

# Fabrication procedure for poloidal coils of COMPASS-Upgrade tokamak

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# Specification of poloidal field coils of COMPASS-Upgrade tokamak

**This document describes the manufacturing procedure of magnetic coils**

**PF coil design is not finalized and it can be modified.**

**This document represents a working version which is subject to change by IPP based on changes in design and recommendations from preliminary market consultations**

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# 1 INTRODUCTION

The COMPASS tokamak [1] has been in operation in the Institute of Plasma Physics since 2006 and now it is undergoing a major upgrade – COMPASS-U [2] with the first plasma planned for the end of 2022. The COMPASS-U tokamak will be larger in size: major radius of 0.89 m compared to 0.56 m of COMPASS, minor radius of 0.28 m versus 0.18 m. The plasma current will be up to 2 MA compared to 0.4 MA for COMPASS and the magnetic field on the plasma magnetic axis of 5 T compared to less than 2 T for the previous machine.

This document serves as a manual for the production process of the new PF coils of the COMPASS-U tokamak (C-U). The development of PF coils design is ongoing, with presumed end in the second half of 2020. Manufacture of the coils is planned between years 2020 - 2021. Tokamak assembly is planned for year 2022. The first tokamak plasma is expected at the end of 2022.

PF coils magnet system will be made from hollow conductors made of high conductivity oxygen free copper alloy (OFHC). To decrease the resistivity of coils, they will be cooled to temperature close to LN2 (80 K, coolant medium is gaseous helium) to be able to bear high currents (up to 50 kA, 3 s flattop). Poloidal field coils are divided to Central Solenoid (CS) coils (8 coils with equal diameter and equal number of turns), Equilibrium Field (EF) coils (4 pairs of coils) and Vertical Stabilization (VS) coils (a pair of coils). CS coils have to be wound on inner TF core (TF core will be delivered by IPP). The purpose of 2 symmetric vertical stabilization coils is to actively control plasma vertical stability. Therefore, a fast response is needed from these coils and they will be wound with only a few turns for small inductance.

Manufacture of coils will be divided to three phases:

Phase 1 - Manufacture and testing of a prototype coil

Phase 2 - Manufacture of EF coils and vertical stabilization coils

Phase 3 - Manufacture of CS coils (winding and impregnation on TF core)

## 2 APPLICABLE DOCUMENTS

### 2.1 Standards and Codes

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 following currently approved applicable regulations, safety codes, specifications and standards, including applicable technical definitions as acknowledged and accepted in industry.

These Standards and Codes set forth the minimum requirements. Subcontractor is encouraged to recommend superior or more economical designs, processes, or materials.

General Tolerances will be set by DIN ISO 2768 for m class.

Table 1 - linear dimensions

class of accuracy (mm)	from 0.5 to 3	from 3 to 6	from 6 to 30	from 30 to 120	from 120 to 400	from 400 to 1000	from 1000 to 2000	from 2000 to 4000
<b>m</b>	<b>±0.1</b>	<b>±0.1</b>	<b>±0.2</b>	<b>±0.3</b>	<b>±0.5</b>	<b>±0.8</b>	<b>±1.2</b>	<b>±2</b>

note: Table 1 is also used for circularity tolerance.

## 3 APPLICABLE DRAWINGS AND SCOPE OF THE WORK

### 3.1 IPP Drawings

Coil design drawings provided by IPP will be listed in the Annex. All dimensions refer to room temperature (20° C) conditions. Dimensional characteristics including tolerances and insulation builds are given in the drawings. For the G-10 fillers some geometry is only defined in the model using STP files, available on request.

### 3.2 Subcontractor Drawings

Subcontractor shall prepare manufacturing and tooling drawings as required to complete the fabrication. The manufacturing and tooling drawings shall be submitted to IPP for review and approval prior to use.

### 3.3 Scope of the work

#### 3.3.1 Prototype coil

In the first phase, the prototype coil will be manufactured to demonstrate feasibility of the design. The coil will be tested in order to find any design flaws. CS1 (or possibly PF1) coil will be chosen as the prototype coil. Slight modification to improve the coils design is possible.

#### 3.3.2 Equilibrium field coils

There will be 8 equilibrium field coils in total (four pairs). The four upper coils are named PF1U, PF2U, PF3U and PF4U with parameters shown in Table 1 (Section 5.1.1). Lower coils PF1L, PF2L, PF3L and PF4L are symmetrical to their counterparts. The coil windings will be planar with sharp localized joggles between turns and layers (toroidal angle less than

90°) spread evenly around the winding. The winding pattern is optimized for error magnetic fields in the vacuum vessel and will be provided in drawings for each coil. Coils will be wound from a hollow conductor to allow flow of cooling medium - gaseous helium. Each EF coil will have to accommodate multiple separate cooling circuits (the exact number will be specified later). There are two working versions to solve the connection of cooling circuits described briefly in Sections 3.3.2.1 and 3.3.2.2 with suggested conceptual designs in Annexes 1,2. The most suitable solution is to be found after communication with the Subcontractor. Coolant inlet will be made of copper - stainless steel swagelok connection. EF coils will have parallel current feeds.

### 3.3.2.1 Uninterrupted coil conductor

The coils will be wound from one uninterrupted conductor and the coolant inlets connections will be made consequently by one of the suggested methods (Annex 1 - figures 1a, 2, 3).

### 3.3.2.2 Interrupted coil conductor

Each coil will be made of several co-wound individual coils forming the individual cooling circuits (see Fig.4 in Annex 2 for illustration). The advantage of the concept is that the joint of stainless steel cooling channels can be done well outside the high-field, poorly accessible area. The downside is the necessity to ensure electrical connection of the separate coil windings. The presumed way is to weld/solder together two parallel coil turns (on ~90° toroidal angle, see Annexes 1,2 - figures 1b, 1c, 5 for illustration).

### 3.3.3 Central solenoid coils

There will be 8 central solenoid coils in total, placed on top of each other in a stack-like structure. The four upper coils are named CS1U, CS2U, CS3U and CS4U with parameters shown in Table 1 (Section 5.1.1). Lower coils CS1L, CS2L, CS3L and CS4L are symmetrical to their counterparts. Basically, the CS coils are equal and differ only by toroidal position of inter-turn and inter-layer joggles and current feeds. The coil windings will be planar with sharp localized joggles between turns and layers (toroidal angle less than 90°) spread evenly around the winding. The winding pattern is optimized for error magnetic fields in the vacuum vessel and will be provided in drawings for each coil. Coils will be wound from a hollow conductor to allow flow of cooling medium - gaseous helium. Each CS coil will have two parallel current feeders with particular length to reach out of support structure of the tokamak. CS coils have only one inlet and outlet of the coolant medium. Because poloidal field are inside of toroidal field coils, CS coils have to be wound on TF core which will be supplied by IPP (through subcontractor of TF coils).

**note: Current feeds design of CS coils is not yet decided. Therefore, for a rough price estimation purposes we suppose parallel current feeds same as for EF coils.**

### 3.3.4 Vertical stabilization coils

There will be two identical coils VS1U and VS1L which will be used for active vertical plasma stabilization. The insulation system will be the same as for EF coils. The coil windings will be



planar with sharp localized joggles between turns and layers (toroidal angle less than 90°). The winding pattern will be provided in drawings for each coil.

### 3.3.5 Material tests

All types of materials used for coils manufacture have to be tested to verify their compliance with materials listed by IPP (material tests will be specified by IPP).

In the case of Subcontractor suggested solutions for insulation systems, these have to be tested to assure their compliance with the requirements made by IPP.

*Form and list of the tests to be specified later.*

### 3.3.6 Coils overview

Table 1 - Coils overview

Coil	R at room temp. [mΩ]	Cu turn cross section [mm <sup>2</sup> ]	Coil mass [kg]	L [mH]	Turns layout	numb. of turns	medium radius [m]
CS1	3.1	509.8	391	1.051	4 x 8	30	0.42
PF1	13.98	185.7	300	7.202	8 x 8	64	0.576
PF2	9.32	185.7	481	2.653	4 x 8	32	0.749
PF3	19.39	185.7	476	5.268	6 x 6	36	1.06
PF4	21.91	300	1145	9.589	4 x 8 + 2 x 4	40	1.42
VS1	6.99	79	34	0.138	2 x 2	4	1.126

note: Due to coil winding joggles, the number of turns in the table does not correspond precisely to the layout of turns. Valid is the provided model and drawings.

## 4 RESPONSIBILITIES

### 4.1 IPP

IPP will identify a point of contact, called the Technical Representative (TR) for this procurement. The name of the TR will be identified in the contract.

### 4.2 Subcontractor

Subcontractor will provide the name and contact information for the project manager and technical point of contact for this procurement. The name of Subcontractor's point of contact shall be identified in the contract.

# 5 MATERIALS

## 5.1 Supplied Materials

All supplied materials shall be inspected upon receipt and any discrepancies, deviations, or other defects shall be noted and communicated to IPP and supplier as soon as possible. Excess materials shall be returned to IPP at the conclusion of the contract unless otherwise agreed by IPP in writing.

### 5.1.1 Conductor

The conductor material will be C10700 oxygen-free silver bearing copper. Nominal dimensions and characteristics are given in Table 1.

Table 1 – Copper Hollow Conductor Characteristics

Coil a quantity	material of the conductor	height [mm]	width [mm]	hole diam. [mm]	radius [mm]	Temper of material	length of conductor [m]
8 x CS	C10700	22	25	elliptical (8x6.125)	1	half-hard	90
2 x PF1	C10700	15	15	7	1	half-hard	150
2 x PF2	C10700	15	15	7	1	half-hard	100
2 x PF3	C10700	15	15	7	1	half-hard	208
2 x PF4	C10700	20	17	9	1	half-hard	380
2 x VS1	C10700	10	10	5	1	half-hard	40

\*Note: Dimensions in Table 1 are provided for information only. Refer to the drawings for complete dimensions including tolerances.

Use of grit blasting and priming of the conductor is necessary to ensure good adhesion of the cyanate-ester or other Subcontractor proposed resin to the conductor.

Suggested primer:

Product name: CTD-450

Thickness: 0.76 µm - 2.54 µm

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

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

### 5.1.2 Mandrel

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

### 5.1.3 Insulation

This section describes insulation system proposed by IPP, however the **Subcontractor is encouraged to propose an alternative insulation system with equivalent or superior properties** with respect to the insulation requirements.

Table 2 - Working voltage and frequency of power supplies for PF coils.

coils	voltage [kV]	frequency [kHz]
central solenoid (CS)	1	0.5 - 2
equilibrium field (EF)	1	0.5 - 2
vertical stabilization (VS)	0.3	2 - 20

Two half-lapped layers of wound glass fiber tape shall be applied with the glass facing the conductor.

#### 5.1.3.1 Insulation of EF and VS coils

##### **conductor insulation**

- S2 glass fiber 8H satin weave tape, style 6781, **total thickness 0.5 mm**, 50 % overlap of 0.25 mm tape thickness, width of tape from 14 to 20 mm depending on size of the conductor

##### **interlayer insulation**

- S2 glass fiber 8H satin weave tape, style 6781, **total thickness 1.05 mm**, 50 % overlap of 0.25 mm tape interleaved with kapton tape 0.025 mm, width of tape from 20 - 40 mm depending on size of the conductor. Kapton tape will be at 80% of glass fiber tape width.

##### **ground insulation**

- S2 glass fiber 8H satin weave tape, **total thickness 3 mm**, 50 % overlap of 0.25 mm tape thickness, width of tape from 20 - 40 mm depending on size of the conductor.

## interlayer insulation layout



### 5.1.3.2 Insulation of CS coils

#### conductor insulation

- S2 glass fiber 8H satin weave tape, style 6781, **total thickness 0.5 mm**, 50 % overlap of 0.25 mm tape thickness, width of tape from 14 to 20 mm depending on size of the conductor.

#### interlayer insulation

- S2 glass fiber 8H satin weave tape, style 6781, **total thickness 1.05 mm**, 50 % overlap of 0.25 mm tape interleaved with kapton tape 0.025 mm, width of tape from 20 - 40 mm depending on size of the conductor. Kapton tape will be at 80% of glass fiber tape width.

It is presumed there will be no extra ground insulation as the CS coils will be wound on TF core and therefore not allowing to wind a tape poloidally around the coil.

Note: The tolerance for a half-lapped layer is defined as the half of width of the used tape, so that there is a minimum of a half-lap layer with the possibility of exceeding the overlap with the second half. Around the bends, this tolerance applies to the outer diameter where the inner diameter is allowed to exceed the additional 0.3 mm overlap as required by the radius. Excessive overlap should be avoided to ensure that the radial build of each layer (and the coil overall) is maintained.

### 5.1.4 Shims and Spacers

IPP will supply G-10 winding shims and spacers as indicated on the IPP drawings. Trimming of these parts as necessary to wind the coil is the responsibility of Subcontractor. Lead blocks and fillers provided by IPP are to be inspected prior to assembly for burrs or sharp edges and de-burred if necessary. The parts shall be cleaned with an appropriate solvent prior to use.

### 5.1.5 Tooling

All tooling (including the VPI mold) shall be supplied by Subcontractor. The design of tooling used for fabricating the deliverable items of the contract shall be reviewed and approved by IPP prior to use.

### 5.1.6 Coil terminal blocks

Machined blocks for coil terminals shall be fabricated from a copper bar or plate per IPP supplied drawings. Certified Material Test Reports (section 10.15.1) shall be provided for the materials used.

### 5.1.7 Braze materials

Suitable braze material will be supplied by Subcontractor. Brazing will be done at room temperatures but brazing material has to be suitable for cryogenic temperatures.

### 5.1.8 Coil lead and transition fillers

Any required fillers not supplied by IPP shall be supplied by Subcontractor. The insulating lead blocks and coil fillers shall be constructed from G-10. Material Certifications (section 10.15.1) are required. All machining of G-10 must be done so as to comply with its use in a high vacuum environment. The fillers and lead blocks shall be free of burrs and sharp edges. All G-10 surfaces unless machined shall be sanded to remove any high gloss surface, to promote bonding of the epoxy to the lead blocks. The parts shall be cleaned with an appropriate solvent prior to use.

### 5.1.9 Void materials

All regions within the winding volume not occupied by conductor or ground insulation shall be filled with certified (section 10.15.1) S-2 glass or G-10 fillers to minimize resin rich areas. When using S-2 glass to fill voids, the glass shall be densely applied to avoid resin rich areas. Void areas where there is no glass or G-10 filler shall not exceed 0.08 mm.

### 5.1.10 Insulating Resin

#### 5.1.10.1 Required parameters of coil impregnation:

- Cryogenically compatible. All PF and CS coils will be operated at least at LN2 temperature (77 K).
- Vacuum compatible. All PF and CS coils will be placed in a vacuum cryostat with ultra high vacuum (down to 1e-5 Pa).
- Very good match of thermal expansion with the OFHC copper conductor for the working range of temperatures (77 - 157 K) to minimize thermal stresses and prevent cracking/delamination of the resin.

- Resistance to neutron irradiation. It is estimated (upper estimate) that COMPASS-U will produce  $5e18$  neutrons/year. For PF, CS coils this can be roughly translated as a neutron flux of  $2e13$  neutrons/cm<sup>2</sup>/year.
- Very high mechanical strength. Especially CS coils will have to withstand very high stresses. While the coil design is still under development, currently the calculations show stresses in epoxy impregnation of CS coils reaching maxima of up to 40 MPa both in shear and tension in 1 coil cycle (at least 20000 coil cycles at maximum parameters are presumed)

#### 5.1.10.2 Suggested resin

Product name: CTD-425

Manufacturer: Composite Technology Development Inc. 1505 Coal Creek Drive

Lafayette, Colorado 80026 , (303) 664-0394

Description: Two-part system with Epoxy (EP) and Cyanate Ester (CE) catalyst in part A and Cyanate Ester (CE) in part B

**Subcontractor may propose an alternate VPI resin with properties equivalent to or more suitable than the suggested product.**

#### 5.1.11 Degreasing/cleaning solvents

All conductors, insulation blocks, and VPI mold 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 Subcontractor shall be approved by IPP prior to use. Recommend solvents are acetone and alcohol, however only alcohol is permitted for use on the primed copper.

#### 5.1.12 VPI Mold

Subcontractor shall supply the VPI mold. The design of the mold and sealing shall be submitted to IPP for review and approval (refer to section 5.1.5).

#### 5.1.13 Mold release

Subcontractor shall propose a mold release agent for use on the surfaces of mold parts that are to be removed after VPI. Mold release material shall be proposed by Subcontractor and approved by IPP prior to use.

#### 5.1.14 Other materials

All other materials not listed in section 5.1 or above required to fabricate, test, and ship the deliverable items shall be supplied by Subcontractor. All insulating materials, including general-purpose kapton adhesive tape for joining and tailoring insulation, shall be of the same composition as the IPP-supplied materials listed in 5.1.3 and 5.1.4. Additional insulating materials provided by Subcontractor shall be reviewed by IPP prior to purchase to verify compliance with this specification.

### 5.1.15 Sensors

Coils will be equipped with certain number of thermoelectric sensors and strain gauges. Exact numbers, types and placement will be specified later.

## 6 QUALITY ASSURANCE (QA) AND MANUFACTURING/INSPECTION/TEST (MIT) PLANS

### 6.1 QA plan

Subcontractor shall submit a 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 revisions require review and approval by IPP prior to the start of design or manufacturing of the equipment under this specification.

### 6.2 MIT plan

Subcontractor shall submit a Manufacturing, Inspection and Test (MIT) plan for IPP approval prior to the start of manufacture. The MIT 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 Plan may include flow chart(s), Process Sheets, Shop Travelers, and inspection sheets, etc. Equipment to be used for all fabrication, inspections and tests shall be specified.

A traveler, whether integral to the MIT Plan or a separate document, shall be used for data entry and operation sign-offs. Relevant data for inspections and tests include equipment ID and calibration status, acceptance values, actual values obtained, and pass/fail determination. IPP will designate selected steps as mandatory "witness" points. Subcontractor shall notify IPP a minimum of five (5) working days in advance of these witness points. Revisions or changes to the approved MIT or traveler shall be reviewed and approved by IPP prior to use.

## 7 FABRICATION

### 7.1 Cleanliness/housekeeping

Cleanliness and housekeeping is an essential element to the success of the manufacturing of the PF coils. The following steps shall be taken during the fabrication of the PF Coils to enforce this practice.

### 7.1.1 Clean environment

The final preparation of all insulating materials, the final preparation of the mold, 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. If other activities that pose a risk of contamination are conducted in the same room, the work environment shall be enclosed, shall include an intermediate entry area with double doors in which workers can put on protective wear (section 7.1.3), and shall employ a positive pressure fan with a HEPA filter.

### 7.1.2 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.

### 7.1.3 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, G-10 fillers or other components used in the construction of the PF coils. 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.

### 7.1.4 Markers and Pencils

The use of lead pencils is prohibited in the fabrication stations due to electrical tracking concerns. Used brand of markers have to be approved by IPP.

### 7.1.5 Chips and filings

Filing, grinding, or any other operation that generates any kind of electrically conductive chips shall not be allowed in the clean area (section 7.1.1). 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 IPP in advance of the work.

### 7.1.6 Material Protection

Material controls shall be addressed in the QA Plan (section 6.1) or MIT Plan (section 6.2). Copper conductor and all insulating materials shall be stored and processed in controlled areas free from metallic dust or other contaminants. All materials shall be protected from contamination from skin oil, etc. (see section 7.1.3). The winding line shall be covered during off-shifts.



## 7.2 Copper receipt, inspection and handling

### 7.2.1 Identification

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

### 7.2.2 Receipt inspection

Upon arrival of each shipment of conductors Subcontractor 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 IPP-approved NCR disposition. Repairs should be photographed. This receipt inspection step shall be delineated on the MIT plan.

### 7.2.3 Conductor handling

The conductor shall be fed into the winding line from the original shipping spools, or transferred from the shipment spools to payout spools in such a way that it is not unwinding and rewinding. When the conductor is transferred and when it is fed into the winding line it shall be inspected and any surface defects shall be repaired. Immediately prior to application of the turn insulation, the conductor shall be wiped down with alcohol to remove excess oil, lubricant and grease. Sufficient time shall be allowed for the alcohol to fully evaporate before turn insulation is applied.

## 7.3 Key winding steps

Key steps of the winding sequence are described in this section. The Subcontractor shall include all winding steps in the MIT and sub-tier procedures or travelers referenced by the MIT.

### 7.3.1 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 don't 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.

### 7.3.2 Turn insulation

The turn insulation shall be applied to the conductor using an automated taping machine so that precise control of dimensions is achieved. 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 Kapton and to avoid excess build. See section 5.1.3.1 for turn insulation details

### 7.3.3 Dimensional control

Apply sufficient tension on the conductor feed and a force normal to the conductor to achieve the nominal compression of the insulation 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 spiral 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 IPP before continuing with the winding process.

### 7.3.4 Start and finish leads

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

## 7.4 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 and by IPP before use.

## 7.5 Pre-VPI electrical tests

Before completing the mold (refer to section 5.2.8) the dry coil shall be tested as indicated in the following sections. Ambient temperature and humidity shall be recorded. Test results shall be reviewed and approved by IPP before proceeding with VPI.

### 7.5.1 DC resistance

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

$$R_{20} = 254.5 \times R_{C234.5} + T_C$$

Where:

R<sub>c</sub> = measured resistance of the conductor (milliohms)

T<sub>c</sub> = temperature of coil when resistance measurement is made (C°)

Measured resistance shall match the nominal value (specified later for each coil). The nominal value is based on the average of the conductor min/max cross-sectional areas (as calculated from the allowable tolerances on the conductor) and a nominal length of coil. Adjustment to the nominal resistance to correct for the as-built length of the wound coil is permissible.

## 7.5.2 AC impedance

AC impedance and phase angle shall be measured over the range 0.1 to 100 kHz. Impedance test device and test procedure shall be proposed by Subcontractor and approved by IPP.

## 7.5.3 Insulation quality test

Test procedure to measure insulation strength shall be proposed by Subcontractor and approved by IPP.

## 7.6 VPI preparations

### 7.6.1 Mold cleaning

Subcontractor shall thoroughly clean and degrease all surfaces of the mold prior to coil winding activities using the pre-approved solvent (refer to section 5.2.7).

### 7.6.2 Mold leak test

Prior to VPI, Subcontractor shall demonstrate that the VPI mold is capable of achieving the base pressure, leak and out-gassing rates, as specified in the MIT/Traveler, from room temperature up to the planned out-gassing temperature.

## 7.7 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 rise test
- Resin fill volume measurement (recommend expanding a pressurized volume of nitrogen at into the evacuated VPI mold and performing 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.

## 8 ACCEPTANCE TESTS and MEASUREMENTS

### At Subcontractor's premises

### 8.1 Prototype

All tests performed at Subcontractor's premises shall be delineated on the MIT and all test data shall be recorded in the MIT or sub-tier documents referenced by the MIT. IPP will witness the tests as indicated on the MIT. If a coil fails any of the tests, IPP shall be immediately notified and a non-conformance report documenting the failure shall be generated and provided to IPP. Subcontractor may elect to perform repairs and additional tests with prior approval by IPP.

Test and inspection results from Phase 1 prototype will be compared to predicted values as a means to judge the adequacy of the fabrication.

#### 8.1.1 Electrical tests

The pre-VPI electrical tests described in section 7.5 shall be repeated with the exception of the insulation resistance test (section 7.5.3) - in this case the test voltage will be raised to 3 kV DC. 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 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 IPP as a prerequisite for shipment. Test procedures developed for section 7.5 shall address both the pre-VPI and final coil configurations, accounting for the differences in test methods that may be required.

#### 8.1.2 Dimensional Inspection

Dimensional inspection of the completed coil shall be performed. An inspection report indicating all measured dimensions relative to their nominal shall be generated. Deviations beyond the tolerance shall be reported as a non-conformance.

#### 8.1.3 Leak inspection

The coil has to be air-flow tested to ensure that the cooling path is free from obstructions. Hydrostatic pressure test will be performed for 60 minutes (at 30 bar) to check that the coil is leak-free. No discernible loss of pressure or visible leaks are permitted.

#### 8.1.4 Tests after cutting coil into sections

The prototype coil will be cut into multiple sections. The section ends will be visually examined under magnification. The precision of the conductor locations within the winding

pack array will be evaluated. Any voids evident in the turn or ground insulation will be noted including void size and location. After visual examination the section ends will be encapsulated in an insulating material to increase the dielectric strength between the ends of the cut turns. The following electrical tests will be performed:

- Megger test of turn-to-turn insulation resistance at 0,5 kV DC, performed between adjacent turns
- DC breakdown test of turn-to-turn insulation, performed between adjacent turns

During the DC breakdown tests, if the turn-to-turn insulation is sound, breakdown should occur at the ends of the sections before breakdown through the turn-to-turn insulation, at voltage levels well below the theoretical breakdown voltage of the turn-to-turn insulation.

## 8.2 Poloidal coils (EF and CS coils) and VS coils

### 8.2.1 Electrical tests

The pre-VPI electrical tests described in section 7.5 shall be repeated with the exception of the insulation resistance test (section 7.5.3) - in this case the test voltage will be raised to 3 kV DC. 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 presences 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 IPP as a prerequisite for shipment. Test procedures developed for section 7.5 shall address both the pre-VPI and final coil configurations, accounting for the differences in test methods that may be required.

### 8.2.2 Dimensional Inspection

Dimensional inspection of the completed coil shall be performed. An inspection report indicating all measured dimensions relative to their nominal shall be generated. Deviations beyond the tolerance shall be reported as a non-conformance.

### 8.2.3 Leak inspection

The coil has to be air-flow tested to ensure that the cooling path is free from obstructions. Hydrostatic pressure test will be performed for 60 minutes (at 30 bar) to check that the coil is leak-free. No discernible loss of pressure or visible leaks are permitted.

## 8.3 At IPP

### 8.3.1 General quality evaluation

IPP will perform a general inspection of workmanship and dimensions of the delivered prototype. Any defects will be noted, characterized, and recorded.

### 8.3.2 Tests on complete coil

The electrical tests performed at Subcontractor’s premises (section 8.1.1) will be repeated.

## 8.4 Test & Inspection Matrix

The following table summarizes the tests, measurements and inspections to be performed on the coil. Additional testing and inspections that will be performed at IPP after the coil is delivered are listed as reference. Tests and measurements indicated in the “Acceptance Criteria” column, must meet the specified values in order for the coil to be considered acceptable to ship.

Test & Inspection Matrix

Test	ref.	Pre VPI	Post VPI	Acceptance criteria	location	Notes
insulation test	7.5.3	yes	yes	no	Vendor	
Impedance	7.5.2		yes	no	Vendor and IPP	Compare pre and post VPI values
insulation test	8.1.1 8.2.1		yes	yes	Vendor and IPP	Must pass acceptance criteria
Terminal DC Resistance	7.5.1	yes	yes	no	Vendor and IPP	Compare pre and post VPI values
Dimensional Inspection	8.1.2 8.2.2		yes	yes	Vendor and IPP	Conforms to drawing dimensions/tolerances
Visual evaluation sectioned coil	8.3.1		yes	no	IPP	Evaluate conductor spacing, VPI quality.
Hi-Pot of sectioned coil			yes	no	IPP	Determination of turn-to-turn voltage standoff

## 9 SPECIAL PROCESSES

### 9.1 Metal connection qualification program

Subcontractor shall qualify the metal connection procedure (Braze, solder, Ultrasonic welding, etc.), equipment and operators prior to use. Metal connection qualification requirements are as follows.

#### 9.1.1 Procedure

The selected coil manufacturer shall develop a metal connection procedure for performing the lead terminals. Procedure shall be reviewed and approved by IPP.

#### 9.1.2 Qualification of Procedure/Process

A minimum of three (3) successful metal connection samples shall be made to qualify the metal connection process and settings.

#### 9.1.3 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).

#### 9.1.4 Qualification Requirements

A visual inspection of the finished joint shall be made to confirm complete flow of material into the joint area. The joint shall be free from all cracks under 10x magnification. Qualification shall be documented along with the samples provided to IPP for their examination and concurrence before production of metal connection begins.

## 10 QUALITY ASSURANCE REQUIREMENTS

### 10.1 Inspection, Surveillance, and Audit

Subcontractor shall perform daily inspections and surveillance throughout the manufacturing of the coils as delineated in this specification. Such inspections and surveillances will be documented and available to IPP. IPP reserves the right to designate selected manufacturing, inspection and/or test operations as mandatory Witness or Hold points. Subcontractor shall provide IPP with notice five working days in advance of such points.

In addition, due to the critical nature of these components, authorized representatives of IPP will be on-site on a regular basis to perform general inspection and surveillance. This IPP on-site representative will serve as a liaison to resolve questions, inform IPP of progress, and will have the authority to halt the fabrication process until issues are resolved.

## 10.2 Subcontractor Quality Assurance Program

Subcontractor shall establish and maintain an effective Quality Assurance Program to assure that Subcontractor's work meets the required level of quality and is performed in accordance with contractual requirements. Subcontractor's quality assurance function shall be organized to have sufficient authority and independence to identify quality problems, verify conformance of supplied items or services to specified requirements and obtain satisfactory resolution of conflicts involving quality. IPP will conduct an on-site pre-award assessment of the Subcontractor's Quality Assurance Program and capabilities of meeting the requirements of this specification.

## 10.3 Submittal of Quality Assurance Program Description

Subcontractor shall submit with the proposal, one (1) copy of its Quality Assurance Program Manual, describing Subcontractor's quality capability and general approach to quality assurance. Subcontractor shall also complete and submit at the time of proposal the IPP PQA Supplier Quality Survey, which will be provided separately from this document. The manual and survey shall be subject to IPP's review and acceptance prior to contract award.

## 10.4 Inspection and Test Procedures

Inspections and tests shall be performed in accordance with the MIT plan (section 6.2) with approved (separate or incorporated) procedures referencing criteria for acceptance or rejection. Adequate records shall be maintained and available for IPP reviews.

## 10.5 Document Traceability and Records

Subcontractor 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 will include completed MIT plan (sections 6.2 and 10.7) and relevant data such as materials certifications, material test reports, inspection reports, discrepancy reports, etc. This information shall be complete and legible and validated by responsible personnel and shall be traceable to subject items.

## 10.6 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.

## 10.7 Manufacturing/Inspection/Test (MIT) Plan

The MIT Plan or referenced traveler shall be used as a signoff/approval document noting that critical manufacturing steps have been completed. Authorized personnel associated with the manufacturing, inspection and test processes shall initial and date the MIT Plan/traveler



for this purpose. In addition, the MIT Plan/traveler is to provide witness points as well as references for test results, and measurements.

## 10.8 Witness/Hold Points and Notification of IPP in Advance

IPP reserves the right to designate selected manufacturing, inspection and/or test operations as mandatory Witness or Hold points. Subcontractor shall provide IPP with notice five (5) working days in advance of such points. These default hold points apply, in addition to any others that may be added for this work:

- When welding / brazing qualifications are specified, welding / brazing must not occur until all required welding documentation is submitted and approved by IPP.
- When a Release for Shipment form is specified, shipment must not be made until the shipping release form is signed and returned by IPP.

## 10.9 Non-Conformance & Corrective Actions

Non-conforming items shall be positively identified, and, where possible, segregated to prevent use. Subcontractor shall document each non-conformance. IPP's written approval is required prior to the use of any non-conforming item. Subcontractor's 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.

## 10.10 Configuration Control

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

## 10.11 Calibration of Test and Measuring Equipment

Inspections and tests shall be performed using properly calibrated measuring and test equipment. Calibration standards shall be traceable to the National Institute for Standards and Technology (NIST) or equivalent. Where such standards do not exist, the basis used for calibration shall be documented. Test and measurement equipment identification numbers and last calibration date shall be recorded on corresponding steps of the MIT plan or procedures referenced by the MIT plan.

## 10.12 Performance and Documentation of Inspections and Tests

Each item to be delivered to IPP shall be inspected and tested by Subcontractor to verify that they meet IPP's requirements. Results shall be documented and reported to IPP.

## 10.13 IPP Receiving/Inspection

IPP will perform Receiving Inspection on items or services supplied by Subcontractor, using either a sampling plan or 100% inspection. Discrepant items or services may be rejected and returned to Subcontractor or reworked by IPP.

## 10.14 Process History

Subcontractor shall provide a Process History that includes a compilation of documents (digital preferred, in pdf, Microsoft Word, or Microsoft Excel format), detailing the objective evidence of the acceptability of the work performed. The Process History for each coil shall be provided to IPP with the Shipping Release Request. The Process History shall include as a minimum, but not be limited to the following:

### 10.14.1 Material Certifications

Manufacturer's Certified Material Test Reports (CMTRs) showing relevant chemical, mechanical and electrical properties of materials used, where applicable, shall be submitted to IPP. Certifications for the insulation epoxy, copper material (lead blocks, etc.) braze material, and fillers are required as a minimum. It is recognized that only certificates of grade may be available for materials such as fillers. Certifications shall be provided to IPP when Subcontractor approves the material for use (start of the job).

### 10.14.2 Inspection & Test Reports

The completed MIT form, plus 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 the inspector/tester. Reports shall be reviewed by appropriate Subcontractor personnel prior to submittal to IPP.

### 10.14.3 Non-conformance Reports

Signed copies of any non-conformance reports generated per section 10.10 shall be included in the process history.

### 10.14.4 Shipping Release

Subcontractor shall not ship (full or partial) without a "Product Quality Certification and Shipping Release" Form signed by IPP's Representative. Subcontractor shall complete and sign the certification section, deliver the form to IPP Representative, and hold the shipment until the form is signed and returned. A copy of the fully executed form shall accompany each full or partial shipment.

## 10.15 Changes to IPP Approved Documents

Revisions or changes by Subcontractor to documents approved by IPP shall be reviewed and approved by IPP prior to use.

## 10.16 Subcontractor's Responsibility for Conformance and Flowdown of Requirements to Subtier Suppliers

IPP's review and/or approval of Subcontractor's documents nor IPP's inspection of Subcontractor's items or services shall not relieve Subcontractor of responsibility for full compliance with requirements of the purchase order/contract. Subcontractor is responsible for assuring that all requirements and restrictions are imposed on any subtier suppliers.

# 11 SHIPPING STORAGE AND HANDLING

## 11.1 Preparation of cooling passages

Coolant passages will be sealed for storage and subsequent shipment.

## 11.2 Coil identifier

Each coil shall be affixed with a name tag that provides, as a minimum the coil identifier, Subcontractor serial number, date when the coil was completed, and coil weight in kilograms.

## 11.3 Packing and crating

Subcontractor is responsible for shipment to the IPP site. Each coil shall be prepared for shipment in such a manner as to ensure its acceptance by a common carrier and to afford its protection from normal hazards of transportation.

Packing and shipping details shall be submitted by Subcontractor for review and approval by IPP. Each coil shall be wrapped in a minimum 0.127 mm thick polyethylene and crated for shipment. The crate shall be wooden and built for handling with slings from overhead cranes and forklifts. The crate shall protect the coil from shock, damage from load shift, and weather conditions, including precipitation. Shock sensors shall be added to the shipping crate. Characteristics of the shock sensors shall be provided with the packing and shipping details. Special care shall be taken to ensure that the lead area is adequately protected. Subcontractor's name, customer's name, purchase order number, coil identifier, and gross weight shall be marked on the shipping container. Photographs of the packed and crated items shall be submitted to IPP prior to request for shipment.

# 12 DELIVERABLES

## 12.1 Document deliverables

All documents shall be provided in digital (.pdf) format.

Deliverable item	when required	Specification reference
QA Plan	Prior to any manufacturing, inspection, or test activities specific to the scope of supply of this specification, including its further revisions.	6.1
Manufacturing and tooling drawings	Prior to use.	3.2, 5.1.5
List of subcontractor-supplied materials	Prior to procurement of materials and whenever their list is revised.	5.1
Certified Material Test Reports for coil terminal blocks	Prior to any manufacturing, inspection, or test activities specific to the scope of supply of this specification	5.1.6
Certified Material Test Reports for coil lead and transition fillers		5.1.8
Design of VPI mold and sealing features	Prior to use.	5.1.12
Procedures identified in the MIT	Prior to any manufacturing, inspection, or test activities specific to the scope of supply of this specification	6.2
Manufacturing/Inspection/Test (MIT) plan, template	After receipt of order, for IPP approval prior to the start of manufacture.	7.1.5
Protective measures in clean area during operation that could produce chips and filings	prior to work.	7.3.3
Non-conformance reports	Immediately following detection.	7.3.3

Non-conformance on dimensions	Immediately following detection.	7.3.3
Procedure for repair of damaged insulation	Prior to use.	7.4
Impedance test procedure	Prior to use.	7.5.2
Resistance test procedure	Prior to use.	7.5.3
Pre-VPI electrical test results	Immediately following testing.	7.5, 8.1.1
Raze procedure	Prior to use.	9.1.1
Dimensional Inspection of completed coil	Prior to submittal of IPP Shipping Release Form.	8.1.2
Manufacturing/Inspection/Test plan, filled out and signed off, per coil	After completion of all manufacturing, inspection, or test activities specific to the scope of supply of this specification	6.2
Photographs of packed and crated items	Prior to submittal of IPP Shipping Release Form	11.3

## 12.2 Physical deliverables

Deliverable item	When Required	Specification reference
EF coils	After completion, testing and preparation for shipment and approval of IPP Shipping Release	3.3
CS coils	After completion, testing and preparation for shipment and approval of IPP Shipping Release	3.3
VS coils	After completion, testing and preparation for shipment and approval of IPP Shipping Release	3.3
Process history and IPP Shipping Release Form	Prior to shipment of each coil	10.15

## ANNEX 1 - Connection of the coolant feeds to the coil

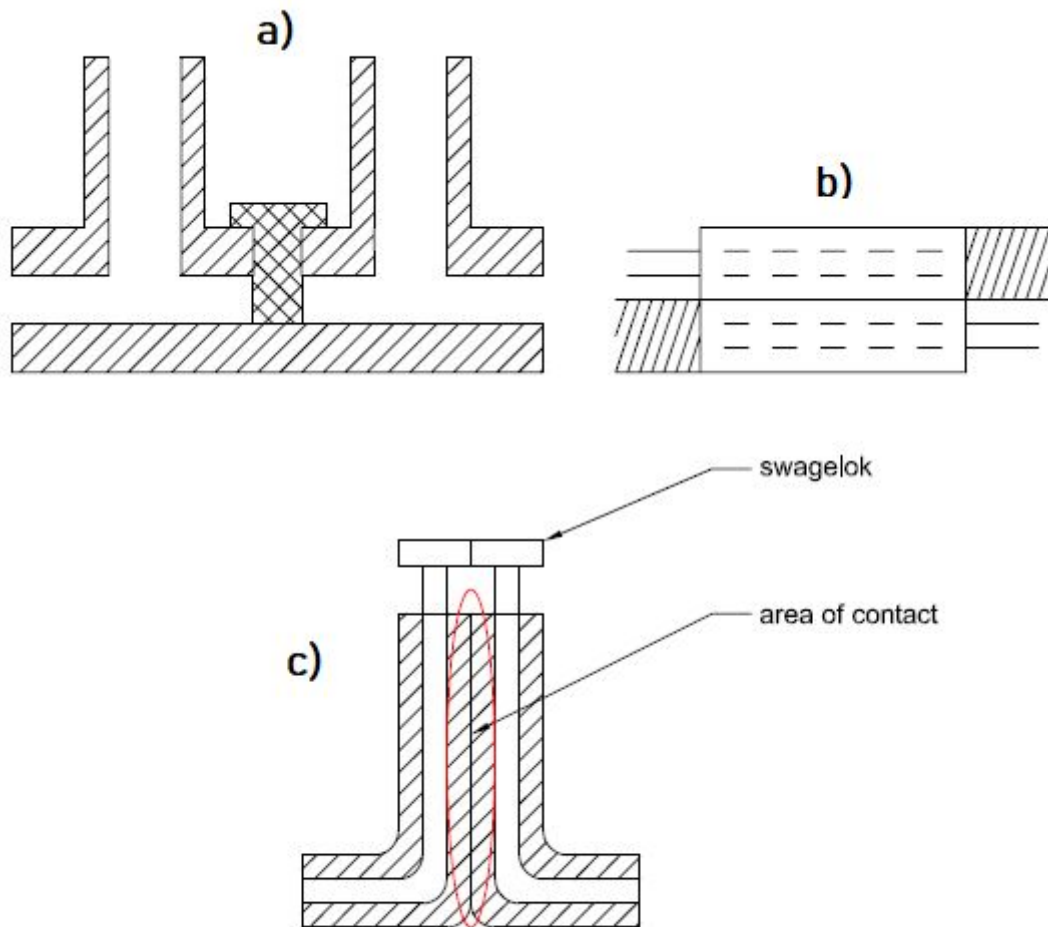


Figure 1: Three proposed design options for connection of the cooling channels to the coil conductor

### Description:

#### option a)

Three holes are drilled to the hollow conductor. The first is used for inlet/outlet of cooling medium, plug is inserted to the second to divide the cooling circuits and the third is again used for inlet/outlet of the cooling medium. Electron beam welding (or another connection method) is then used to connect pipes (Fig.3) from commercially available copper-stainless steel swageloks (Fig. 2).

#### options b) and c)

Instead of layer to layer coil winding transition, the conductor is terminated after the top of the second layer. Conductor can be terminated radially or vertically so that it is possible to connect the cooling channels directly (modified version of bi-metal swagelok). The next coil

layer is electrically connected to the terminated layer through electron beam welding or a dismantable connection.

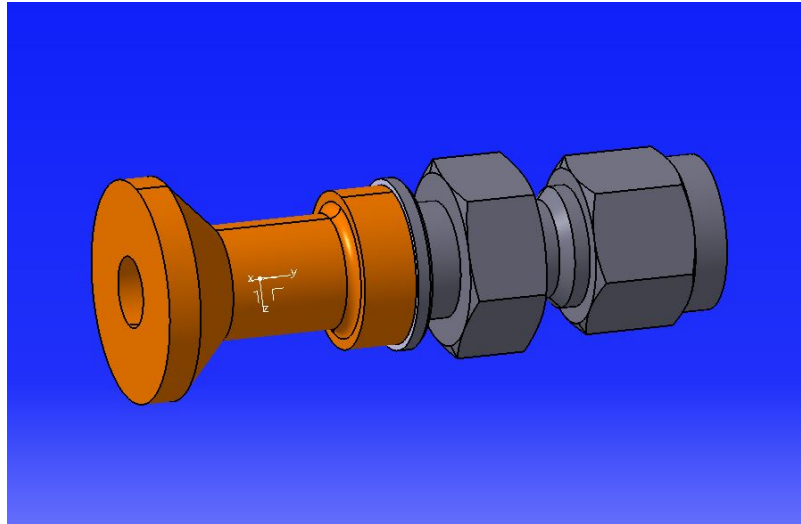


Figure 2: Model of a welded bi-metal swagelok for connection of the stainless steel cooling tubes to the conductor.

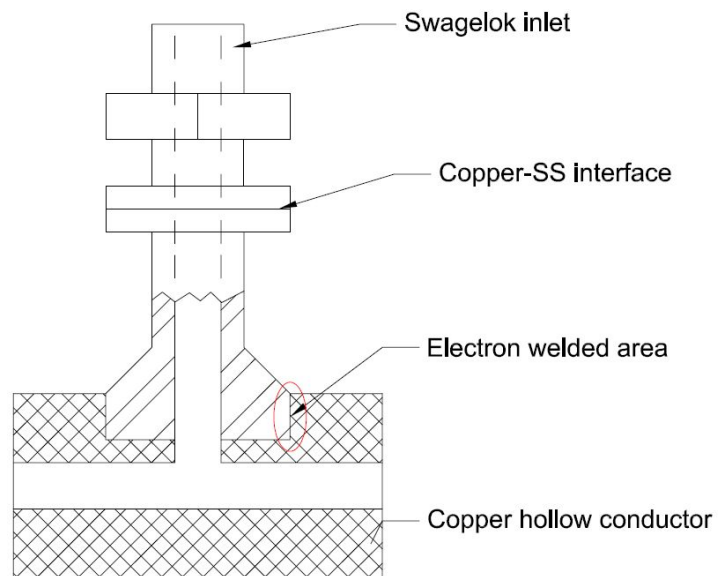


Figure 3: Scheme of the swagelok connection to the copper conductor.

## ANNEX 2 - multiple feeds

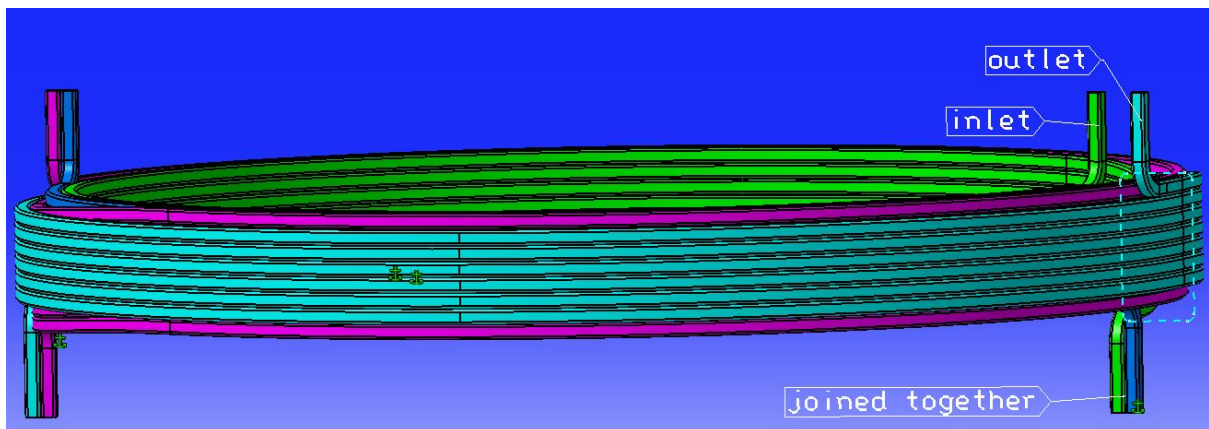


Figure 4: Model illustrating PF coil made of co-wound separate coils with their own inlets  
**note: this model serves only to illustrate the concept**

The coil is divided to “individual coils” which can be wound separately and then put together or co-wound as “standard coil” on one mandrel.

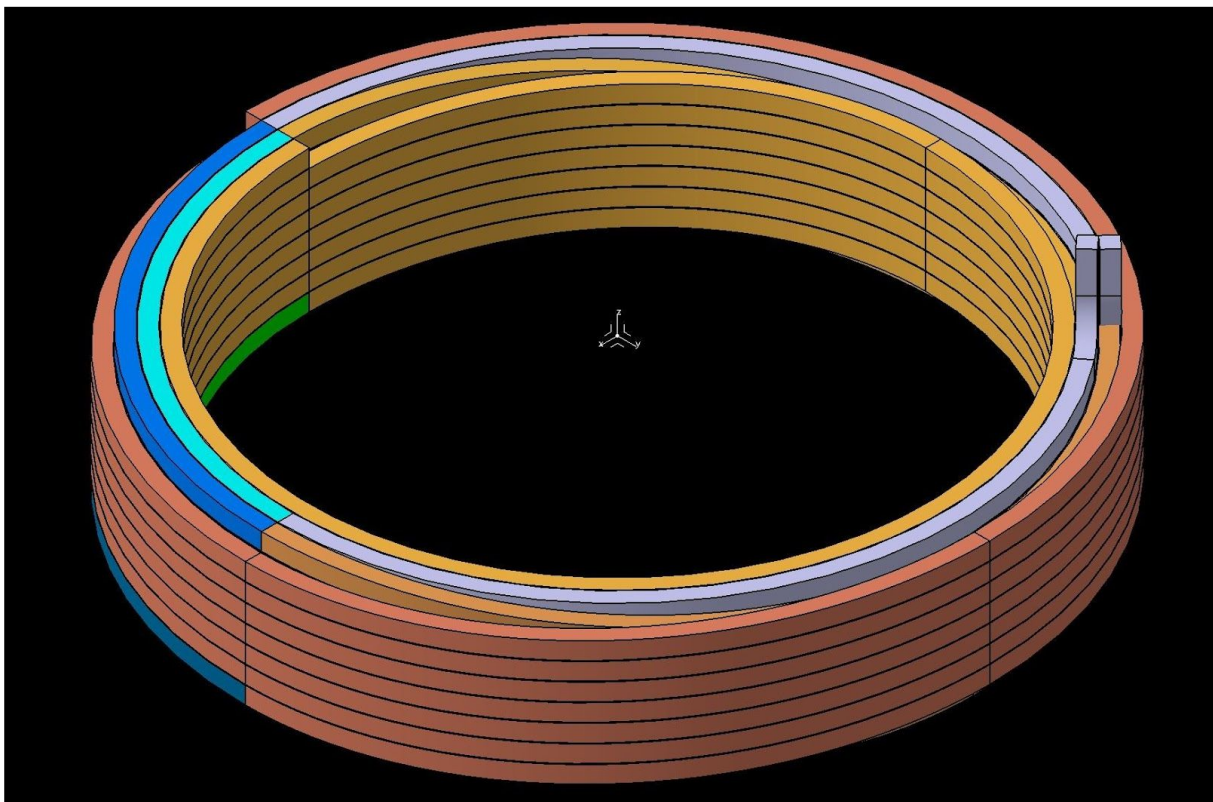


Figure 5 : Model illustrating electrical connection of two co-wound separate coils (permanent connection of parallel cyan and dark blue conductor parts)



## Questions

1. Keystoning effect: IPP will perform bending tests to assess keystoning effect for the central solenoid coils (smallest diameter ~0.8 m, conductor 22 x 25 mm). From your experience, do you think it is necessary to take the effect in account for larger PF coils?
2. Is it necessary to use hollow conductor (as for the final coil) for keystoning tests to correctly assess the effect, or full conductor is sufficient?
3. Is it possible to manufacture a coil with "interrupted conductor" as mentioned in Section 3.3.2.2?
4. What is your recommendation of the weave pattern of fiberglass tape? Satin weave recommended in this document for S2 glass fiber tape is not common for standard manufacturers. Could a plain weave (or other standardly made weave) tape be used? The biggest importance is the (shear, tensile) strength of the insulation system.
5. Do you have the capabilities to perform all mentioned tests?
6. Can you perform Paschen test of the prototype coil?
7. Can you perform a cryogenic test of the prototype coil - the coil will be cooled down to 80 K and loaded with the working current waveform (50 kA, 3 s)?
8. Can you propose a fatigue test for the prototype coil to simulate real working conditions (cryogenic temperature, electromagnetic-thermal stresses, 50000 cycles) and especially how it affects insulation (shear and tensile strength)?  
Or would it be better to perform the insulation strength tests for smaller mockups with a simple geometry (lap shear test, tensile test) to evaluate the insulation system?

## Rough price estimation

Please let us know if the information provided in this document and other documents and attached models published on IPP website:

[http://www.ipp.cas.cz/o-ufp/Verejne\\_zakazky/doc.html](http://www.ipp.cas.cz/o-ufp/Verejne_zakazky/doc.html)

are sufficient for a rough price estimate of the manufacture of COMPASS-U PF coils. If not, please let us know what additional materials are needed.

IPP would like to know:

1. Preliminary cost of all PF coils (including the prototype coil) based on the solutions suggested by IPP (designs, connections, material choice for insulation). EF coils shall be wound from one uninterrupted conductor (see Section 3.3.2.1).
2. Preliminary cost of all PF coils (including the prototype coil) based on manufacturer's suggested solution (designs, connections, material choice for insulation). EF coils shall be wound from one uninterrupted conductor (see Section 3.3.2.1).