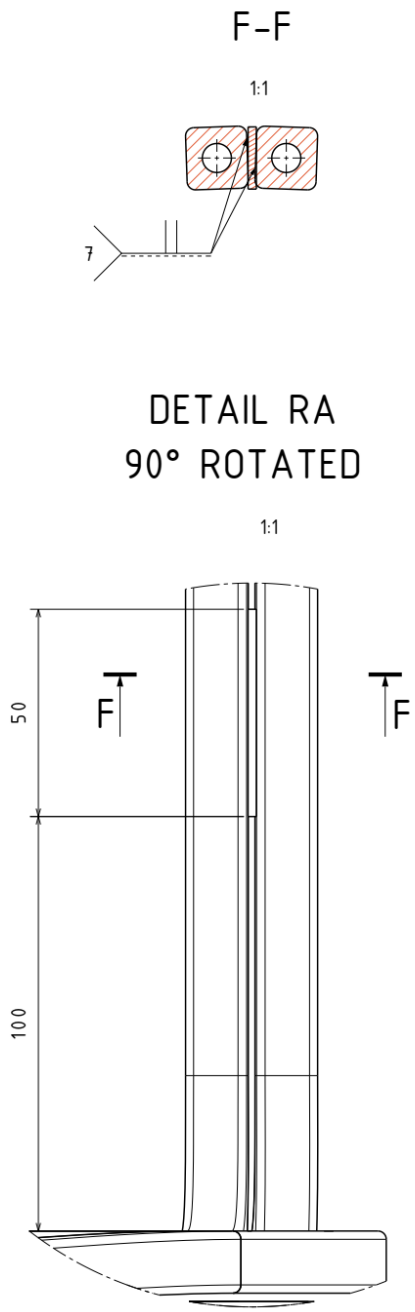


Figure 5-13 - Example of the area to be soldered (excerpt from the drawing, 50 mm to be soldered).

- welding of electrical break on the coolant feeders (depicted in drawings)
  - The electrical break shall be welded by orbital welding machine.
  - The temperature at the measuring point shall not rise over 200°C. The measuring point is on the copper side of the break and it is 10 mm from the Kovar part (Kovar is used at the transition between metal and ceramic part of the electric break; therefore, the requirement is to place the measuring point 10 mm from the end of ceramic part of the electric break).
  - Connection procedure must avoid joint embrittlement at cryogenic temperatures and

provide helium leak tightness.

5.8.9.2 *Qualification of Procedure/Process*

A minimum of three (3) successful metal connection shall be made to qualify each metal connection process and settings:

- Soldering – lap joint of two hollow conductors soldered together – simulating solder joint on cooling feeders
- Welding – simulate the process of joining coil´s cooling channel in the form of pipe with the electrical break part. The electrical break part can be substituted by a copper pipe with the same outer and inner diameter as the cooling channel.

5.8.9.3 *Qualification of metal connection Operator*

A minimum of three (3) successful metal connection samples shall be made by each metal connection operator to qualify his/her ability to perform successful metal connection (these may be the same samples used for procedure qualification).

5.8.9.4 *Qualification Requirements*

All joints and joints samples (solder and weld) shall be tested according to chapters 6.2.6 and 6.2.7.

5.9 Operational environment – vacuum compatibility

The requirements valid for both the procedure and the final product (PF coils) are described in the Annex of technical specification No. 1 - vacuum compatibility.

5.10 Dimensions and tolerances

In general, dimensional tolerances of all components included in the extent of delivery described in this tender must comply with the standard ISO 2768-m. For some selected dimensions specifically denoted in the text of this technical specification and/or in the technical drawings provided to the Seller, different (and often more stringent) tolerances are required. In case of a conflict between the required dimensional tolerance values, the tolerances specified in the technical drawings shall always take precedence. All dimensional tolerance values are valid for room temperature.

Several crucial dimensional tolerances specifically defined for the coils (including the prototype coil) are listed in Table 5-10. General insulation tolerances are defined in chapter 5.1.4.

Table 5-10 - Coil dimensional tolerances

coil	PF1a, PF1b, prototype coil	PF2	PF3	PF4
Inner diameter tolerance	-0 +0.5 mm	-0 +0.5 mm	-0 +0.5 mm	-0 +0.5 mm
Outer diameter tolerance	-0.6 +2 mm	-0.6 +2 mm	-0.6 +3 mm	-0.6 +3 mm
total height	-0 +1 mm	-0 +1 mm	-0 +1 mm	-0 +1 mm

Surface flatness (top and bottom surface)	0.2 mm	0.2 mm	0.2 mm	0.5 mm
Parallelism (top and bottom surface)	0.2 mm	0.2 mm	0.2 mm	-

In addition to the tolerances defined in Table 5-4 and Table 5-10 and in the technical drawings, the Buyer would like to emphasize one more point of their interest. Two sets of coils are held in a common holder structure (upper and lower coils PF1a, PF1b and PF2) and thus it is important to keep their mutual height as close as reasonably possible. There is no tolerance strictly required by the Buyer. However, when selecting the manufacturing procedure, the Seller is encouraged to consider finding ways to minimize the height difference of these sets of coils.

To achieve the strict tolerance of coils surface flatness, **the Seller is allowed to perform fine machining of the ground insulation on the coils' top and bottom surfaces**. Moreover, as an exception, **the ground insulation thickness tolerance** (as provided by Table 5-4) **on the respective top and bottom coil surfaces shall be increased** to 2.5 mm -0.25 mm + 0.75 mm.

It is of essential importance to the Buyer, that the position of the coil winding joggles (turn-to-turn and layer-to-layer) is done according to the technical drawings. The joggles are designed in a way to minimize the intrinsic error field of the coils which would negatively impact the tokamak plasma. **The Seller is therefore required to record the positions of conductor joggles of each manufactured coil and provide it to the Buyer in the respective fabrication process reports.**

6 Testing specification

Table 6-1 - List and sequence of individual tests of the qualification samples

Tested item	interim checks **description**	**Reference**
Insulation samples **(these tests constitute FAT of the Insulation samples)**	(through thickness) Tensile strength tests	See Table 5-9 – Insulation sample tests: Required values, samples and methodology
	Shear/compression tests	See Table 5-9 – Insulation sample tests: Required values, samples and methodology
3x3 mock-up **(these tests constitute FAT of the 3x3 mock-up)**	Visual inspection, photographs from each side and photographs with magnification	
	Insulation resistance test (T-T, T-G)	See chapter 6.3.3
	DC Hipot test (T-T, T-G) – coil testing voltage	See chapter 6.3.6
	DC Hipot test (T-T, T-G) – mock up testing voltage	See chapter 6.3.6
	After Thermal cycling (see Table 6-6)	
	Insulation resistance test (T-T, T-G)	See chapter 6.3.3
	DC Hipot test (T-T, T-G) – coil testing voltage	See chapter 6.3.6
	DC Hipot test (T-T, T-G) – mock up testing voltage	See chapter 6.3.6
	Visual inspection and photographs from each side and photographs with magnification	
	Volumetric fiberglass ratio, resin rich area, void gap, void ratio	See chapter 6.2.3, Table 5-4

Metal connection tests performed on the samples and on the prototype coil	Visual inspection Capillary inspection Radiographic testing Standard static transverse tensile test Standard static longitudinal (shear) tensile test Macroscopic and microscopic examination Charpy pendulum impact test	See chapter 5.8.9, 6.2.6
Integrity test of the bent conductor samples	metallographic cuts, tensile tests, low cycle fatigue tensile test	See chapter 6.2.1
Conductor hardening process – test samples	If applicable (i.e. if the Seller uses conductor which needs hardening) – tests proposed by the Seller	See chapter 5.1.1, 6.2.4

Table 6-2 - List of required FAT tests - prototype coil. Proposed sequence (the sequence can be changed by the Seller, but only with approval of the Buyer).

Tested item	Test description	Reference
prototype coil	***During coil winding (pre-VPI)***	
	Integrity check	See chapter 6.5.3
	Metal connection tests performed on the samples and on the prototype coil: Visual inspection, Radiographic testing, Standard static transverse tensile test, Macroscopic and microscopic examination	See chapter 6.2.6
	After coil winding (pre-VPI)	
	Coil DC resistance test	See chapter 6.3.1
	Coil Impedance test	See chapter 6.3.2

	Insulation resistance test	See chapter 6.3.3
	After VPI of the coil	
	Coil DC resistance test	See chapter 6.3.1
	Coil Impedance test	See chapter 6.3.2
	Insulation resistance test	See chapter 6.3.3
	After Thermal cycling (see Table 6-6)	
	Leak inspection	See chapter 6.5.5
	Cooling channel pressure testing	See chapter 6.5.4
	Dimensional inspection	See chapter 6.5.2
	Insulation resistance test	See chapter 6.3.3
	Dissipation test	See chapter 6.3.4
	Partial discharge test	See chapter 6.3.5
	DC Hipot test	See chapter 6.3.6
	Full surface coverage Paschen test (performed after previous tests, which can potentially damage the coil)	See chapter 6.3.7
	Insulation resistance test (repeated, check that the previous tests did not damage the coil)	See chapter 6.3.3
	Coil DC resistance test (check that the previous tests did not damage the coil)	See chapter 6.3.1
	Coil Impedance test (check that the previous tests did not damage the coil)	See chapter 6.3.2
	Resistance of the ground plane	See chapter 6.3.9
	Controlled short circuit between turns test	See chapter 6.3.8

	After coil sectioning (see chapter 6.2.2)	
	Cross-sections examination	See chapter 6.2.2 and technical drawings
	Integrity check	See chapter 6.5.3
	Tensile test of conductor	See chapter 6.2.5
	Volumetric fiberglass ratio, resin rich area, void gap, void ratio	See chapter 6.2.3, Table 5-4

Table 6-3 - List of requested FAT/SAT tests - PF coils. Proposed sequence (the sequence can be changed by the Seller, but only with approval of the Buyer).

Tested item	Test description	Reference	FAT/SAT
PF1aU, PF1aL, PF1bU, PF1bL, PF2U, PF2L, PF3U, PF3L, PF4U, PF4L coils	***During coil winding (pre-VPI)***		
	Integrity check	See chapter 6.5.3	FAT
	Metal connection tests performed on the coils: Visual inspection, Radiographic testing	See chapter 6.2.7	FAT
	After coil winding (pre-VPI)		
	Coil DC resistance test	See chapter 6.3.1	FAT
	Coil Impedance test	See chapter 6.3.2	FAT
	Insulation resistance test	See chapter 6.3.3	FAT
	After VPI of the coil		
	Coil DC resistance test	See chapter 6.3.1	FAT
	Coil Impedance test	See chapter 6.3.2	FAT
	Insulation resistance test	See chapter 6.3.3	FAT

	During thermal cycling		
	Measurement of DC resistance of cooled coil	See chapter 6.3.1	For reference only
	After thermal cycling (see Table 6-6)		
	Leak inspection	See chapter 6.5.5	FAT
	Cooling channel pressure testing	See chapter 6.5.4	FAT
	Dimensional inspection	See chapter 6.5.2	FAT
	Insulation resistance test	See chapter 6.3.3	FAT
	Dissipation test	See chapter 6.3.4	FAT
	Partial discharge test	See chapter 6.3.5	FAT
	DC Hipot test	See chapter 6.3.6	FAT
	Local Paschen tests (only if Full surface coverage Paschen test was not ordered by the Buyer; the Seller can opt to perform Full surface coverage Paschen test instead)	See chapter 6.3.7	FAT
	Full surface coverage Paschen test (if ordered by the Buyer) (performed after previous tests, which can potentially damage the coil)	See chapter 6.3.7	FAT
	Insulation resistance test (repeated, check that the previous tests did not damage the coil)	See chapter 6.3.3	FAT
	Coil DC resistance test (check that the previous tests did not damage the	See chapter 6.3.1	FAT

	coil)		
	Coil Impedance test (check that the previous tests did not damage the coil)	See chapter 6.3.2	FAT
	Resistance of the ground plane	See chapter 6.3.9	FAT
	Delivery		
	Dimensional inspection	See chapter 6.5.2	SAT
	Visual inspection for damage	See chapter 6.6	SAT
	Insulation resistance test	See chapter 6.3.3	SAT
	Leak inspection test	See chapter 6.5.5	SAT

All test procedures shall be designed for reproducibility wherever possible and the test procedures shall be clearly described in the MIT plan and test reports. This is especially important for the tests which are also part of SAT.

6.1 Material acceptance tests

All materials used for coils manufacture have to comply with the requirements described in this technical specification. Relevant chemical, mechanical and electrical properties of materials used shall be demonstrated by test reports and material certificates (also see chapter 7.4.1) per every production batch. All such documents shall be provided to the Buyer as soon as they are available. **Samples of every production batch shall be kept and provided to the Buyer for reference or later testing** (Table 6-5). Any non-conforming items shall be documented and prevented from use and the non-conformance shall be resolved according to chapter 8.3.

As was already indicated, the Buyer requires that, additionally to material certificates, several critical material properties shall be tested by the Seller per each production batch of the respective material. The required material acceptance tests are listed in Table 6-4. The test reports have to be to approved by the Buyer before further processing of the respective materials. If the identified material properties do not meet the requirements set out in this specification and the approved MIT plan, it shall be documented and the material prevented from use. The non-conformance shall be resolved according to chapter 8.3.

The material provided by the Buyer (electrical breaks) shall be inspected by the Seller upon its receipt, which shall be confirmed in an acceptance protocol.

Table 6-4 – Material acceptance tests at room temperature.

Material	Property	Required value

Conductor (applicable norms for testing defined by EN 13600)	Chemical composition	see chapter 5.1.1, Table 5-1
	Yield strength (0.2% proof strength)	see chapter 5.1.1, Table 5-1, or alternatively as defined in the Seller's MIT plan
	Ultimate tensile strength	see chapter 5.1.1, Table 5-1, or alternatively as defined in the Seller's MIT plan
	Dimensional inspection	The conductor cross section shall be dimensionally inspected to confirm that the conductors meet the requirements in the technical drawings. The dimensions shall be measured at each end of the conductors.
	Surface finish	The external surfaces shall be visually inspected and must be free from serious defects which may impair the strength and constructional use of the material e.g. serious cracks and mechanical damage, blisters and voids and inclusions of foreign matter.

Table 6-5 - List of samples of raw materials to be provided by the Seller to the Buyer from each production batch.

Material	**Sample size** (estimated dimensions, can be modified after approval by the Buyer)	**pieces** (per raw material production batch)
Conductor	100 mm length	3
Glass fibre tape	3 m	1
Polyimide tape	3 m	1
Primer (cured)	on conductor of approx. 100 mm length	1
High pressure laminate (HPL)	50 mm x 30 mm x 20 mm	3
Conductive varnish	0.5 x 0.5 m High Pressure Laminate sheet with conductive varnish	1
Epoxy resin (without glass fibre tape, cured)	10 mm x 10 mm x 2 mm	- 1 per each PF coil for each material production batch (used for manufacturing of the individual PF coil) - this includes prototype coil - this sample must be procured during the manufacturing of the PF coil, not beforehand - see chapter 5.8.8

6.2 Mechanical tests

6.2.1 Integrity test of conductor bends

The Seller shall demonstrate their ability to wind the coils including 90° small radius conductor bends located at places where the conductor is leaving the bulk of the coil and forms coil feeders. These feeder bends will be subject to strong electromagnetic forces and it is of essential importance that the integrity of the conductor in this area is not compromised and that the yield strength conforms to the requirement provided in Table 5-2.

To illustrate the situation, the smallest radius bend on PF1a coil conductor has inner radius 37.5 mm (2.5x conductor width). A simple geometrical calculation gives copper elongation 16.7% for bending around the centre of the conductor. This may be problematic due to the required material condition of the conductor (R290, min. YS 250 MPa, min. UTS 290 MPa, see Table 5-1), as elongation at break of such a hard copper tends to be low.

The Buyer acknowledges that there is not an established bending process to perform the small radius conductor bends and as such this activity carries a risk for the Seller. Therefore, the development of the bending process shall be as follows. The Seller shall try to qualify the technological process of small radius conductor bends by testing the three following bending processes:

- Bending of conductor at room temperature as is
- Bending of conductor sub-cooled to LN2 temperature (77 K) (see justification of such approach in Figure 6-1)
- Bending of locally annealed conductor (however, the conductor needs to be sufficiently work hardened during the bending process to restore its yield strength lost by annealing)

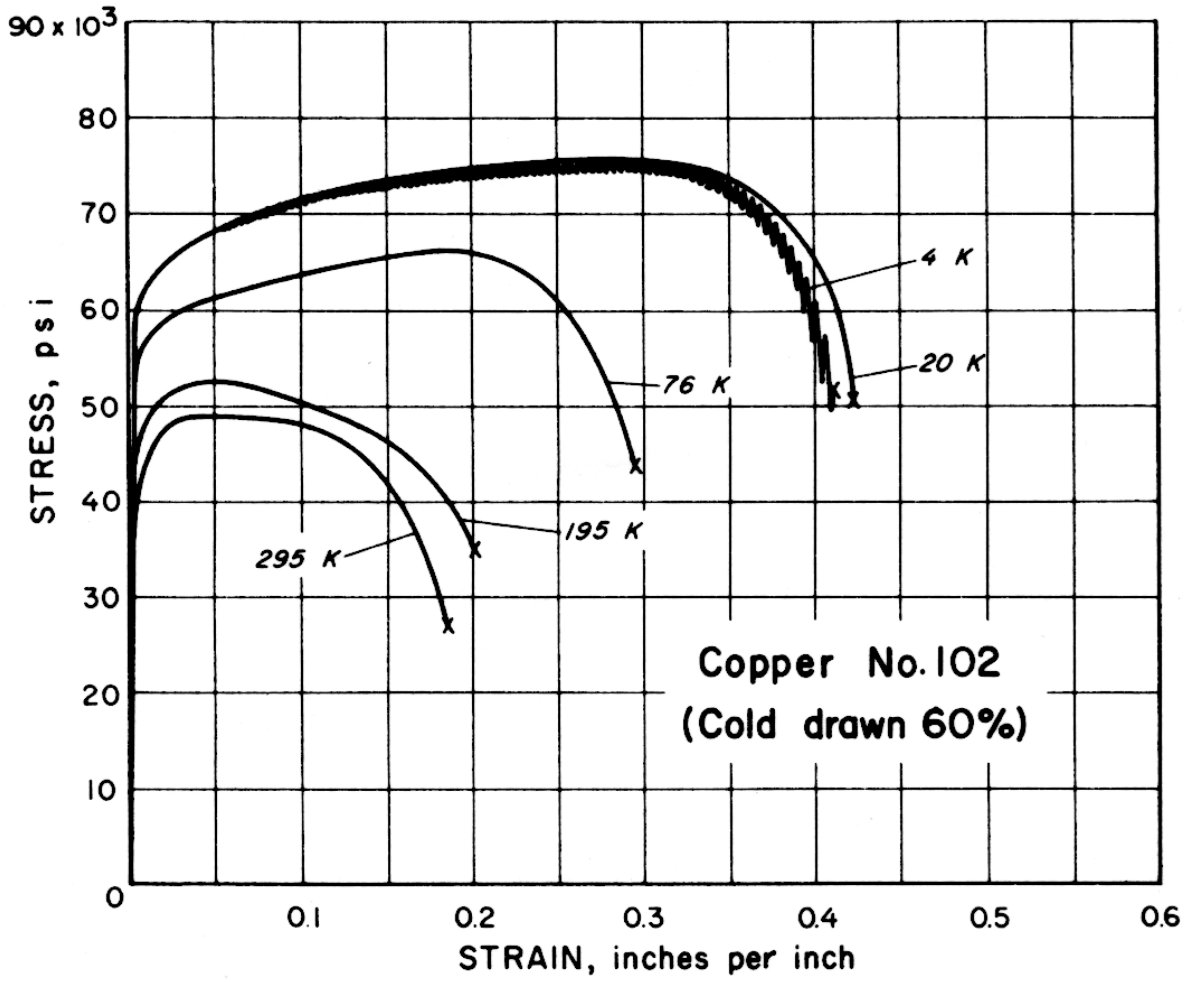


Figure 6-1 – Stress – strain curves of hard copper at room temperature and lower temperatures. Taken from https://www.copper.org/resources/properties/144_8/

The testing shall be done by bending hollow conductor samples and their subsequent inspection. The requirements on the samples and their tests are listed below:

- there shall be at least 3 samples per each bending process
- the samples shall be made of material conforming to the required conductor properties in Table 5-1 for PF1a coil conductor
- the sample conductor cross section shall be the same as PF1a coil conductor, including the inner cooling channel
- the performed small radius conductor bend of the samples shall be the same as PF1a coil conductor small radius bend (feeder 90° bend, according to the technical drawing, see also

Figure 6-5)

- bent conductor samples shall be inspected and tested: i/ metallographic cuts shall be done on all of the samples and inspected for potential micro-cracks or other defects ii/ tensile test at room temperature shall be done on all samples to prove YS and UTS was not compromised. Iii/ in case the inspection of metallographic cuts and the tensile tests did not reveal any defects, low cycle fatigue tensile tests at room temperature shall be done as follows:
    - the test samples shall be subjected to a tensile force with a sinusoidal waveform and a cycle asymmetry R = 0.1 (ratio of F_{min}/F_{max}). Maximum of the force loading shall correspond to tensile stress of 200 MPa. Number of cycles shall be 10 000, however, the test is considered successful if failure does not occur during the first 2000 cycles.
    - the low cycle fatigue tensile test may be done only for one selected bending process, which the Seller presumes to be the best candidate to be qualified, lowering the total number of low cycle fatigue tensile tests to 3 samples only
- after bending and inspection, the samples (metallographic cuts, tensile test residues) shall be provided to the Buyer
- additionally, 20 pieces of 50 cm long straight hollow conductor (with the same material properties and cross section dimensions as the above mentioned bending samples) shall be provided to the Buyer for their own bending tests.

Deadline to perform the required sample bending, tests and inspection, listed in bullets above, including Inspection and test reports, is 12 months (see also Table 3-4).

If no faults are detected for 3 consecutive bending samples of one or more bending processes, the yield strength of these samples is not compromised during the bending (i.e. it still conforms to the requirements in Table 5-2 as verified by the standard tensile tests) and the low cycle fatigue tensile tests of these samples are successful, this represents a qualified technological process. The Seller shall use the technological process to manufacture the coils (i.e., the prototype coil and other PF coils).

However, if, despite the Seller's best efforts, the process is not developed within the deadline, the Buyer shall assume responsibility for the development of a suitable technological process from that moment until the developed process is provided to the Seller and the Seller’s delivery periods are temporarily suspended (see Framework Purchase Agreement, article 6.21).

6.2.2 Sectioning

The prototype coil shall be cut into sections for further inspection. The cuts are depicted on Figure 6-2. Multiple smaller sections may be subsequently extracted from the halves for detailed inspection. Special care shall be taken not to damage the surfaces during the process, and a skimming cut (small depth, slow tool feed) shall be taken to fully polish the surface.

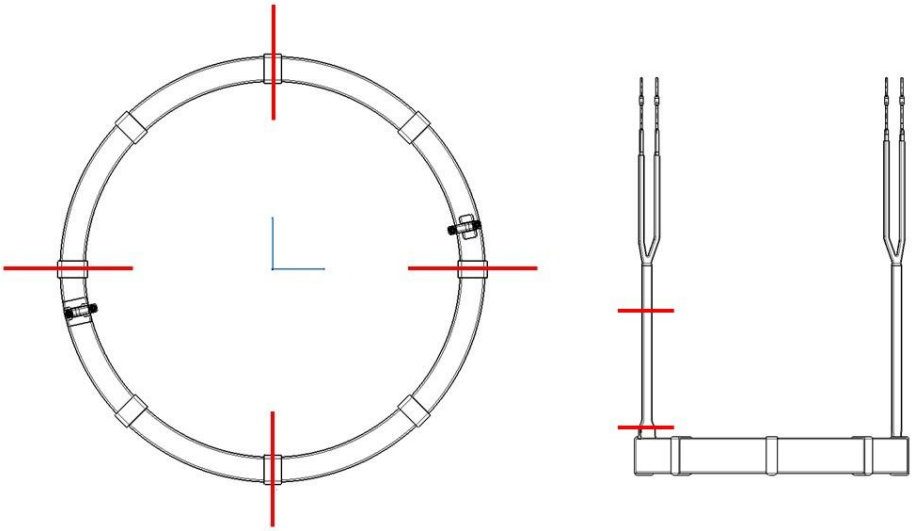


Figure 6-2 - Cuts of prototype coil

After sectioning, coil section ends shall be visually examined under magnification.

Any voids visible in the turn-to-turn or ground insulation shall be noted including void sizes and locations. In particular, the sectioned coil shall be examined for voids, cracks, crazing such as surface cracks, de-laminations and dry spots within the insulation. Special attention shall be paid to potential resin-rich areas during the examination. Surface examination shall be undertaken using at least 20x magnification with photographs taken to aid further analysis of any potential defects. Any identified dry spots, cracks, ruptures or de-bonding between conductor and insulation within the coil winding pack shall be recorded as well.

All sections shall be delivered to the Buyer after all required inspection steps unless mutually agreed otherwise.

6.2.3 Volumetric fiberglass ratio, resin rich area, void gap, void ratio

The Seller shall propose inspections and tests as a part of the MIT plan to check the conformance of insulation to the requirements on volumetric fiberglass ratio, resin rich areas, void gaps and void ratio (see Table 5-4). The proposal is a subject to the Buyer's approval. The inspections/tests shall be done for the 3x3 mock-up and for the prototype coil after sectioning. It is part of FAT of both these items (see Table 6-1, Table 6-2).

6.2.4 Tensile tests proposed by the Seller

If the Seller chooses to receive coil conductor in a different condition than defined in Table 5-1, it is their responsibility to propose specific tests to prove the feasibility of the conductor hardening process (chapter 5.1.1).

6.2.5 Tensile tests of the prototype coil conductor

The yield strength of the manufactured prototype coil conductor shall be tested. After sectioning of the prototype coil, samples shall be cut out and a standard tensile test shall be performed. The location of the samples is indicated in Figure 6-3. In addition to the locations marked in the figure, the tensile

tests shall be done also in the location of the small radius conductor bend, if bending of the coil conductor during winding involves a process which can compromise the yield strength of the conductor (i.e. local annealing).

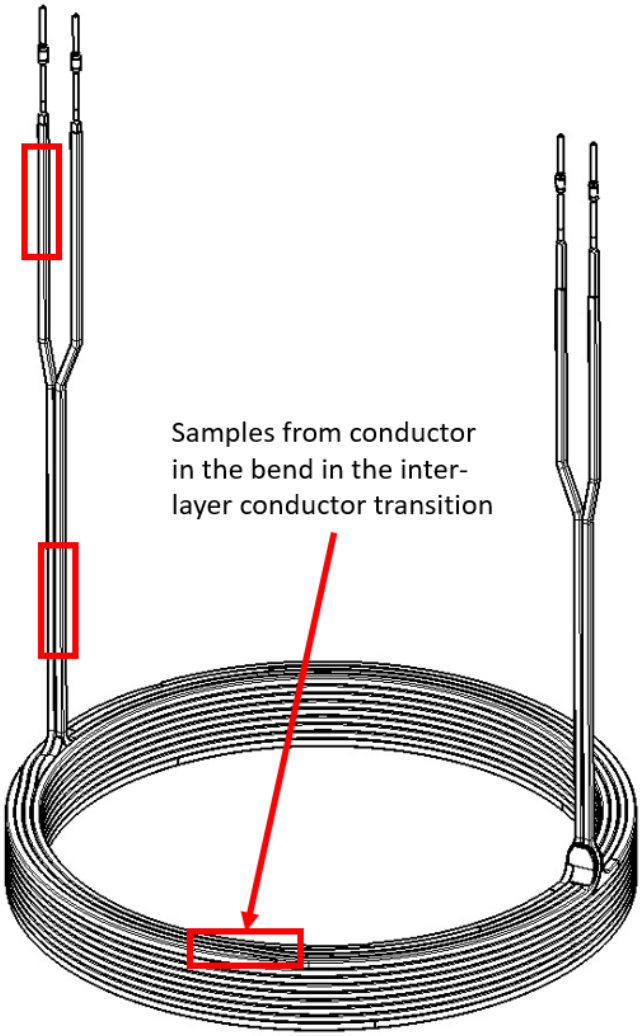


Figure 6-3 - Location of conductor for tensile tests

For each location, at least three tensile tests at room temperature shall be made. The required values are in the Table 5-1 – Required conductor physical properties at 20 °C.

6.2.6 Metal connection tests performed on the samples and on the prototype coil

Metal connection tests shall be performed on the samples manufactured according to the requirements in the chapter “5.8.9 - Metal connection and its qualification program” and on the soldered joint of the prototype coil.

At least three samples for individual tests are required to reach the minimum statistical relevance for the samples manufactured according the requirements in the chapter “5.8.9 - Metal connection and its qualification program”. Samples shall be manufactured in a way that the mechanical and thermal influence is minimized.

6.2.6.1 *Visual inspection*

The visual inspection is required to check any imperfections, surface properties, unwanted deformations or scratches, pollution and cleanliness. The industry standard EN 13018 shall be followed.

The visual inspection shall be performed on the samples manufactured according to the requirements in the chapter 5.8.9 and on the prototype coil joint.

6.2.6.2 *Capillary inspection*

For capillary inspection of joints, the industry standard EN ISO 3452 Part 1 to 6 (Non-destructive testing – Penetrant testing) shall be followed. Results shall be evaluated according to EN ISO 23277 – allowed grade no. 1.

The capillary inspection shall be performed **only on the samples** manufactured according to the requirements in the chapter 5.8.9. It shall not be performed on the prototype coil joint, in order to avoid possible interaction between the chemicals used for the capillary inspection and resin of the insulation.

6.2.6.3 *Radiographic testing*

For radiographic testing of joints, the industry standard EN ISO 17636 Part 1 and 2 shall be followed – required technique class B.

The testing records, including images, shall be provided to the Buyer.

The radiographic testing shall be performed on the samples manufactured according to the requirements in the chapter 5.8.9 and on the prototype coil joint.

6.2.6.4 *Standard static transverse tensile test of the whole joint*

Standard static transverse tensile test of metal connection samples (excluding orbital welding) shall be performed according to the industry standard EN ISO 4136. The test shall be performed at room temperature.

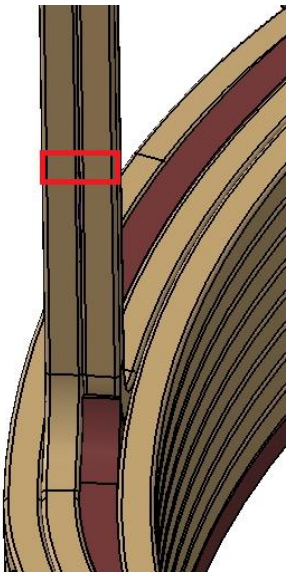


Figure 6-4 – Sample for static tensile test from prototype coil

Ultimate tensile strength of samples shall be Rm ≥ 25 MPa.

The standard static transverse tensile test shall be performed on the samples manufactured according to the requirements in the chapter 5.8.9 and on the prototype coil joint.

6.2.6.5 Standard static longitudinal (shear) tensile test of the whole joint

The standard static longitudinal (shear) tensile test shall be performed **only on the samples** manufactured according to the requirements in the chapter 5.8.9. It shall not be performed on the prototype coil joint. The test shall be performed at room temperature.

6.2.6.6 Macroscopic and microscopic examination

Macroscopic and microscopic examination of samples shall be performed according to the industry standard EN ISO 17639.

The macroscopic and microscopic examination shall be performed on the samples manufactured according to the requirements in the chapter 5.8.9 and on the prototype coil joint.

6.2.6.7 Charpy pendulum impact test

Charpy pendulum impact test shall be performed according to the industry standard ENISO 148-1, EN ISO 14556 and EN ISO 9016. The test shall be performed at 80 K for three samples.

The Charpy pendulum impact tests shall be performed **only on the samples** manufactured according to the requirements in the chapter 5.8.9. It shall not be performed on the prototype coil joint.

6.2.7 Metal connection tests performed on the coils

6.2.7.1 Visual inspection

Each joint has to be check for any imperfections, surface properties, unwanted deformations or scratches, pollution and cleanliness. The visual inspection is required for checking all joints of the PF coil and shall be unequivocally documented. The industry standard EN 13018 shall be followed.

6.2.7.2 Radiographic testing

For radiographic testing of joints, the industry standard EN ISO 17636 Part 1 and 2 shall be followed – required technique class B.

The testing records, including images, shall be provided to the Buyer.

6.3 Electrical tests

If not defined specifically in description of the tests listed below, the value of **AC voltage is nominally RMS.**

A test report of these tests must include a record of the ambient temperature and humidity and of the measured electrical quantities, such as currents, applied voltages, resistivity etc. In case of DC electrical tests, the report shall include information about the polarity of connection. Additionally, the **time traces of recorded parameters** shall be provided to the Buyer. A list of the recorded parameters for each test will be specified in the MIT plan as a part of the test plan.

This chapter contains general description of electrical tests, some of which are required during the manufacture (pre-VPI) and some for FAT and SAT, as is summarized in Table 6-1, Table 6-2 and Table

6-3. Test results shall be reviewed and approved by the Buyer. Electrical tests shall prove that the insulation is performing well also after thermal cycling, hence thermal cycling (described in Table 6-6) is integrated in the testing sequence.

Table 6-6 - Coils thermal cycling setup for the purpose of electrical FAT.

Number of thermal cycles	3x
Temperature range	From Room temperature down to 85 K
Temperature gradient (for cool down and warm up)	0.5 – 5 K/min
Max. temperature gradient between the hottest and the coldest spots of the coil	40 K
Environment	Atmospheric pressure air

6.3.1 Coil DC resistance

DC resistance of the coils shall be measured and corrected for temperature as follows:

$$R_{20} = \frac{254.5 \times R_C}{234.5 + T_C}$$

where R_C = measured coil resistance, T_C = coil temperature at the time of measurement (°C).

The measured coil DC resistances shall fulfil the requirement on maximal allowed resistance specified for each coil in Table 6-7. Table 6-7 also provides nominal coil conductor resistance values based on the average of the conductor min/max cross-sectional areas (as calculated from the allowable tolerances on the conductor), nominal length of the conductor and minimal conductor material conductivity (as defined by norm EN 13600). Adjustment of the coil resistance requirement to correct for the as-built length of the wound coil is permissible.

Coil DC resistance measurements are prescribed by Table 6-2 and Table 6-3 at several points of coils' manufacture process (pre-VPI, after VPI, after thermal cycling …). In addition to fulfilling the maximal resistance requirement, **these measurements must be within 1% of the first measured value (pre-VPI)**.

During thermal cycling of manufactured PF coils specified in Table 6-6, the Seller shall **at least once measure the DC resistance of the coils at the cooled state** and mark down the temperature at the time of measurement.

Table 6-7 - Coil resistances and impedances at 20 °C.

Coil	nominal DC resistance [mΩ]	maximal DC resistance [mΩ]	nominal DC inductance [mH]

	(for reference only)	(requirement)	(for reference only)
PF1aU, PF1aL	12.3	12.6	2055
PF1bU, PF1bL	14.1	14.5	2510
PF2U, PF2L	16.0	16.5	2980
PF3U, PF3L	24.8	25.5	5783
PF4U, PF4L	22.0	22.8	8498

6.3.2 Impedance and phase angle measurement (Coil impedance test)

AC impedance and phase angle shall be measured over the range 20 Hz to 500 kHz (or higher, if the resonant frequency is higher), minimal number of measured values is 30. The expected corresponding inductance values are in Table 6-7 for reference. The measured data of impedance vs. frequency shall be provided to the Buyer. Impedance test device and test procedure shall be proposed by the Seller and approved by the Buyer, an example of suitable measurement device is BK Precision 894.

6.3.3 Insulation resistance test (IR)

Test has to be done according to **IEEE Std. 43-2000** together with polarization index (PI).

The measured IR shall be > 500 MΩ. Polarization index value will be measured for reference.

IR test shall be carried out before any other HV tests (test voltage > 1 kV). Fulfilling the acceptance criteria for IR test indicates good condition of insulation and correct setup.

The recommended voltage ramp is 1 kV/s because of the significant capacity of coils and feeders. Test starts at the moment when the applied voltage is equal to test voltage and the test time shall be 1 minute and 10 minutes. Applied voltage, measured current and measured insulation resistance shall be recorded at minimum every minute and plotted in a current vs. time plot. The table of recorded values and the plot shall be part of the test records. Polarity of measurement shall be recorded as well.

Testing voltage: 1 kV

The ground shall be defined for the ground insulation testing, for example a conducting layer wrapped around the tested item.

Additional tests for insulation mock-up:

- **turn to turn testing T-T**

Two mock-up turns neighbouring each other shall be chosen for testing of insulation resistance. Three such turn pairs will be proposed for testing by the Seller and approved by the Buyer.

- **turn to ground testing T-G**

Insulation resistance of the mock-up turns shall be tested against ground insulation. Three such turns will be proposed for testing by the Seller and approved by the Buyer.

6.3.4 Dissipation factor (Tan delta test)

Test has to be done according to **IEEE Std. 286-2000**.

Dissipation factor is equal to the tangent of dielectric loss angle. Tan delta test is complementary to Partial discharge test. Increase of dissipation factor is caused by the energy dissipated by the discharge in voids and cracks in the insulation. The test also detects delamination of the insulation.

Test measures the relative active and reactive components of current through the insulation under AC conditions, with the former due to the effective resistance of the insulation and the latter due to the effective capacitance.

Tan delta shall be measured at least for three (5) voltage steps: 0.2 U_0; 0.4 U_0; 0.6 U_0; 0.8 U_0 and U_0 (where U_0 is 2.9 kV). The tan delta difference between each step shall be recorded.

The applied frequency of the AC voltage waveform shall be 0.1 Hz (Very Low Frequency Test) to facilitate the field testing. The frequency shall be clearly specified in the procedures and records. To avoid conditioning of the component, tan delta shall be measured again at 0.6 U_0 after the highest voltage measurement.

6.3.5 Partial discharge test

Test has to be done according to **IEC 60270**.

Signal from the partial discharge test cannot be used directly. All measurements of the partial discharge in time shall be accumulated and synchronised with respect to the tested voltage. This partial discharge “fingerprint” plot can be used also for a long-term monitoring of insulation health.

Peak testing AC voltage = **2.9 kV**, Duration = **60 seconds**, record leakage current.

Acceptance criterion is defined as **absolute partial discharge level q < 10 pC.** No partial discharge shall be present during the test. If a partial discharge occurs, then the following additional test on prototype coil shall be done: the Seller shall identify the inception voltage and they shall load the coil with the inception voltage for 30 minutes to prove that insulation survives without degradation. Insulation resistance test (chapter 6.3.3) shall be repeated.

6.3.6 DC Hipot test

Test has to be done according to **IEEE Std. 95**.

The aim of the test is to prove that the insulation system is resistant to realistic overvoltage scenarios.

The application of a ramped voltage, instead of discrete voltage steps, linearize the absorption current component so that deviations in the leakage current are easily detected and allow the test operator to anticipate the end of the test in case of anomalies. The duration of the test is 10 s from reaching a requested testing voltage and recommended voltage ramp is 1 kV/s.

Testing voltage for coils is 7 kV.

Insulation resistance (IR) test shall be carried before each DC Hipot test to check that the component is in good condition.

The acceptance criterion is no evidence of distress and/or insulation failure observed by the end of the total time of voltage application.

The applied voltage and the measured current shall be recorded in time and plotted in a current vs. time plot. The table of recorded values and the plot shall be part of the test records; the measured data shall be provided in a digital form to the Buyer as well. Polarity of measurement shall be recorded as well.

Special additional tests for mock-up:

For mock-up there will be an exception. A standard test with 7 kV voltage shall be done and then an additional test with higher voltage shall be done to check if the insulation system still has a reserve. The second testing voltage for the mock-up shall be 10 kV. If any break occurs on the elevated voltage level, it will not be considered as a non-conformance.

- **turn to turn testing T-T**

Two mock-up turns neighbouring each other shall be chosen for DC hipot test. Three such turn pairs will be proposed for testing by the Seller and approved by the Buyer.

- **turn to ground testing T-G**

DC hipot test of the mock-up turns shall be performed against ground insulation. Three such turns will be proposed for testing by the Seller and approved by the Buyer.

6.3.7 Paschen test

Paschen tests are one of the Critical activities, which are summarized in chapter 9.9. This chapter describes the consequences for failing the repeated Paschen test (i.e. second Paschen test performed after the repair of the coil) on one of the coils PF1, PF2, PF3 and PF4. The information about the consequences is repeated in the chapter 9.9 - Critical activities.

There are two types of Paschen tests in the FAT:

- **Local Paschen** – tests of the individual coolant and current feeders (the locations are indicated in “technical drawings – Locations of local Paschen tests”) – mandatory on all coils. The Seller can opt to perform Paschen test of the entire coil instead of a local Paschen test.

  Local Paschen tests are aimed at testing particularly vulnerable parts of the coil insulation (i.e. electric feeders and cooling channel exits) while avoiding the need of a large vacuum vessel to accommodate the whole coil. However, it requires the Seller to prepare an ad-hoc vacuum enclosure (vacuum vessel or plastic bag or other means) to provide vacuum around the tested area.

- **Full surface coverage Paschen** – test of the whole coil. Mandatory for the prototype coil, subject of additional order by the Buyer for the other coils (items No. 2 and 3 in “Annex No. 3 - Price Schedule and Deliverables”, coils are divided into groups A and B, as specified in chapter 3).

  Full surface coverage Paschen test is designed to check the integrity of the whole coil’s insulation. There are 2 options for the Buyer (the selection is explicitly the Seller’s decision – the Buyer – Institute of Plasma Physics – is obliged to accept this selection):

    - Place the whole coil with coolant and current feeders inside a large enough

vacuum chamber and test the entire surface at once,

- or perform a series of local Paschen tests covering the entire surface of the tested coil with sufficient surface overlap between the individual local Paschen tests. This method does not require access to a large vacuum vessel, however, it brings additional laboriousness and complexity.

It is recommended, but not required, that the vacuum chamber used in the test allows monitoring of the flashes by a camera. The test record shall include voltage-leakage current measurement and pressure measurement. The graph in the test protocol shall show the applied voltage and the measured leakage current versus time. In case of a discharge, the location must be also determined and documented on a photo (either in situ during the Paschen test or post mortem). The detailed procedure (for Local and/or Full surface coverage Paschen tests) shall be proposed by the Seller and shall be described in the MIT plan initial version, but the test parameters specified below have to be fulfilled unless it is agreed with the Buyer otherwise. The procedure has to be approved by the Buyer. We recommend the Seller to follow the good standards for performing Paschen tests of coils, which can be found in article by J. Knaster et al.: Paschen Tests in Superconducting Coils: Why and How, doi: 10.1109/TASC.2011.2175475

The deadline for ordering the Full surface coverage Paschen test by the Buyer is specified in Annex No. 3 of the Tender Documentation – Price Schedule and Deliverables. The Buyer can choose to test any of the PF coils. After delivery of either Full surface coverage or Local Paschen test protocol, the Buyer has 2 weeks for evaluation (grades A, B and C defined below).

Test parameters:

- Applicable standard: IEEE Std. 95
- Testing voltage: **3 kV DC**
- The ramp-up and ramp-down of voltage to the nominal testing value shall be ≤ 1 kV/s.
- The polarity shall be such as to have the anode (positive pole) on the ground plane since the glow will appear in the anode environment.
- The final ground plane shall be placed after the Paschen tests (see chapter **5.1.6.4**). The temporary ground plane during the tests could be a metallic mesh placed around the coil that would allow the visualization of flashovers. Alternatively, grounded vacuum chamber could be used with adequate precautions.
- Pressure shall be swept from vacuum values (10^{-2} Pa) to atmospheric ones (10^{5} Pa). The testing voltage shall be maintained at each pressure decade for at least 1 minute.
- Venting gas of the vacuum enclosure: Air
- The leakage current shall be continuously monitored and shall not exceed 20 μA during the steady state voltage period.
- Test shall be stopped immediately in case any of the passing conditions is broken.

Passing conditions: The leakage current value must not exceed the specified limit. No evidence of distress and/or insulation failure shall be observed during the test, in particular:

- Gradual decrease of the insulation resistance.
- Sudden increase of the leakage current, which afterwards falls down again or remains elevated.
- Visible flash accompanied by highly uneven current on the source.

Test evaluation:

Local Paschen tests are part of FAT of the PF1-4 coils. Full surface coverage Paschen test is part of the FAT of the prototype coil PF1aU and in case of order, it becomes part of the FAT of the chosen PF1-4 coil (see Table 6-3). Acceptance requirement is grade A. Paschen test evaluation shall follow the rules in chapter 6.5.6:

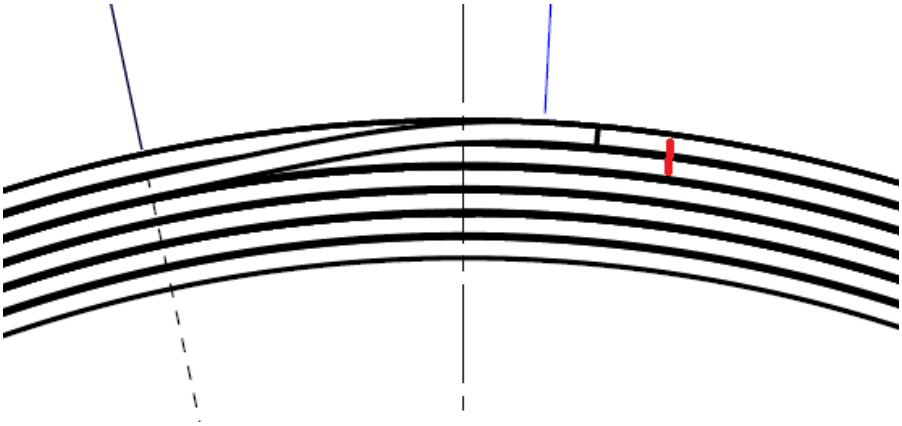
- grade A – The coil passed the test – passing conditions were achieved and no faults were detected.
- grade B – In case passing conditions were not achieved. Faults have to be documented and repair procedure shall be proposed by the Seller and agreed by the Buyer. Thermal cycling of the coil and FAT sequence after thermal cycling (see Table 6-3), including the Paschen test, shall be repeated after the repair.
- grade C – Passing conditions were not achieved in the repeated Paschen test of the coil or there was a failed test in the FAT sequence prior to the Paschen test. Faults have to be documented and repair procedure shall be proposed by the Seller and agreed by the Buyer. Moreover, the Buyer can request (and the Seller has to comply with the request) to discard the coil and re-start the manufacturing procedure of the coil according to Framework Purchase Agreement, Article 4.21 (see chapter 9.9 - Critical activities for details, namely the fact that the grade C is considered as a Critical Activities Incident – level 3, with the only consequence that the Buyer may require the Seller to manufacture a new coil).

6.3.8 Controlled short circuit between turns

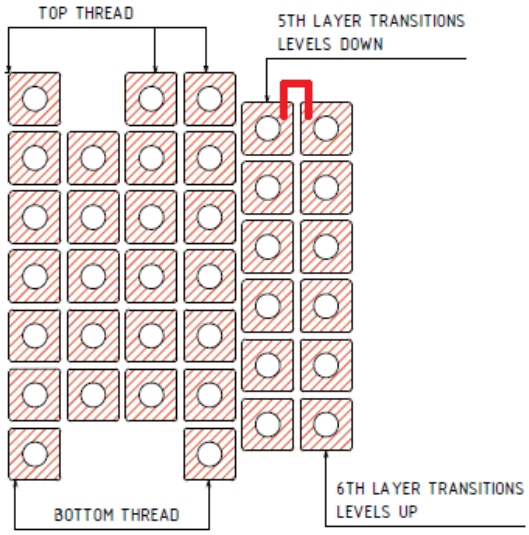
The last electrical test of the prototype coil before cutting it into sections shall simulate partial short circuit between the coil turns. Two adjacent turns will be drilled and connected to bypass the turn (or layer, see below) through a resistor. The coil impedance shall then be measured as described in chapter 6.3.2. The test shall be done for at least four (4) resistor values (1000 Ω, 100 Ω, 10 Ω and 1 Ω).

The short circuit shall be simulated for both

a) **inter-turn** – between two adjacent turns, only one turn is bypassed



b) **inter-layer** – between two adjacent layers of winding, i.e. several turns are bypassed



The measured values shall be provided to the Buyer and serve as a reference.

6.3.9 Ground plane resistance

The value of the resistance shall be 500 Ω/square ± 5% for all coils. There shall be at least 4 measurements from different areas of the coil. The Seller shall propose the measuring points which will be subject to approval by the Buyer.

6.4 Pre-VPI tests

Before completing of the mould (refer to chapter 5.1.15) the dry coil shall be tested as indicated in the following chapters. Ambient temperature and humidity shall be recorded. Test results shall be reviewed and approved by the Buyer before proceeding with VPI.

6.4.1 DC resistance and AC impedance

The DC resistance and AC impedance of the coil shall be measured. The resistance shall agree to the values specified in chapter 6.3.1 and 6.3.2. The impedance value will be measured for reference.

6.4.2 Insulation resistance test

The procedure is the same as the one described in chapter 6.3.3.

6.4.3 Mould leak test

Prior to VPI, the Seller shall demonstrate that the VPI mould is capable of achieving the base pressure, leak and out-gassing rates, as specified in the MIT (see chapter 5.8.8), from room temperature up to the planned out-gassing temperature.

6.5 Factory acceptance tests (FAT)

6.5.1 Electrical tests

The pre-VPI electrical tests described in chapter 6.4 shall be repeated after VPI. Measured DC resistance values shall match the pre-VPI values. Measured AC impedance and insulation resistance values shall be consistent with the pre-VPI values, taking into consideration the differences arising

from the presence of resin in the insulation. No electrical breakdown shall be observed. Ambient temperature and humidity shall be recorded. Test results shall be reviewed and approved by the Buyer as a prerequisite for shipment. Test procedures developed for chapter 6.3 shall address both the pre-VPI and final coil configurations, accounting for the differences in test methods that may be required. Note that some of the FATs are done after thermal cycling of the coil and some of the electrical tests shall be done also before the thermal cycling – refer to Table 6-2 and Table 6-3.

6.5.2 Dimensional Inspection

Dimensional inspection of the completed coil shall be performed. An inspection report indicating all measured dimensions relative to their nominal values defined by the drawings shall be elaborated. Deviations beyond the allowed tolerance render the coil unacceptable for the FAT.

The MIT plan shall delineate details of the inspection plan, including where and which instruments will be used.

For the measurement of the Inner Diameter and the Outer diameter, as a minimum, the coil shall be measured at 8 locations evenly spaced around the circumference of the coil and at 5 locations vertically along the inner and outer bore (80 total points).

The Buyer has the right to measure coils during the manufacture with his own measuring equipment.

6.5.3 Integrity check

The integrity of the conductor at the places with small radius bends (indicated in technical drawings by “Check for microcracks”) shall be checked for all coils – no micro-cracks shall be present. The method of the integrity check shall be proposed by the Seller in the MIT plan.

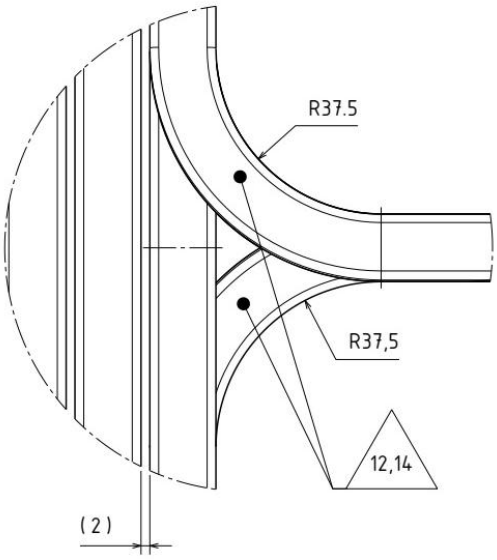


Figure 6-5 – Detail of Inspection areas in technical drawings of PF1aL

6.5.4 Cooling channel pressure testing

Pressure test shall be performed on all finished coils. Its objective is to check that

- coils can safely work on required pressure level and

- no leak from cooling channel is present.

Test must be done on 1.5x of nominal working pressure, as specified in Table 6-8. Test length (time with pipe pressurized) must be minimally 15 minutes. No leak or rupture shall be present after the time has passed.

Pressure test must be done either using

- inert dry gas (nitrogen, CO2, helium) or
- inert liquid without presence of dissolved solids (demineralized/distilled water, isopropyl alcohol).

If liquid is used for the test, it shall be flushed out of the coil channel directly after the test using dry gas. No liquid shall remain in the coil channel.

No gas/liquid used for flushing/cleaning of the coil coolant channel shall contain any contaminants (oil, dust, moisture, dirt, …).

6.5.5 Leak testing

Leak testing shall be performed on the finished coils (all coils in the "Basic configuration") on high vacuum level according to Annex of technical specification No. 1 – Vacuum compatibility.

Test shall be done on coil outlets (including ceramic insulation breaks), orbital welds and other connections. Testing main coil body is not necessary.

The requirements for coils in the terms of leak rates are indicated in Table 6-8, suitable test method shall be selected. It is suggested to use technique B.2 according to EN ISO 20485:2018. Technique B.4 (according to EN ISO 20485) shall be used only if all other techniques are not performable.

Before leak test, coil channel shell be verified to be non-obstructed either by means of ball-test or by blowing with dry gas.

During leak test, no humidity or liquid shall be present in the channel or in its surroundings. This means that if cooling channel pressure test is done with liquid (see chapter 6.5.4), it shall be done after leak test.

Coil outlets (pipes coming from ceramic breaks) shall not be anyhow damaged/altered while performing leak test. Use of metal compression fittings (Swagelok or similar) is not allowed!

Table 6-8 - Coils pressure and leak test parameters

circuit	gas	nominal working pressure [Bar]	testing pressure [Bar]	max. leak rate [Pa.m^3/s]
PF	helium	20	30	$<10^{-10}$

6.5.6 Evaluation of FAT

There are several items which have to successfully pass FAT – Insulation samples (see chapter 5.2.1, Table 6-1), 3x3 mock-up (see chapter 5.2.2, Table 6-1), prototype coil (see Table 6-2) and 10 PF coils: PF1aU, PF1aL, PF1bU, PF1bL, PF2U, PF2L, PF3U, PF3L, PF4U, PF4L (see Table 6-3). The general

evaluation of FAT is as follows:

- grade A – The respective item passed all of the required tests. All requirements and passing conditions/acceptance criterions of the tests were achieved and no faults were detected. All respective inspection and test reports were delivered to the Buyer in appropriate form (see chapter 7.4.4 and specifics for each test/inspection in chapter 6). This is considered as a successful completion of FAT of the respective item. Exceptions/specific rules for the items:
    - Prototype coil: The prototype coil may be awarded grade A even in the case that not all requirements and/or passing conditions of the tests were achieved. The faults must be documented with non-conformance report and MIT plan shall be updated describing solutions to avoid the failure on the PF coils. If the Buyer believes that the proposed solutions are clear to provide a flawless coil, they may elect to award grade A, otherwise grade B or grade C will be awarded (see below).
- grade B – Awarded if one or more tests did not meet all of the requirements and passing conditions/acceptance criterions OR if inspection and test reports were not delivered to the Buyer in appropriate form. All test failures have to be documented and repair procedure shall be proposed by the Seller and agreed by the Buyer. All inadequate inspection and test reports have to be corrected and sent to the Buyer for re-evaluation. Exceptions/specific rules for the items:
    - Insulation samples: In case grade B was awarded due to a failed test (not report), new samples shall be manufactured and tested. The Buyer has the right to request that the Seller uses recommended insulation materials to produce the new insulation samples (and all of the following items – mock-up, prototype coil and PF coils).
    - Mock-up, prototype coil and PF coils: In case grade B was awarded due to a failed test (not report), then after the repair of the item, the FAT sequence (Table 6-2, Table 6-3) shall be repeated from the beginning of the respective group of tests in which the failed tests occurred (i.e. tests during coil winding, after coil winding, after VPI and after thermal cycling). If the failed tests occurred after thermal cycling, the thermal cycling shall be also repeated. This rule also applies in case of failed Paschen tests.
- grade C – Awarded if one or more tests did not **repeatedly** meet all of the requirements and passing conditions/acceptance criterions. It can also be awarded after the first failure in a test if the non-conformance of the item **is obviously irreparable** without a high risk of compromising of the item long-term performance. Faults have to be documented and if applicable, repair procedure shall be proposed by the Seller and agreed by the Buyer. Exceptions/specific rules for the items:
    - Insulation samples: the same rules apply as in the case of grade B
    - Mock-up, prototype coil and PF coils: the same rules apply as in the case of grade B. Moreover, the Buyer can request (and the Seller has to comply with the request) to discard the item and re-start the manufacturing procedure of the item according to Framework Purchase Agreement, Article 4.21 (see chapter 9.9 - Critical activities for details, namely the fact that the grade C is considered as a Critical Activities Incident – level 3, with the only consequence that the Buyer may require the Seller to manufacture a new coil).

6.6 Site acceptance tests (SAT)

The full list of **SAT performed by the Seller** after delivery of the item to the Buyer is in Table 6-3. Successful SAT are a necessary condition for acceptance of the item by the Buyer. Here are some notes to the SAT tests:

- **Dimensional check** – coil dimensions shall be checked again and compared to the values from FAT.
- **Visual damage check** – no damage on the coils shall be discovered.
- **Insulation DC resistance** – same limit value as in chapter 6.3.3 applies
- **Leak inspection** – same limit value as in chapter 6.5.5 applies

During these tests, it shall be allowed to do the same tests by Buyer with Buyer's own instrumentation.

7 Documentation

The documentation of the whole "Poloidal Field Coils for COMPASS Upgrade tokamak" Contract can be divided into three groups:

- **documentation provided by the Buyer** – all inputs from the Buyer, e.g. drawings, Technical specification, ...
- **MIT plan** – inputs from the Seller – e.g. description of the manufacturing processes, manufacturing drawings, QA plan, ...
- **travellers** – output documents from the Seller, related to the individual ordered items – e.g. test reports, material conformance certificates, ...

7.1 Approval of the documents and changes of the Buyer Approved Documents

Approval of the documents by the Buyer must be in writing, either as a signed protocol or by an e-mail (see contact information in the Framework Purchase Agreement, chapter 12).

Revisions or changes by the Seller to the documents, that were previously approved by the Buyer, shall be reviewed and approved by the Buyer again prior to use (see chapter 7.3.3).

7.2 Buyer's Drawings

Coil design drawings provided by the Buyer will be provided in Annex of technical specification No. 3 – Technical drawings. All dimensions refer to room temperature (RT, 20° C) conditions. Dimensional characteristics including tolerances and insulation builds are given in the drawings and in chapter 5.10 - Dimensions and tolerances). For the HPL fillers (coil fillers, void fillers), some geometries are only defined in the model using STP files, see Annex of technical specification No. 3 – Technical drawings.

7.3 MIT plan

The Seller shall submit a Manufacturing, Inspection and Test (MIT) plan for the Buyer approval prior to the start of manufacture. Manufacture shall not start without an approved MIT plan, or its update, where applicable (e.g. after qualification samples evaluation, prototype coil tests, ...). The **deadline for submission, evaluation and acceptance of the "MIT plan initial version"** (forming basis of Milestone M1) **is specified in Annex No.3 of the Tender Documentation – Price Schedule and Deliverables**.

The MIT plan initial version must delineate the sequence of all processes and operations affecting quality, including in-process and final acceptance inspections and tests. The plan shall identify parts; show their integrated flow into end items; identify critical manufacturing operations; and show inspections and the characteristics/dimensions to be inspected. The manufacturing drawings shall be submitted as a part of the MIT plan initial version. The MIT plan may include flow chart(s), Process Sheets, Shop Travellers, and inspection sheets, etc. Equipment to be used for all fabrication processes, inspections and tests shall be specified. Bill of Materials and Quality Assurance are part of the MIT plan initial version (see chapters 7.3.4 and 7.3.5). The MIT plan initial version will be updated during the manufacturing process of the PF coils (e.g. depending on the results of manufacturing of the prototype coil, before the FAT start, etc.; see 7.3.2 - MIT plan life cycle).

7.3.1 MIT plan evaluation and acceptance

The Buyer will evaluate the delivered MIT plan with following grading:

Grade A: The MIT plan is complete and fulfils all requirements of the Technical Specification.

Accepted without objections.

Grade B: Minor flaws found in the delivered MIT plan, corrections and/or clarifications required. The Seller is obliged to remedy the objections and re-submit the MIT plan for new evaluation. The re-submitted MIT plan is evaluated again in the same manner.

Grade C: Major flaws found, the MIT plan needs a significant revision or amendment. The Seller is obliged to remedy the objections and re-submit the MIT plan for new evaluation. The re-submitted MIT plan is evaluated again in the same manner.

The Buyer shall evaluate the MIT plan initial version in 2 weeks from submission. This applies also to the re-submitted MIT plan initial version, if it was rated B or C before, and subsequent partial updates of the MIT plan.

Please note, that the Framework Purchase Agreement provides rules for advance payments tied to the approval of the MIT plan initial version (Article 5.5), acceptance and payment of the MIT plan initial version (Article 5.6.1) and penalties for the delay in delivery (Articles 10.2.1 and 10.3). The rules for serious delay or two times repeated grade "C" evaluation of the MIT plan initial version are in Articles 11.2.11 and 11.3.1.

7.3.2 MIT plan life cycle

The MIT plan is expected to evolve during the Contract duration:

- **A brief general overall description** provided as a part of the Seller's Bid (see item 1 in chapter 4.1) is a predecessor of the MIT plan. A related document required in the Bid is "**Time Schedule**" (described in chapter 4.2 of "CU_CUPG-03_PTD_Tender Documentation_Poloidal Field Coils" document). Both of these documents contain information which must be respected by further iterations of the MIT plan.
- **MIT plan initial version – delivered as Milestone M1** shall contain the information required in chapter 7.3 and it shall be detailed to the point to allow start of the manufacture. All production methods shall be specified, manufacturing drawings shall be ready. If some manufacturing steps or details are not possible to be defined at this point, e.g. they depend on the qualification sample tests, it shall be clearly stated and reasoned.
- **Updates to the MIT plan** can occur during the manufacture. It is expected to be done after some key steps, e.g. 3x3 mock-up manufacture and FAT, prototype coil FATs, cases of non-conformance, etc. Any MIT plan update is a subject of the Buyer's approval. The approval process is described in chapter 7.3.3.

7.3.3 MIT plan updates approval process

Any change to the MIT plan shall be approved by the Buyer prior to the works affected by this update. The need for an update may be triggered by passing some qualification step or interim checks in the manufacture of the coils and test samples, or by a non-conformity occurrence (chapter 8.3). The Seller shall inform the Buyer forthwith about such need of corrective action in the MIT plan and shall prepare a document describing the updated procedure or detail of the design. The Buyer has 2 weeks from delivery of the update proposal to evaluate it, in a way similar to the scheme in chapter 7.3.1.

7.3.4 Bill of Materials

"Bill of Materials" (BOM) is a part of the MIT plan, but can be submitted for a separate acceptance. BOM shall list all the required materials and input parts, their description and amount. Accepted BOM forms a basis for evaluation of Milestone M2 and the subsequent advance payment (see Framework

Purchase Agreement, Article 5.5).

7.3.5 QA plan

The Seller shall submit Quality Assurance (QA) plan describing the specific quality assurance and quality control procedures and practices, including special process training and qualifications, which will be in force to meet the requirements of this specification. The QA plan and any of its revisions require review and approval by the Buyer prior to the start of design or manufacturing of the equipment under this specification. The QA plan is a part of the MIT plan and as its integral part, QA plan is a subject of acceptance within MIT plan acceptance procedure (milestone M1).

Detailed requirements on the QA plan are provided in chapter 9. Below are highlighted topics which shall be included in the QA plan submitted within the MIT plan:

- Responsibility of the management, responsible person for fulfilling the Contract
- Documents and records management
- Management of resources
- Processes of Contract realization
- Monitoring, control and measurements
- Non-conformance and corrective actions
- Work procedures and practices to ensure Photo and video documentation (see chapter 7.4.3)

7.3.6 Seller's Drawings

The Seller shall prepare manufacturing and tooling drawings as required to complete the fabrication. The manufacturing and tooling drawings shall be submitted to the Buyer for review and approval prior to use. The drawings form a part of the MIT plan, which is a subject of approval prior to key and relevant manufacturing steps.

7.4 Traveller

The Seller shall document the lifecycle of the manufacturing of the individual delivered item with a compilation of documents (preferred in digital form - pdf, Microsoft Word or Microsoft Excel format, drawings can be provided in CATIA or STP file format), detailing the objective evidence for the acceptability of the work performed. The set of these accompanying documents is denoted as "Traveller" and listed in Table 3-3. The complete Traveller for each delivered item shall be provided to the Buyer with the delivered item, while partial documents are required earlier, as denoted in Table 3-3.

7.4.1 Material Certification

The test reports showing relevant chemical, mechanical and electrical properties of materials used, where applicable, shall be submitted to the Buyer (see chapter 6.1). Besides the test reports, technical data sheets and certificates of conformity shall be provided for all materials used, including (but not limited to) the insulation resin, conductor, glass fibre tape, polyimide tape, solder and flux material, coil and void fillers. Documents and certificates have to be provided to the Buyer before use of the respective materials.

7.4.2 Fabrication Process Reports

Fabrication Process Reports shall include records of the important manufacturing steps. If applicable, the reports shall include (but not be limited to) the following information:

- Timeline
- Description of the fabrication process and/or link to the relevant part of MIT plan covering the fabrication process
- Waveforms of relevant parameters (e.g. temperature, pressure, el. current etc.)
- Parameters of tooling setup during the fabrication process which may affect parameters of the manufactured item (e.g. tape tension during coil winding etc.)
- Environment conditions (e.g. temperature, humidity etc.)
- Photo and/or video documentation
- Name and signature of responsible person and names of key operators and workers

At minimum, reports shall cover the following manufacturing steps: fabrication of insulation qualification samples; fabrication of 3x3 mock-up; thermal cycling of mock-up; fabrication of metal connection qualification samples; fabrication of bent conductor samples; conductor cleaning and priming (all coils including prototype); coil winding and application of insulation tape, coil and void fillers (all coils including prototype); coil VPI and curing (all coils including prototype), metal connection procedures (all coils including prototype), thermal cycling (all coils including prototype), application of ground plane (all coils including prototype), fabrication of additional wrap (all coils including prototype).

7.4.3 Photo and video documentation

All crucial manufacturing steps for the PF coils shall be recorded on video, with exception of the prototype coil. It is recommended to the Seller to follow the rules also for the prototype coil (in order to qualify the procedures without facing penalties). Photographic documentation of the manufactured items at important stages of manufacture shall be also included in the Fabrication process reports.

Note that the photo and video documentation as described in this chapter is one of the Critical activities, which are summarized in chapter 9.9. Chapter 9.9 includes definition of the “Critical activities incident” levels.

Note that the Framework Purchase Agreement, Article 6.7 provides a requirement to secure the written consent of all persons recorded.

Following rules shall be followed:

1. A live stream video shall be available to the Buyer during activities listed in Table 7-1. Table 7-1 also indicates the required number of cameras and frequency of time-lapse photos, which shall be stored and available as a documentation of the manufacturing process.
2. The Seller shall propose an updated table in the MIT plan within milestone M1, reflecting the actual manufacturing sequence, with quality of documentation equivalent to requirements set in the Table 7-1. The actual positions and views of the cameras shall be approved by the Buyer prior to commencement of each individual manufacturing activity.
3. The access to the live stream shall be secured by encryption and password, to allow the Buyer a real-time view while maintaining privacy of the Seller. The Buyer is allowed to create a redundant recording from the live stream independently on the Seller. The Buyer shall not provide access to the live stream to a third party and shall not distribute (publish) the video and photo documentation of the manufacturing process without explicit agreement of the Seller.
4. There shall be a monitor/display placed at the relevant working area, showing the live stream

of all relevant cameras. The display shall be visible to the operators carrying out the observed activity. The intended purpose of this rule is to provide feedback to the operators about live stream functionality.

5. The resolution of the saved time lapse and the live stream shall be at least 2 Mpx, the format of the photos shall be JPEG. An example of a suitable video camera is Uniview IPC675LFW-AX4DUPKC-VG. The cameras must be sufficiently focused on the recoded activity/item in order to resolve the level of detail needed for monitoring of the watched activity.

6. For each week, when the activities subjected to video surveillance are planned to be carried out, a document "**Video documentation plan**" shall be sent by the Seller to the Buyer at latest on Wednesday of the preceding week. This document shall contain list of the planned manufacturing activities (subjected to video surveillance), list of cameras for each of the activity and time schedule. If the schedule is not precisely known, a broader time frame can be set, but the stream and time-lapse shall be active through the whole time frame. "Video documentation plan" is not subject of Buyer's approval. If the "Video documentation plan" was not provided, the relevant operations shall not be carried out – otherwise it is considered a breach and is sanctioned according to the Framework Purchase Agreement "Critical activities incident - level 2". Note: Sanctions for the number of missing streams relevant to the activity (as described below) will be evaluated on top of this. If the "Video documentation plan" was not provided to the Buyer on time (up to Wednesday previous week), but still before the operation, the operation can be performed, but it raises "Critical activities incident – level 1".

7. The Buyer has a right to request extension of the video surveillance beyond the "Video documentation plan" outside the operational hours, e.g. one permanent overview camera per recently manufactured coil, running also over the weekends.

8. Each working day (on which activities subjected to the video surveillance are carried out) is supposed to be divided into "**half-shifts**" for the purpose of control of the video documentation. Such "half-shift" shall be less than 6 hours long, shall be defined by the Seller in the MIT plan within milestone M1, to be compatible with the Seller's organization of the work (example: from 7:00 to 12:00 and from 12:00 to 17:00). Any change of "half-shift" definition, even temporary change, shall be approved by the Buyer.

    a. Before the start of work activities on each "half-shift", the Seller shall check that the required time-lapse video and online access to the live stream are running and recording. This shall be recorded in a "**Video documentation log**" – indicating clearly "half-shift", exact time of the check, check and tick all the relevant cameras and shall be signed by the responsible person.

    b. The "Video documentation log" shall be compatible with the "Video documentation plan".

    c. The "half-shifts" form a basis for sanctioning of the video documentation system outages: "Critical activities incident – levels":

        i. A missing stream and/or time-lapse record of 1 camera creates a "Critical activities incident – level 2", if it happens during the hours of the operation subjected to video surveillance and lasts longer than 15 minutes. Malfunction of multiple cameras create 1 incident per camera. For clarification: one incident is either missing stream or missing time-lapse or missing both simultaneously.

        ii. If the incident overlaps into the subsequent "half-shift" (either from the previous "half-shift" or from outside the operational hours, but between the

operations), the works shall be suspended until the video documentation functionality is restored. During the processes which do not allow interruption, e.g. epoxy resin curing, the video-surveillance shall be restored as soon as possible at least provisionally by e.g. hand-held camera, meaning one camera shall be always prepared at hand. Otherwise the "Critical activities incident – level 2" changes into a "video documentation incident – level 3", meaning the Buyer has a right to request a new coil or even terminate the Contract (see Framework Purchase Agreement, Article 11.2.10).

iii. A missing stream and/or time-lapse record of 1 camera creates a "Critical activities incident – level 1", if it lasts longer than 60 minutes and happens outside the operational hours, but between the operations, when overview cameras (see "24 hours" in "Time-lapse frequency" column in Table 7-1) are supposed to be working. If it is clear from the record before and after the missing stream or time-lapse, that the coil was manipulated outside the operational hours during the camera down-time, it is considered "Critical activities incident - level 3".

iv. Explanation: The purpose of the previous paragraphs is to create **strict rules which: 1/** force the Seller **to check the stream and time-lapse twice per a day** (at the beginning of each "half-shift"), 2/ force the Seller **not to start any work before this check** and 3/ force the Seller **not to manipulate with the coils when the stream and time lapse are required. If these strict rules are followed, the Seller can avoid the "Critical activities incident – level 3"**.

d. The "Critical activities incident" shall be reported and handled through "Non-conformance report", see chapter 7.4.5.

9. During all of the video observed activities, there shall be present a responsible person dedicated by the Seller, who shall have a mobile phone on which can be contacted by the Buyer, regarding the video stream and time-lapse. The contact details (name and phone number) shall be in the "Video documentation plan".

Table 7-1 – Video stream and time-lapse documented activities.

Activity	**Live stream**	**Cameras & location**	**Time-lapse frequency**
Conductor cleaning and priming (3-4 cameras, depending on actual location and view of the cameras)	yes	overview of the working area	10 s / 24 hours per day
		cleaning stage	10 s / during operation
		priming (view on the one side of the conductor)	
		priming (view on the other side of the conductor)	

Preparatory works on primed conductor, manipulation with the bare primed conductor (2 cameras)	yes	overview of the working area	10 s / 24 hours per day
		close-up to the activity	10 s / during operation
Conductor cleaning, wrapping with GF and polyimide tape and coil winding (4-6 cameras, depending on actual location and view of the cameras)	yes	overview of the working area	10 s / 24 hours per day
		cleaning stage (if applicable)	10 s / during operation
		wrapping (view on the one side of the conductor)	
		wrapping (view on the other side of the conductor)	
		conductor bending	
		coil winding (the whole carousel)	
soldering of coolant feeders (2 cameras)	yes	overview of the working area	10 s / during operation
		close-up	10 s / during operation
orbital welding of electrical breaks on the coolant feeders (2 cameras)	yes	overview of the working area	10 s / during operation
		close-up	10 s / during operation
Coil insertion into VPI mould (2 cameras)	yes	overview of the working area	10 s / 24 hours per day
		close-up to the coil and the mould	10 s / during operation
Coil VPI – epoxy curing (1 camera)	yes	overview of the working area	10 s / 24 hours per day

7.4.4 Inspection & Test Reports

The reports from all required inspections and tests shall provide the test or inspection parameters, actual results measured, identification and calibration status of the equipment used, and identification of the name of the inspector/tester. The data measured during the tests shall be provided in digital form where appropriate (e.g. impedance dependence on frequency). Persons responsible for communicating the reports are defined in chapter 9.1.

7.4.5 Non-conformance Reports

Signed copies of any non-conformance reports generated per chapter 8.3 shall be included in the process history (Traveller).

8 General assignment

8.1 Requirement on the temporary storage until delivery / installation in the Buyer premises

Responsibility for the storage costs and conditions is described in the Framework Purchase Agreement, Article 4.7. In this chapter, only the technical aspects of the storage are described.

The complete coils shall be stored in a clean and dry place, protected from the weather effects, not exposed to heat sources (sun or heating systems). The coils have to be wrapped to avoid dust accumulation and packed to avoid mechanical damage caused by any activities in the vicinity. The cooling channels shall be dried and sealed. Detailed requirements on packing are given in the chapter about transport (8.2).

8.2 Transportation to the place of installation of the item

The formal requirements and schedule are described in the Framework Purchase Agreement. The technical requirements are listed below:

- The coils shall be clearly labelled. The packing shall be labelled as well and it shall contain clear instructions for manipulation.
- Before packing, the coils shall be clean; vacuum compatible and free from dust and debris.
- During the packing all requirements on the cleanliness do apply (see chapter 5.8.1).
- All coils shall be carefully packed, to avoid contamination of the coils and their insulation during manipulation, storing and transport. Preferred material for wrapping is polyethylene. All materials shall contain minimum of volatile substances, which could potentially damage the insulation or conductor.
- The packing shall protect the coils from mechanical damage during all planned operations (lifting with crane, transport, etc.).
- The packing shall protect surface properties wherever functionally essential (e.g. contact surfaces for electrical connection)
- The openings of the cooling circuits shall be safely protected and sealed to avoid contamination of the channels.
- Adhesive tape, if used, shall not contaminate the surfaces of the coil.
- The coils shall be dry (incl. the cooling channels) at the moment of packing and the packing shall keep the coils dry.
- The amount of packing material shall be minimized, while the quality of packing shall not be compromised.
- The Buyer has the right to witness the packing procedure and thus shall be informed in time about planned operation (see chapter 9.8). After the packing completion, the package shall be sealed.
- All necessary rigs and jigs have to be supplied and are part of the Contract. The rig for turning the coil from transportation position to the installation position shall be supplied (see 5.7).
- All necessary manipulation with the coil (incl. the rigs and jigs) shall be possible with a crane with 25 t lifting capacity (which is available at the place of delivery).

8.3 Non-conformance and corrective actions

Non-conforming items shall be positively identified, and, where possible, segregated to prevent use. The Seller shall document each non-conformance and inform the Buyer forthwith about it. The Buyer's written approval is required prior to the use of any non-conforming item. Seller's Quality Assurance system shall provide not only for timely resolution of non-conformances but also for analysis of non-conformances to determine root causes and to implement appropriate and effective corrective actions.

8.4 Classification from the perspective of radiation and environmental impacts

The subject of this tender does not contain any radioactive substances or sources of ionizing radiation. The final product does not contain substances endangering the environment, but the processes during its manufacture may require precautions to prevent contamination of the environment and health risks to the operators (e.g. process of conductor priming and VPI process). This tender is subject to compliance with the requirements of RoHS 2 Directive (2011/65/EU); in case the RoHS compliance cannot be achieved, the Buyer shall be informed, the non-compliance shall be justified and is a subject of approval by the Buyer.

9 Quality Assurance

Quality Assurance can be divided into two parts:

1. Quality Assurance plan – this is part of the MIT plan (see chapter 7.3 - MIT plan, particularly 7.3.5)
2. Actual realization of the activities planned in the Quality Assurance plan (reports, checks, tests, equipment, work process, …) – the documentation of the actual realization is part of the Traveller of individual items (see chapter 7.4 - Traveller)

This chapter covers both above mentioned parts of the Quality Assurance.

9.1 Representatives for communication

All communication related to the technical aspects and performance of the Contract shall be managed by both "Project Manager" and "Representative in Technical Matters" (the "Project Manager" is stipulated in the Tender documentation, chapter 6.6.3, the "Representative in Technical Matters" is stipulated in the Framework Purchase Agreement, article 12.2).

9.2 Inspection, Surveillance and Audit

The Seller shall perform daily inspections and surveillance throughout the manufacturing of the coils as delineated in this specification. Such inspections and surveillances shall be documented and available to the Buyer. The Buyer designated a set of manufacturing, inspection and/or test operations as mandatory Witness or Hold points, as listed in the chapter 9.8 and described in the chapter 9.9 and in the Framework Purchase Agreement.

In addition, due to the critical nature of these components, authorized representatives of the Buyer have the right to visit and check the production process on site for activities outside of the agreed Witness or Hold points schedule (see framework Purchase Agreement, article 6.8). Such visits do not have to be announced in advance by the Buyer to the Seller. In case of issues related to the Critical activities (chapter 9.9) or Witness points (chapter 9.8) being identified, the visiting Buyer's representatives shall have the authority to halt the fabrication process until these issues are resolved. The Seller and its subcontractors are responsible for the safety of the Buyer's representatives visiting the manufacturing site.

The terms of announcing the dates of witness points and Buyer's visits at the manufacturing site are defined in the Framework Purchase Agreement, Article 6.9.

Video and photo documentation

The video and photo documentation of the manufacturing process shall be recorded and provided to the Buyer as a part of Traveller, while the procedures shall be part of the Quality Assurance plan (within the MIT plan, see chapter 7.3 - MIT plan). The details are specified in chapter 7.4.3 - Photo and video documentation.

9.3 Seller's Quality Assurance Program

Seller's Quality Assurance Program is guaranteed by ISO 9001 certification, which is required for participation in the tender.

9.4 Inspection and Test Procedures

Inspections and tests shall be performed in accordance with the MIT plan (chapter 7.3) with approved

(separate or incorporated) procedures referencing criteria for acceptance or rejection. Elaborated records shall be maintained and available for the Buyer's review as a part of the Traveller of the particular item.

9.5 Codes and standards

Materials and manufacturing/test methods used in fabrication of the equipment covered by this specification shall comply with the latest revision, in effect at date of issuance of this document, of the currently approved applicable regulations, safety codes, specifications and standards, including applicable technical definitions as acknowledged and accepted in industry. The list of relevant standards is in chapter 11.

9.6 Document Traceability and Records

The Seller shall maintain a system of documentation whereby objective evidence of required operations, inspections, examinations, and tests is systematically compiled, indexed and stored. Such objective evidence shall include all types of documentation described in chapter 7 and listed in the Table 3-3. This information shall be complete and legible and validated by responsible personnel and shall be traceable to subject items.

9.7 Equipment/Material Identification and Status

Material and equipment identification shall be maintained throughout the program and shall be traceable to the records. Status of acceptability shall be readily discernible through the use of tags, stamps, serial numbers or other positive means.

9.8 Witness/Hold Points and Notification of the Buyer in Advance

The Buyer designated selected manufacturing, inspection and/or test operations as mandatory Witness or Hold points. Their lists are in Table 9-1 and Table 9-2.The conditions for the Witness points, including notification of the Buyer in advance, are described in the Framework Purchase Agreement, Article 6.9.

Note that the Witness Points and Hold Points as described in this chapter are one of the Critical activities, which are summarized in chapter 9.9. Chapter 9.9 describes further the consequences of the violation of the requirements stated in this chapter.

Table 9-1 - List of Witness points

Witness point
FAT: 3x3 mock-up and insulation samples
Manufacture: welding /soldering qualification samples
FAT: welding /soldering qualification samples
Manufacture: prototype coil (conductor preparation and priming, Metal connection procedures, VPI)

All electrical tests on prototype coil (incl. pre-VPI and before thermal cycling)
FAT: prototype coil
Manufacture: each individual PF coil (conductor preparation and priming, Metal connection procedures, VPI)
FAT: each individual PF coil
Paschen test: coils selected for Full surface coverage Paschen test by the Buyer
Final packing of the individual PF coils for transportation (see chapter 8.2 - Transportation to the place of installation of the item)

Table 9-2 - List of Hold points

Hold point	Activities on hold (unless a written permission for the activity or a part of the activity is obtained from the Buyer beforehand)	Condition for proceeding
MIT plan initial version	• Prototype coil manufacture. • PF coils manufacture.	"A" grade evaluation by the Buyer
Bill of Materials	• Purchase of material for prototype coil and PF coils	Acceptance protocol for Bill of Materials or "A" grade evaluation for MIT plan initial version
3x3 mock-up and insulation samples – final tests	• Prototype coil manufacture. • PF coils manufacture	Successful and accepted tests
welding /soldering qualification samples	• Prototype coil welding /soldering. • PF coils welding /soldering	Successful and accepted tests
FAT: prototype coil	• PF coils manufacture	Successful FAT (grade A)
FAT: PF coils (for each individual coil)	• Shipment of individual PF coils to the Buyer	Successful FAT (grade A). Acceptance of coil Traveller document by the Buyer.

9.9 Critical activities

The critical activities are identified as crucial (listed in Table 9-3) for flawless functionality of the poloidal field coils system and therefore the whole project of tokamak COMPASS-U. Violation of these critical activities leads to penalty and can have additional consequences, up to the Contract termination. There are three levels of the severity of the violation and corresponding severity of the penalty and additional consequences:

i. Critical activities incident – level 1:
   - a minor violation of the requirements;
   - there is a contractual penalty imposed for that violation in the Framework Purchase Agreement, Article 10.4.3;
   - note: there are in principle no other consequences other than the above penalty and the Seller's duty to remedy the situation

ii. Critical activities incident – level 2:

- a major violation of the requirements;
- the contractual penalty imposed for that violation is higher, as stipulated in the Framework Purchase Agreement, Article 10.4.4;
- note: there are in principle no other consequences other than the above penalty and the Seller's duty to remedy the situation

iii. Critical activities incident – level 3:

- a critical violation of the requirements;
- the contractual penalty imposed for that violation is the same as in the previous level, as it is stipulated in the Framework Purchase Agreement, Article 10.4.5;
- the Buyer can request (and the Seller has to comply with the request) to discard the affected item (sample, mock-up or coil) and the Seller has to re-start the manufacturing procedure of the item (sample, mock-up or coil) according to the Framework Purchase Agreement, Article 4.21;
- the Buyer can terminate the Contract (i.e. the Framework Purchase Agreement) according to the Framework Purchase Agreement, Article 11.2.10.

The repeated violation of the requirements results into repeated penalty for each incident.

Table 9-3 – List of critical activities.

Problem	**Consequence**
If the requirements in chapter 5.8.1 (Cleanliness/housekeeping) are violated.	Violation of the rules stated in chapters 5.8.1.1 – 5.8.1.4 is **Critical activities incident – level 1**, for each separate event. Violation of the rules stated in chapters 5.8.1.5 and 5.8.1.6 is **Critical activities incident – level 3**, for each separate event.
Use of material different than described in chapter 5.1 (or in approved MIT) or material which was not approved by the Buyer.	The chapter 5.1 describes in detail rules for selection, properties, testing and validation of the material used for manufacturing of the coils. If the rules are not followed and this results into a use of material not fulfilling the properties required in chapter 5.1, this is considered **Critical activities incident – level 3**.
If the requirements in chapter 7.4.3 (Photo and video documentation) are violated	The consequences (i.e. assigned level for Critical activities incident) are described in chapter 7.4.3 (Photo and video documentation).
If the requirements in chapter 9.8 (Witness/Hold Points and Notification of the Buyer in Advance) are violated	The rules for consequences concerning the Witness Points are described in the Framework Purchase Agreement in Article 6.9. Violation of the rules concerning the Hold Points

	(i.e. performing the activities on hold according the Table 9-2 without written prior permission from the Buyer) is **Critical Activities Incident – Level 3**, for each separate event.
If any of the coils PF1, PF2, PF3, PF4 (i.e. excluding the prototype coil) fails the repeated Paschen test (see chapter 6.3.7), which means that it obtains grade C for the Paschen test.	This event shall be, for the purposes hereof, considered as a **Critical Activities Incident – Level 3**, except that neither the contractual penalty (stipulated in the Framework Purchase Agreement, Article 10.4.5) nor termination of the contract by the Buyer (according to the Framework Purchase Agreement, Article 11.2.10) shall apply in this case. The only applicable consequence of this event is that the Buyer may request (and the Seller must comply with the request) that the affected coil is discarded and the Seller must re-start the manufacturing procedure of the coil according to the Framework Purchase Agreement, Article 4.21

9.10 Non-Conformance and Corrective Actions

The QA plan shall address the procedure of handling an occurrence of non-conformity, compatible with chapter 8.3.

9.11 Configuration Control

The Seller shall completely document the configuration of delivered end items or services, using drawing revisions, specification revisions, unique part numbers, or other suitable means.

9.12 Calibration of Test and Measuring Equipment

Inspections and tests shall be performed using properly calibrated measuring and test equipment. Calibration standards are assumed to be maintained by the Seller's ISO 9001 certification.

9.13 Seller's Responsibility for Conformance and Flowdown of Requirements to Sub-tier Sellers

The Buyer's review and/or approval of Seller's documents nor the Buyer's inspection of Seller's items or services shall not relieve the Seller of responsibility for full compliance with the requirements of the Framework Purchase Agreement. **The Seller is responsible for assuring that all requirements and restrictions are imposed on any sub-tier Sellers**.

10 Annexes of technical specification

- Annex of technical specification No. 1 – Vacuum compatibility
- Annex of technical specification No. 2 – Insulation tests and results
- Annex of technical specification No. 3 – Technical drawings
- Annex of technical specification No. 4 – Electrical break specifications and drawing
- Annex of technical specification No 5. – Overview presentation of the PF coils

11 List of relevant standards and other documents

EN ISO 3834-2	Quality requirements for fusion welding of metallic materials - Part 2: Comprehensive quality requirements
EN ISO 15607	Specification and qualification of welding procedures for metallic materials
EN ISO 3506-1	Fasteners - Mechanical properties of corrosion-resistant stainless steel fasteners Part 1: Bolts, screws and studs with specified grades and property classes
EN 10204	Metallic products. Types of inspection documents
EN 13018	Non-destructive testing - Visual testing
EN ISO 4136	Destructive tests on welds in metallic materials — Transverse tensile test
EN ISO 6892-1	Metallic materials – Tensile testing – Part 1: Method of test at room temperature
EN ISO 4287	Geometrical product specifications (GPS) - Surface texture: Profile method - Terms, definitions and surface texture
EN ISO 22825	Non-destructive testing of welds – Ultrasonic testing Testing of welds in austenitic steels and nickel-based alloys
EN ISO 23279	Non-destructive testing of welds – Ultrasonic testing – Characterization of discontinuities in welds
EN 1779	Non-destructive testing - Leak testing Criteria for method and technique selection
ISO 2768	General tolerances - Part 1: Tolerances for linear and angular dimensions without individual tolerance indications
EN ISO 20485	Non-destructive testing - Leak testing Tracer gas method
IEEE Std. 43-2000	Recommended Practice for Testing Insulation Resistance of Rotating Machinery
IEEE Std. 286-2000	Recommended Practice for Measurement of Power Factor Tip-Up of Electric Machinery Stator Coil Insulation
IEC 60270	High-voltage test techniques - Partial discharge measurements
IEEE Std. 95	Recommended Practice for Insulation Testing of AC Electric Machinery (2300 V and Above) With High Direct Voltage
IEC 60893-3	Insulating materials - Industrial rigid laminated sheets based on

	thermosetting resins for electrical purposes Grades and specifications for industrial rigid laminated sheets based on thermosetting resins for electrical purposes (for insulation materials such as EP GC 203 or its equivalent G-11 according to NEMA LI 1-1998).
EN 13600:2021	Copper and copper alloys - Seamless copper tubes for electrical purposes
EN 10204	Metallic products - Types of inspection documents
Directive 2011/65/EU (and relevant updates)	Restriction of Hazardous Substances (RoHS) - Directive on the restriction of the use of certain hazardous substances in electrical and electronic equipment