IDM UID
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VERSION CREATED ON / VERSION / STATUS
23 Jun 2022 / 1.0 / Revision Required

EXTERNAL REFERENCE / VERSION

Technical Specification

Earthing and bonding design proposal for the IVC busbars system PBS41

The goal of this document is to present the earthing and bonding design proposal for the IVC busbars system. The solution proposed is based on the design requirement of the future IVC power converters and the existing Tokamak building complex.
Indeed, the IVC busbar system is already designed and the installation, inside the Tokamak complex is ongoing. The IVC power supplies will be designed, procured, and installed, in several years according to the "ITER staged baseline". The IVC power converters are composed of 27 ELM converters and one VS3 converter. The equipotential bonding network shall connect the exposed-conductive parts together of the IVC busbar system to the meshed earthing network of the Tokamak complex.

Approval Process			
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Approver	**Benfatto I.**	**17 Oct 2022:requested revision**	**IO/DG/CNST/PLD/EID**
Document Security: Internal Use *RO: Bovet Clément*			
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1 Purpose

The goal of this document is to present the earthing and bonding design proposal for the IVC busbars system. The solution proposed is based on the design requirement of the future IVC power converters and the existing Tokamak building complex.

Indeed, the IVC busbar system is already designed and the installation, inside the Tokamak complex is ongoing. The IVC power supplies will be designed, procured, and installed, in several years according to the “ITER staged baseline”. The IVC power converters are composed of 27 ELM converters and one VS3 converter. The equipotential bonding network shall connect the exposed-conductive parts together of the IVC busbar system to the meshed earthing network of the Tokamak complex.

The following standard are considered:

- NFC 13-200,
- NFC 15-100,
- IEC 61800-5-1,
- IEC 60034-1,
- IEC 62305-3
- NF C18-510.

The main DC output ratings of equipment are the following:

ELM converter	15 kA RMS – 250 Vdc
VS3 converter	120 kA peak – 4 kA RMS – 2400 Vdc
IVC busbars	15 kA RMS – 120 kA during 100 ms ELM insulation voltage withstand test (3.4 kV AC) @ 50 Hz for 60 s • DC voltage test reduced 3.85 kV dc for 60 s VS3 insulation voltage withstand test (6.4 kV AC) @ 50 Hz for 60 s • DC voltage test reduced 7.24 kV dc for 60 s
IVC coils	Copper conductor surrounded by a magnesium oxide (MgO) insulation layer compacted into a stainless steel jacket. SSMIC (stainless steel mineral-insulated cable)

Table 1 : Fixed key design system parameters

2 IVC busbar system description

The IVC busbar system consists of the following parts: busbar segment, flexible and rigid connection, supports and cooling water collectors (CWC). In addition, suitable instrumentation and monitoring is provided in the system.

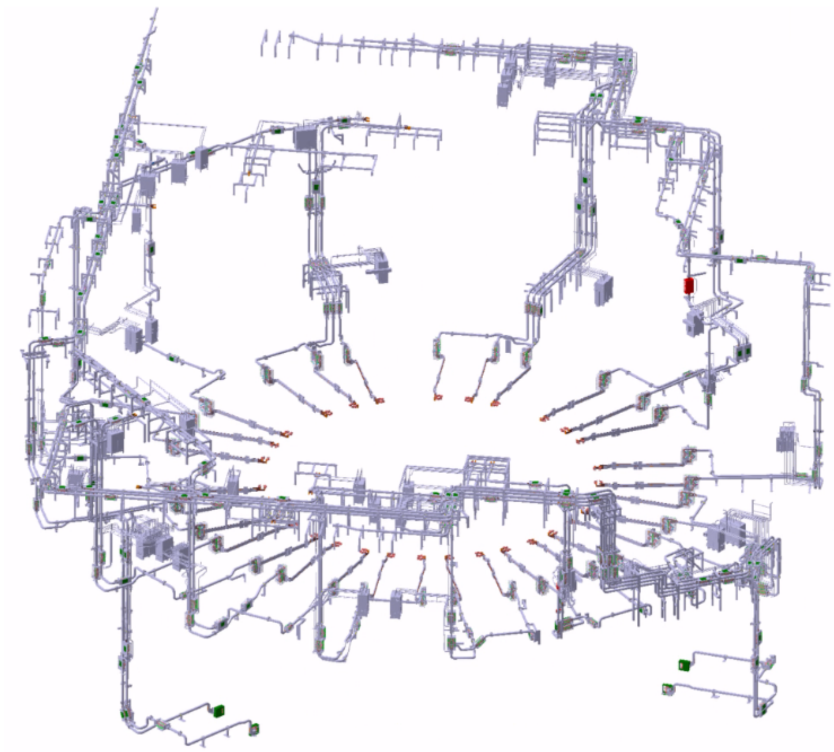


Figure 1: IVC busbars system overview: ELM + VS3 circuits→ 2.5 km of busbars

The busbar conductor is made of extruded copper with cooling channels. Figures 2 and 3 show the ELM busbar and VS3 busbar types. Busbar segments consist of four conductors, an insulation system, and a steel case.

The insulation system includes wrapping of Glass tape and Polyimide film VPI impregnated by a qualified epoxy resin system. Insulation wrapping is done in the order of single conductor, pole assembly, and busbar segment. The conductor was wrapped alternately between Glass tape and Polyimide film.

The case is applied 2.5 mm thickness of stainless S 316L to withstand strong internal electromagnetic force (120 kA peak during pulsed operation) and to provide mechanical protection for the insulation and strength of the busbar.

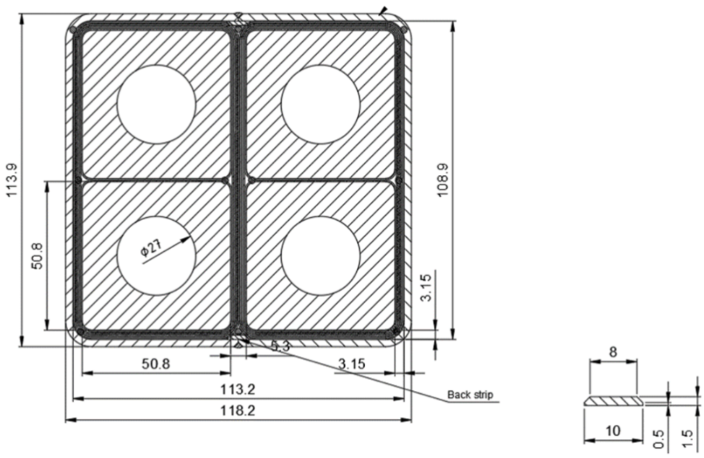


Figure 2 : ELM busbar cross section

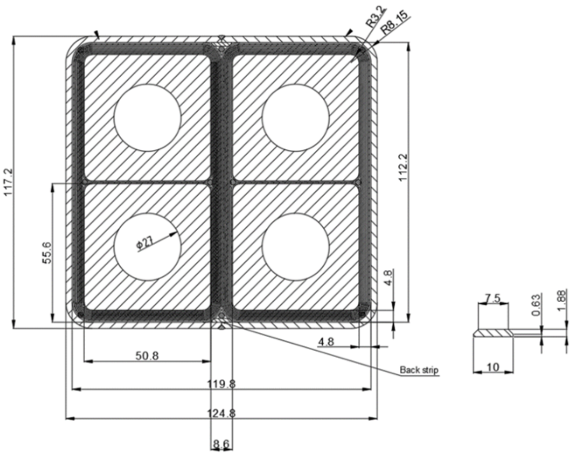


Figure 3 : VS3 busbar cross section

Both IVC busbar types consist of four conductors and two conductors are one pole. The cross-sectional area of one conductor is 2000 mm^2 and the one pole is 4000 mm^2 as shown Figures 2, 3 and the current density is 3.75A / mm^2.

3 IVC coils system description

The IVC cable which is used to build ELM and VS coil is a hollow copper conductor surrounded by a magnesium oxide (MgO) insulation layer compacted into a stainless steel jacket, also called SSMIC (Stainless Steel Mineral-Insulated Cable). The cable is designed for withstanding the maximum operating voltage which is provided by the VS3 circuit, ± 2.4 kV DC. The same conductor is used for ELM and VS coils.

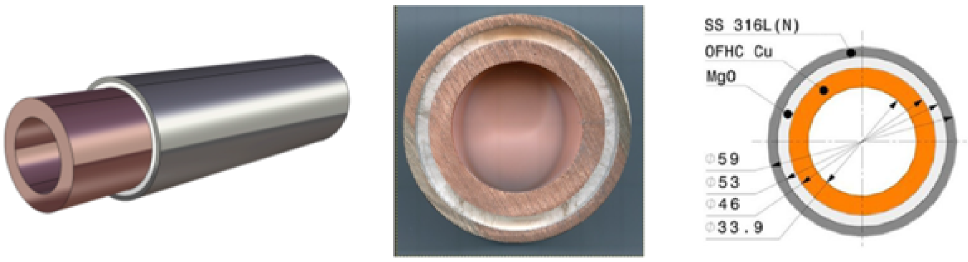


Figure 4 : IVC coil conductor cross-section

The in-vessel coils (IVCs) consist of one set of coils to mitigate the effect of Edge Localized Modes (ELMs) and another set to provide plasma Vertical Stabilization (VS). The ELM coils consist of 27 rectangular coils arranged in 9 toroidal sectors with 3 coils each. The VS coils consist of 2 solenoidal coils connected in anti-series (saddle connection).

The in-vessel components which comprise the IVCs consist of the coils and their associated feeders which carry current and coolant. The coils and feeders are located behind the Blanket Shield Module (BSM). The feeders for all of the ELM coils and for the upper VS coils are routed through the upper ports (#12, #14, #16, and #18). The feeders for the lower VS coils are routed through two separate lower dedicated ports (#12 and #18). The feeders include ex-vessel terminations, which interface with the IVC busbars and with the cooling water supply / return lines at ground potential.

As shown in Figure 5 the VS and ELM coils and their feeders fit within the space envelope defined by the Vacuum Vessel (VV) and BSM. The IVC busbars are connected to the magnet feedthrough.

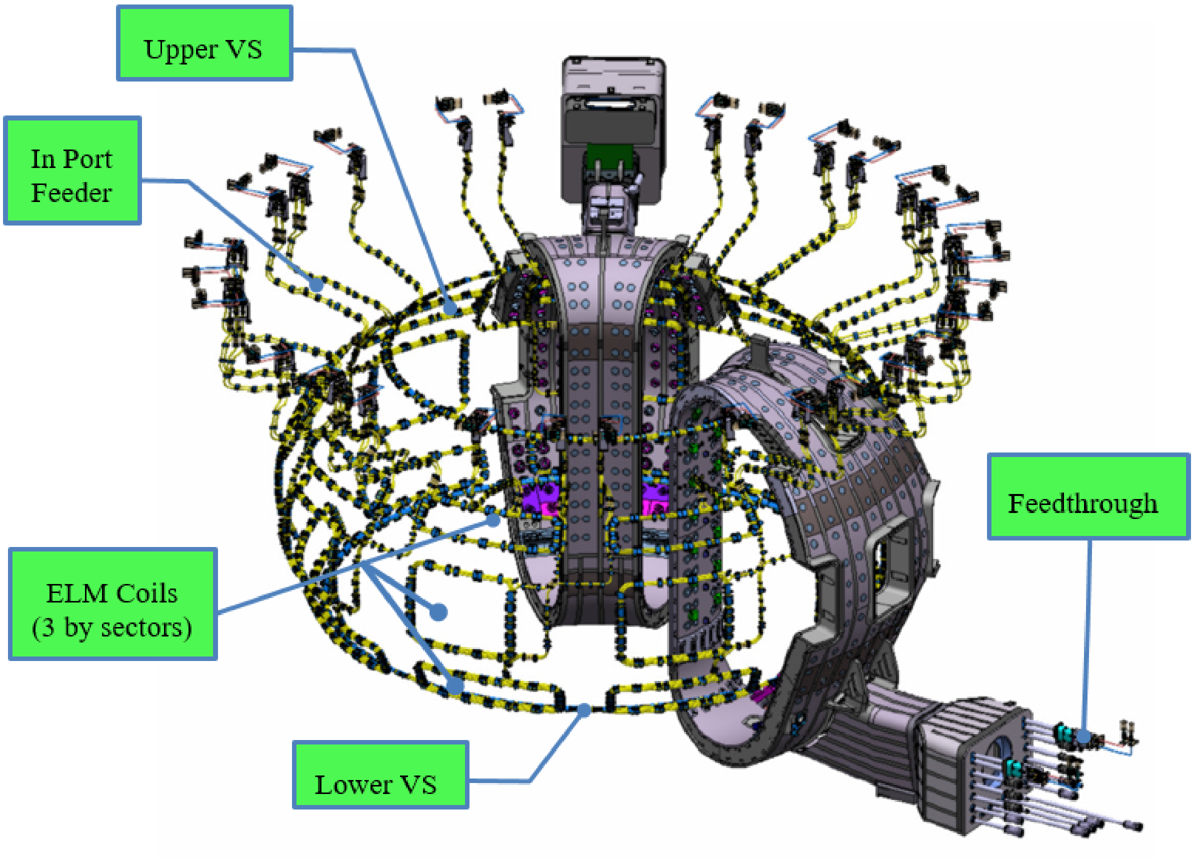


Figure 5 : Overview of the IVC turns and feeders

One IVC busbar feeds one ELM coil composed of one turn.

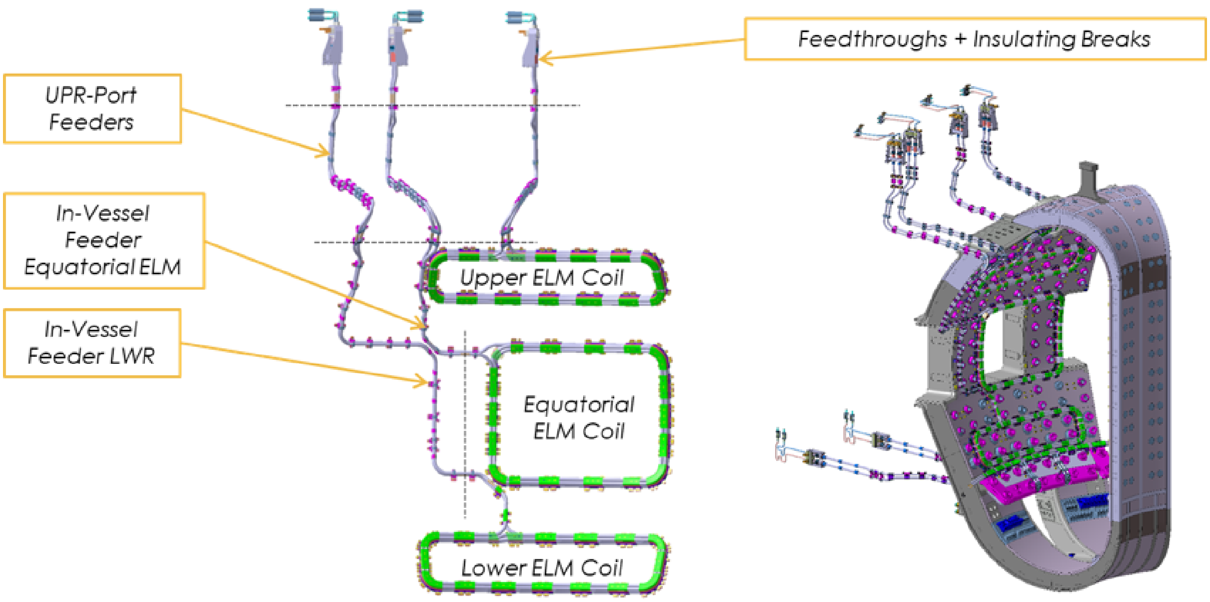


Figure 6 : 3x ELM per sector

Concerning VS coils, they are composed of four upper turns and four lower turns connected electrically in anti-serie and mechanically inside the VS3 Linkboard equipment in the B11- L4 building. From the Linkboard, height IVC busbars are connected to each turn.

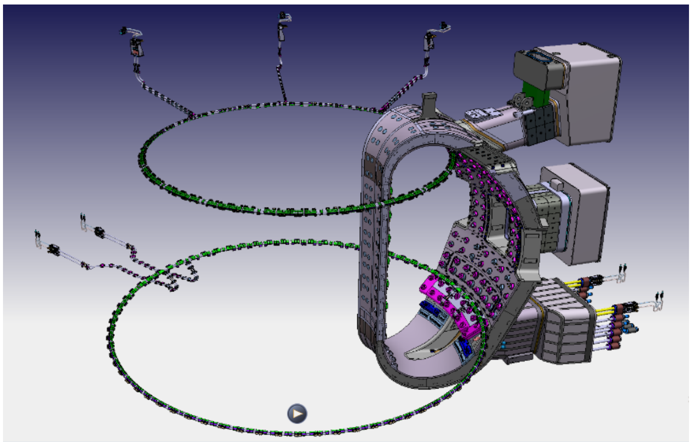


Figure 7 : VS coils powered by VS3 converter

4 IVC power system description

The IVC power system is composed of AC/DC-DC/DC power converters connected to the AC 22 kV network feeding respectively ELM coils and VS coils. These converters power a total of 27 ELM coils and 2 VS coils installed in the In-Vessel.

The DC link, the output, and the coil of these converters are kept floating regarding the ITER site earth grid.

Floating the power supplies with respect to ground insures that a single ground fault will not result in any damage to the IVC busbars and coils.

From the DC output of the rectifier power stage (AC/DC), up to the coil, the system is considered an IT system connect to the earth by a high impedance. The IVC busbar case is considered as a screen by the analogy of HV cable sizing under the NFC 13-200.

A high resistance-grounding network is provided (R1), in each circuit, along with a ground detection scheme. This system including the protection relay acting directly on the 22 kV circuit breaker is called: “Ground fault protection system”. The Detection system is passive. It is composed of a voltage divider connected between positive polarity, negative polarity, and the earth. Voltages and current are measured as represented in the following conceptual schematic.

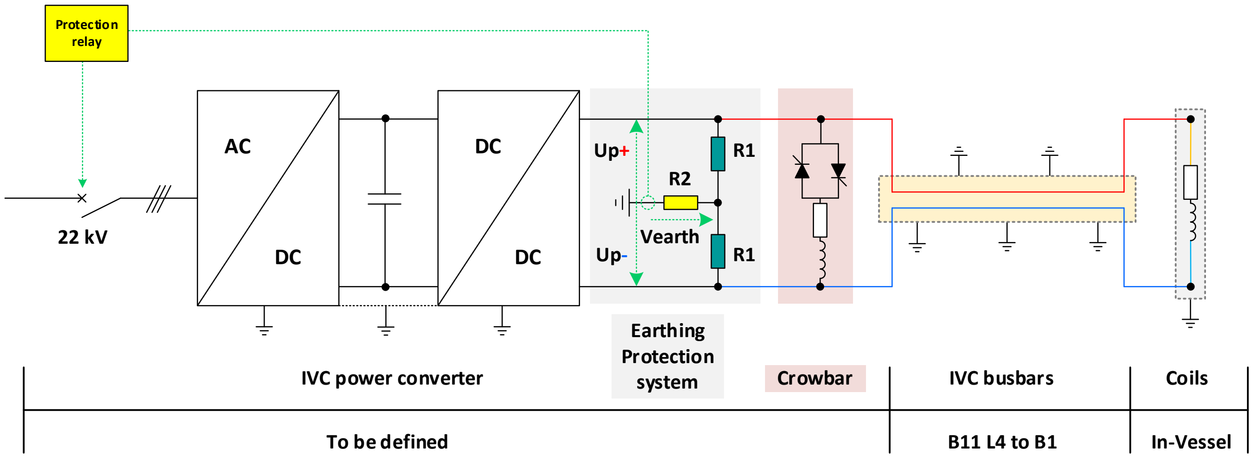


Figure 8 : Simplified* schematic of the IVC power conversion system

Remark*: Mandatory earthing switches for operation & maintenance activity according, NF C18-510, NFC 13-200 and IEC 61800-5-1 are not represented.

5 DC coils protection coordination

In addition, each power converter is equipped with an active thyristor crowbar system. The system is based on a power resistor connected to two thyristors, which are triggered when there is a faulty condition on the converter. Power Converter is part of magnet protection scheme, even if not directly fully responsible for the monitoring and diagnostic of the magnet status. Power Converter is then expected to:

- Always ensure that the external protection system can stop the Power Converter through an external signal called Fast Abort Interlock.
- Stop powering the load in a safe way (handling the magnet energy even when stopping, through the dedicated system called Crowbar). This active system provides a safe resistive discharge path for magnet current (energy).
- Monitor Earth current of the total circuit: IVC busbars + load turns (SSMIC), and take the right action if the threshold is reached.

6 Ground fault detection

The ground fault detection is realized by measuring the ground current or Vearth (Voltage measurement across R2) and sensitivity are set by the selection of grounding resistors R1, R2, and the expected permanent low leakage current threshold. To understand the concept of ground fault detection, the simplified diagram shows the voltage distribution in normal operation and fault conditions.

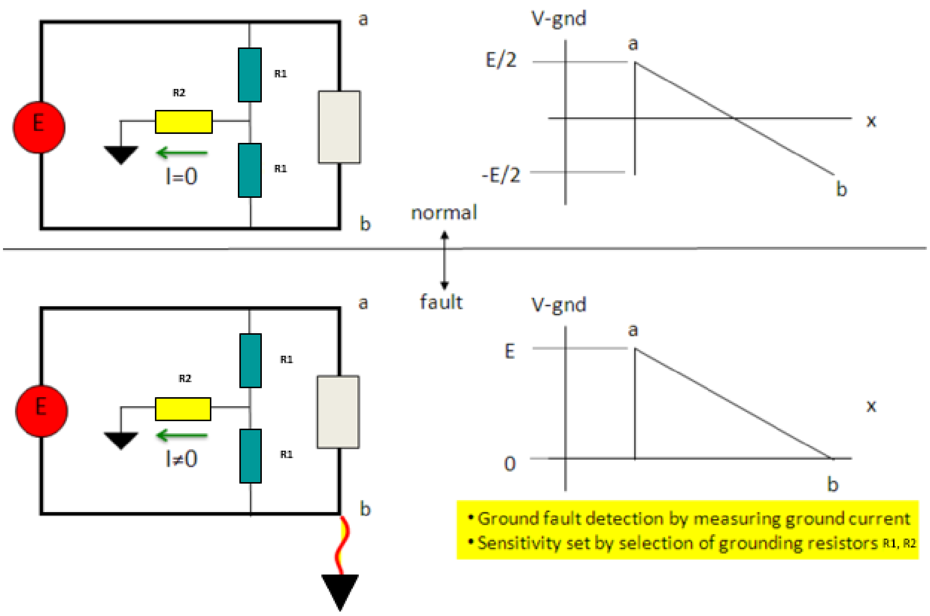


Figure 9: Concept of the ground fault detection system

The ground fault detection is challenging because temperature distribution and radiation flux are not uniform along with each turn and IVC busbar segments.

In addition, these asymmetric distributions of temperature and radiation flux in the Vacuum Vessel are spatial and temporal.

From an electrical point of view, each turn impedance would vary spatially and temporally. Hence, in some circuits, the stray capacitances of the IVC busbar and coils are not balanced which will result in more instantaneous ground current during pulsing and low permanent earthing leakage current flowing through the MGO insulation and the water-cooling channel.

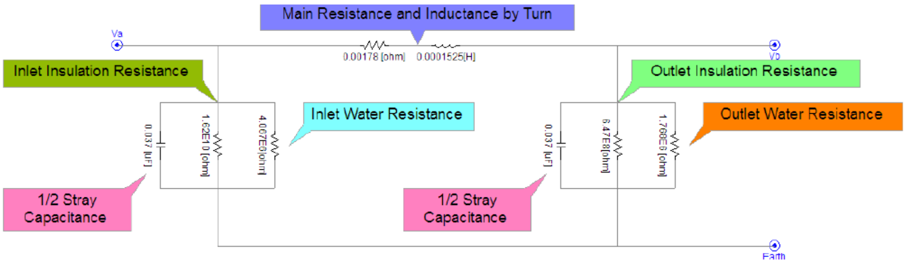


Figure 10 : Exemple of PI electrical model of turn

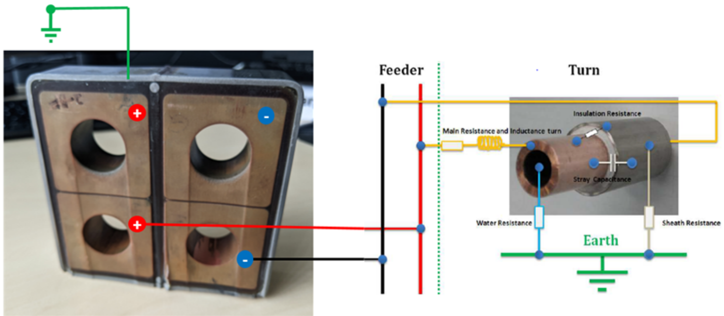


Figure 11 : Electrical parameters naming

Resistors' values are such that no more than 800 mA of current can flow through the circuit in case of a bolted ground fault.

Inverse time over-current relay 51G is a standard DC electromagnetic relay is the recommended solution and has been functioning very reliably for many years in high power systems similar to VS3 and ELM converters.

Typically, the relay is set to trip at 0.8x 800 mA of maximal ground current. In addition, an alarm threshold can be set also to a PLC system to generate an audible and visual alarm in the control room, immediately warning workers of a ground occurrence.

The following is representing fault current sensitivity versus the fault location of the VS3 circuit versus several insulation fault impedances.

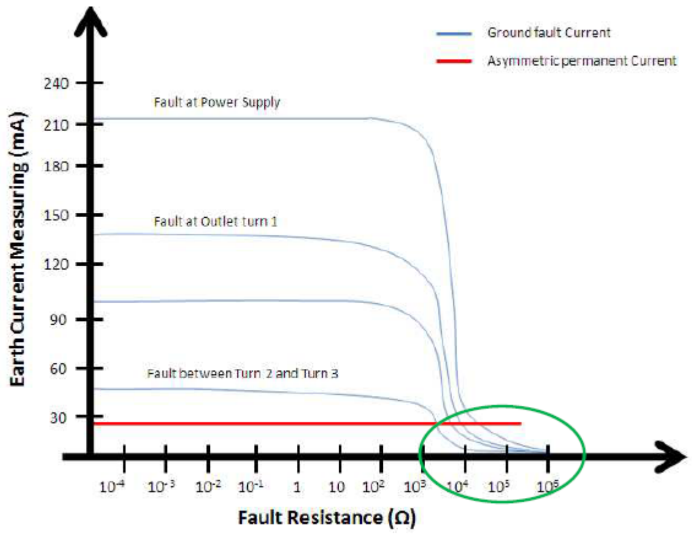


Figure 12 : Fault detection sensitivity

Inside the green circle area, discriminating a ground fault current versus the permanent and variable asymmetric permanent current is difficult due to the high fault impedance considered.

7 Earthing & Bonding design proposal

The exposed-conductive parts of the IVC busbar system shall be interconnected together or in groups and linked to the different fixed earth electrode terminals available on the Tokamak building complex. The connection shall be as many of the fixed bonding terminals in the concrete walls and floors on all sides of its technical area as is possible.

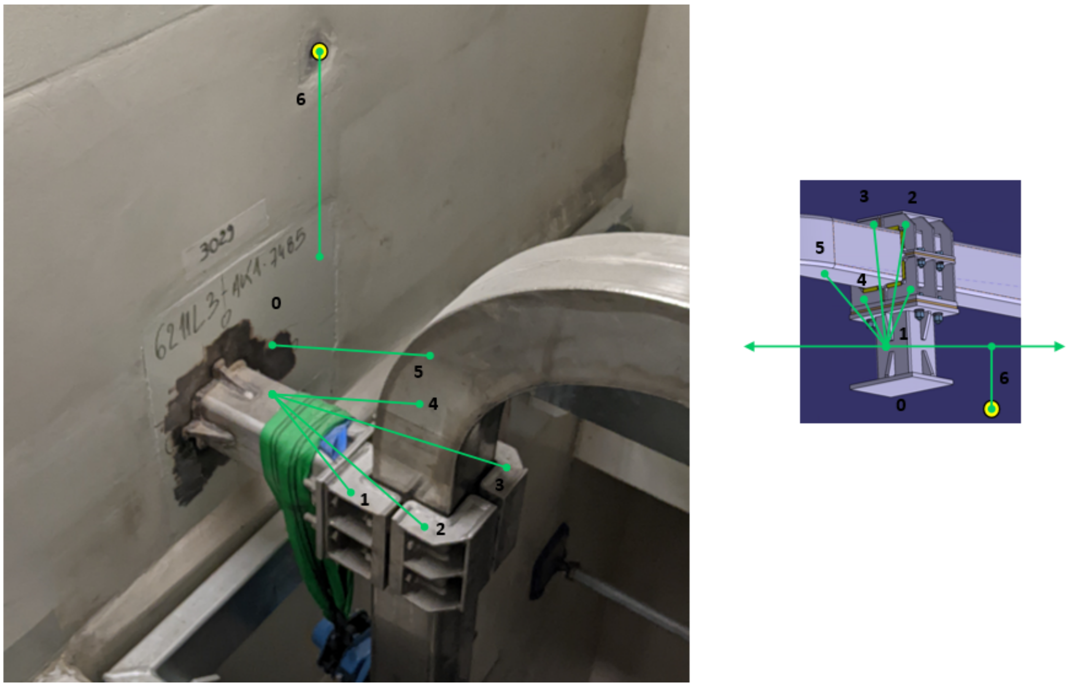


Figure 13 : Minimal bonding connections

The four clamps (1, 2, 3, and 4), the case (5), the embedded plate (0), and the fixed earth electrode terminal (6) shall be connected together by a braid copper conductor of 25 mm2 or 35 mm2 with aluminum (minimal values according to the NFC 13-200). In addition, a connection between each support is recommended as illustrated below.

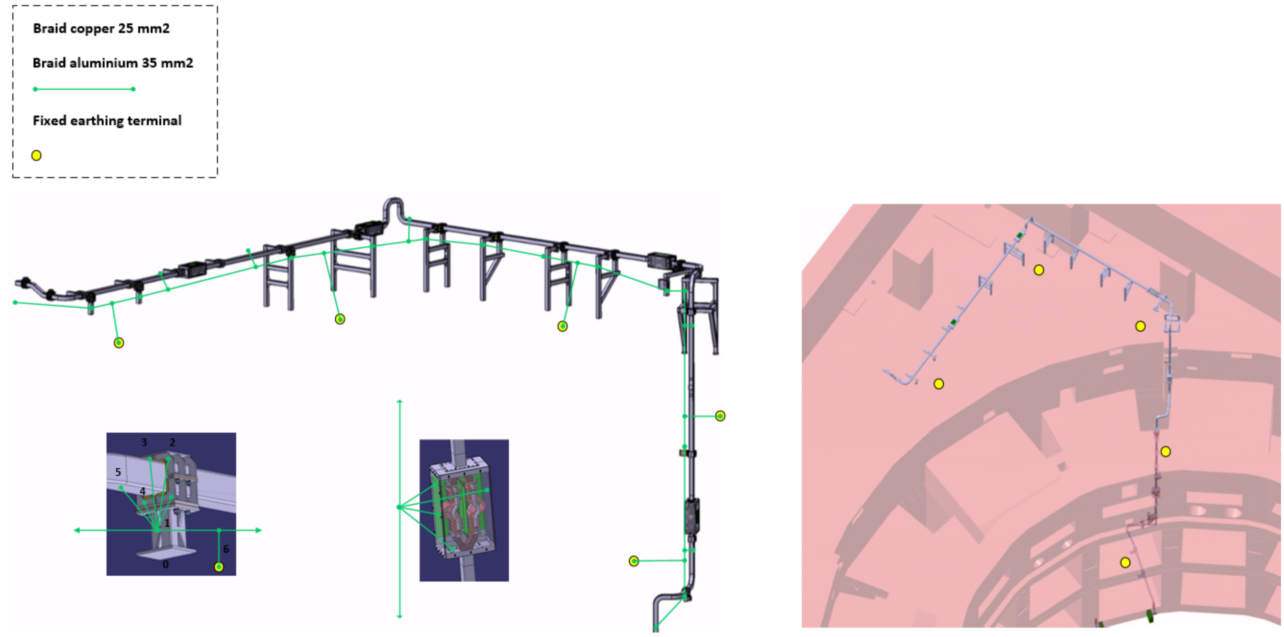


Figure 14 : Equipotential bonding network from the DC output side up the coil feedthrough

In addition, the four metallic panels (Inox 316L, thickness=2.5 mm) closing the connection box shall be bonded with the cable between two supports or with the case as illustrated below:

Figure 15 : Bonding for the connection box between two busbar segments

8 Earthing & lightning network of the Tokamak complex

The earthing and lightning protection of the tokamak complex is ensured by a wire mesh of the building and the continuity of this mesh the has been sized and measured during the construction phase. The IVC busbar system is installed under the 1x1 m mech 5x5 earth connection area from L4 to B1 level.

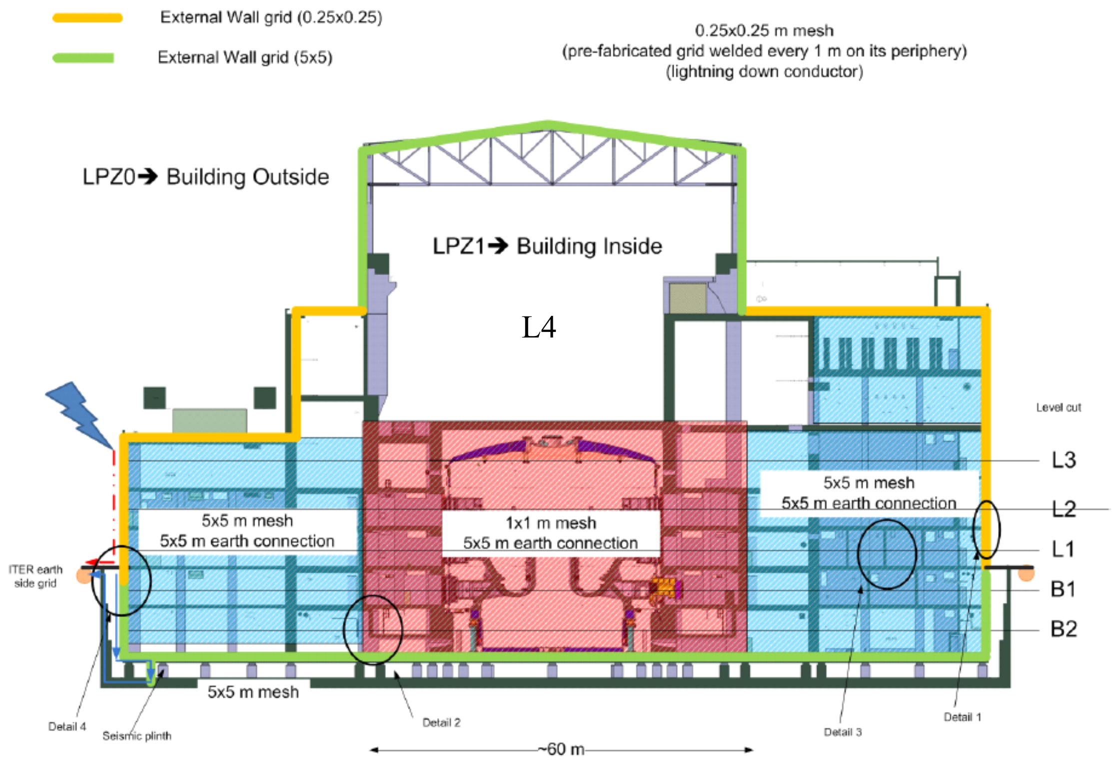


Figure 16 : Tokamak meshed area

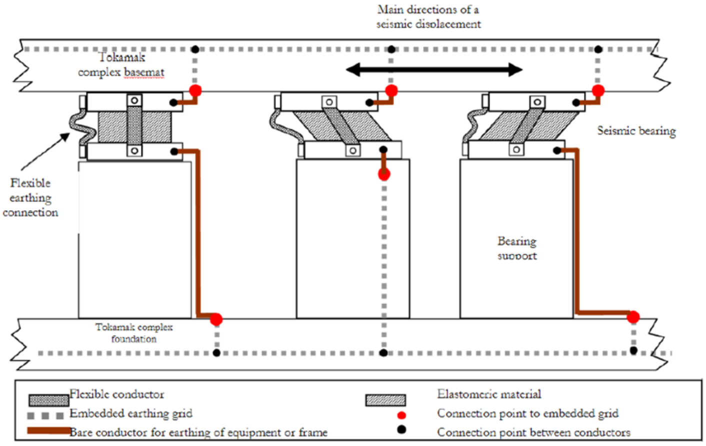
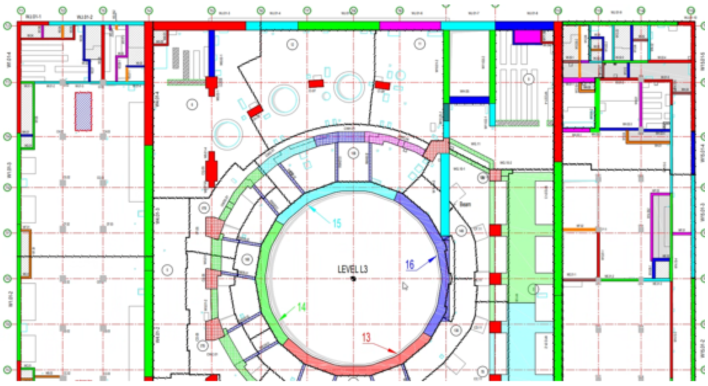


Figure 17 : Earthing of Tokamak Basemat with Flexible Interconnections

The electrical continuity criteria of the interconnected steel reinforcement are below or equal to 10 mΩ. Connection with clamps between rebars is used and connection between the mesh of the building is used. Quality assurance construction phase reports show values below two mΩ. The overall electrical resistance should not be greater than 200 mΩ to be compliant with the IEC 62305-3 (Construction requirement of the Tokamak complex).



Earthing and lightning control sheet:
Electric continuity control

Work Procedure: *VFR-CI-PZ-110057-EL*
BUILDING : 11 LEVEL : L3
Plot/Room N° W4.01-4
Earthing and Lighting drawing: 118669

Ohmmeter # : 001
Control Before Pouring ☑
Control After Pouring ☐

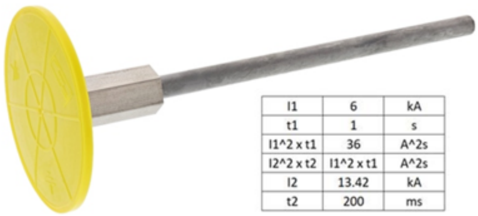
Assembly number		Value (mΩ)	C / NC Compliant if ≤ 10 mΩ	Assembly number		Value (mΩ)	C / NC Compliant if ≤ 10 mΩ
BS182	F674	1.1	C				
BS182	F675	1.1	C				
BS182	F676	1-0	C				
BS182	F677	1.0	C				
BS182	F678	1.2	C				
BS182	F679	1.3	C				
BS182	F680	1-3	C				
BS182	F681	1-1	C				
BS182	F682	1.2	C				
BS182	F683	1.8	C				
BS182	F684	0.9	C				
BS180	F685	1.0	C				
BS180	F686	0.9					
BS180	F639	1.1	C				
BS180	F640	1.4	C				
BS180	F641	1.0	C				
BS180	F642	1.0	C				
BS180	F643	0.9	C				

Figure 18 : Measurement results Exemple

<u>Remark:</u> This measurement come from the document: *VFR-CI-IR-111203-CW for* TB03 - BUILDING 11 - LEVEL L3 INSPECTION REPORT OF CONCRETE WORKS: W4.01-4 - WA.01-4 (1ST PART) - WJ.01-7 (1ST PART) - WA.01-5 - W12.01-3.

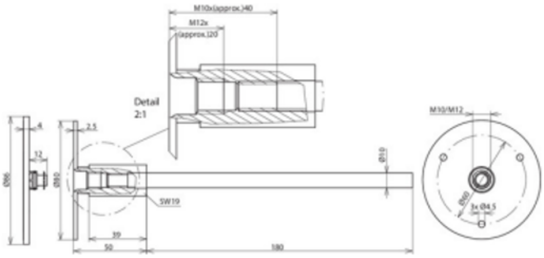
9 Fixed earthing terminal & embedded plate implementation

The fixed earth terminal (from DEHN manufacturer) is clamped to the rebar and the meshed network is composed of braid copper cable of at least 25 mm^2 clamped also to the reinforced rebar.



I1	6	kA
t1	1	s
I1^2 x t1	36	A^2s
I2^2 x t2	I1^2 x t1	A^2s
I2	13.42	kA
t2	200	ms

EFPM M10 12 V4A L230 STTZN (478 011)

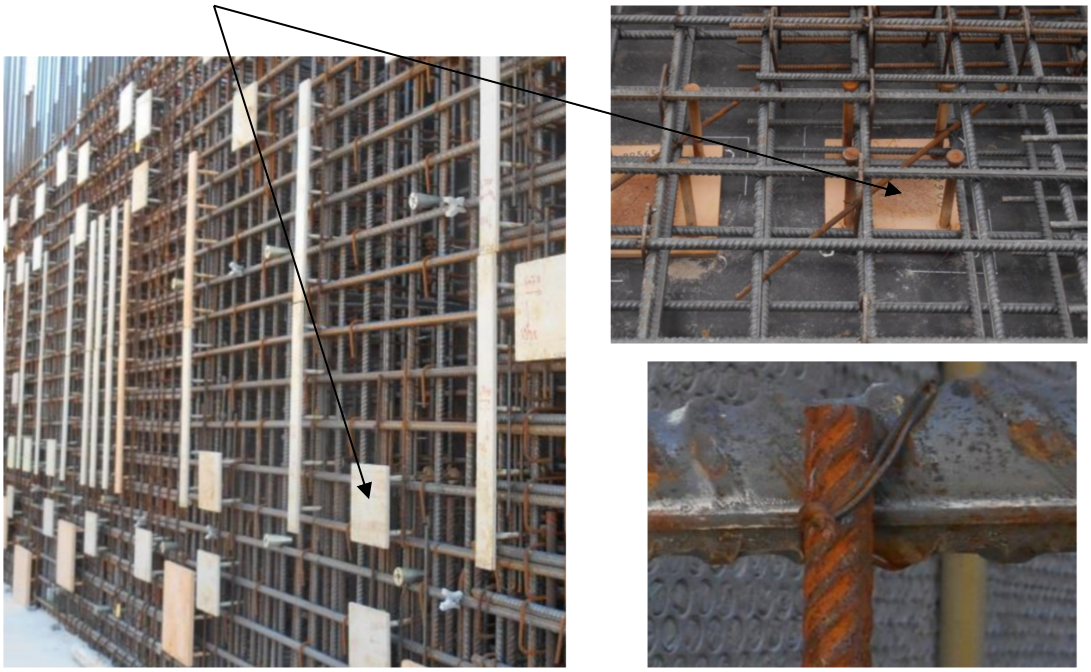


Type Part No.	EFPM M10 12 V4A L230 STTZN 478 011
Connection thread	M10 / M12
Material of plate	StSt (V4A)
Material No.	1.4571 / 1.4404 / 1.4401
ASTM / AISI:	316Ti / 316L / 316
Material of shaft	St/tZn
Connection plate Ø	80 mm
Dimensions of connecting shaft (Ø / length)	10 / 180 mm
Short-circuit current (AC 50 Hz / DC) (1 s; ≤ 300 °C)	6.5 kA
Minimum lengths of M10 screws	35 mm (thread length 40 mm)
Minimum lengths of M12 screws	15 mm (thread length 20 mm)
Standard	EN 62561-1
Weight	301 g
Customs tariff number (Comb. Nomenclature EU)	85389099
GTIN	4013364033054
PU	25 pc(s)

Figure 19 : Fixed earthing terminal implementation for the meshed grounding network

The embedded plates are connected to the rebar with an iron line for EMC bonding purposes. IVC busbar support is welded on these embedded plates. To sustain over time the electrical connection the embedded plates shall be connected to the equipotential bonding network of the IVC busbar sys

Embedded plates



NOTE Clamps conforming to the future IEC 62561 series are suitable.

Welding to the reinforcing rods is only permitted if the civil works designer consents. The reinforcing rods should be welded over a length not less than 50 mm (see Figure E.5).

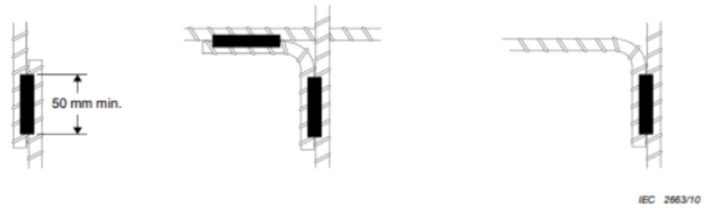


Figure E.5a – Welded joints (suitable for lightning current and EMC purposes)

Figure E.5b – Clamped joints to future IEC 62561 (suitable for lightning current and EMC purposes)

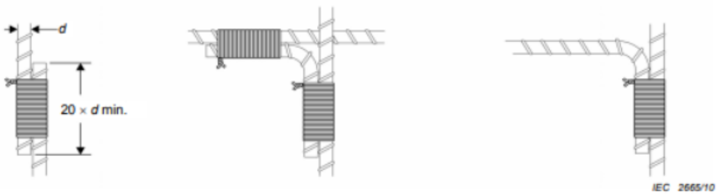


Figure E.5c – Bound joints (suitable for lightning current and EMC purposes)

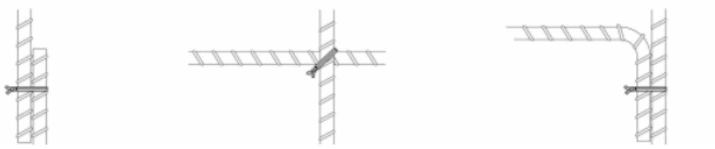


Figure 20 : Embedded plate implementation for EMC purpose only

10 Conclusion

As detailed in **chapter 6**, if an insulation fault occurs (Pole to Case), the ground fault current will be limited by the high impedance network of the power converter. Hence, the case of 2.5 mm thickness in Inox S316L and the IVC equipotential bonding network (Braid copper of 25 mm^2 or Braid aluminum 35 mm^2) can handle permanently the leakage current of 800 mA.

I	0.8	A
k	138	--
t	5	s
S	0.0130	mm^2

- 11 - UTE C 15-106

4 CONDUCTEURS DE PROTECTION

4.1 Sections minimales

La section des conducteurs de protection doit être au moins égale à celle déterminée par la formule suivante (applicable seulement pour des temps de coupure non supérieurs à 5 s) :

$$S = \frac{\sqrt{I^2 t}}{k}$$

dans laquelle

S est la section du conducteur de protection, en millimètres carrés.

I est la valeur efficace du courant de défaut qui peut traverser la canalisation pour un défaut d'impédance négligeable, en ampères.

t est le temps de fonctionnement du dispositif de protection, en secondes.

k est un facteur dont la valeur dépend de la nature du métal du conducteur de protection, de son isolation et de ses températures initiale et finale (les valeurs de k sont données dans le tableau 1).

Si l'application de la formule conduit à des sections non normalisées, la section plus élevée la plus proche doit être utilisée.

Dans les câbles souples, le conducteur de protection a la même section que les conducteurs de phase.

Figure 21 : Minimal cross section for 800 mA @ 5s – copper conductor

This insulation fault current will be injected into the case, into the equipotential bonding network of the IVC busbar system (**chapter 7**), and into the meshed fixed earthing terminal of the Tokamak building complex (**chapter 8**) up to the ITER plant earth site grid.

The leakage current will flow through a large number of parallel paths. Hence, the impedance of the resulting mesh is thus low as parallel paths are important. For the same reason, embedded plates where IVC supports are welded shall be connected as many as possible to the fixed bonding terminals in the concrete walls and floors on all sides are connected.

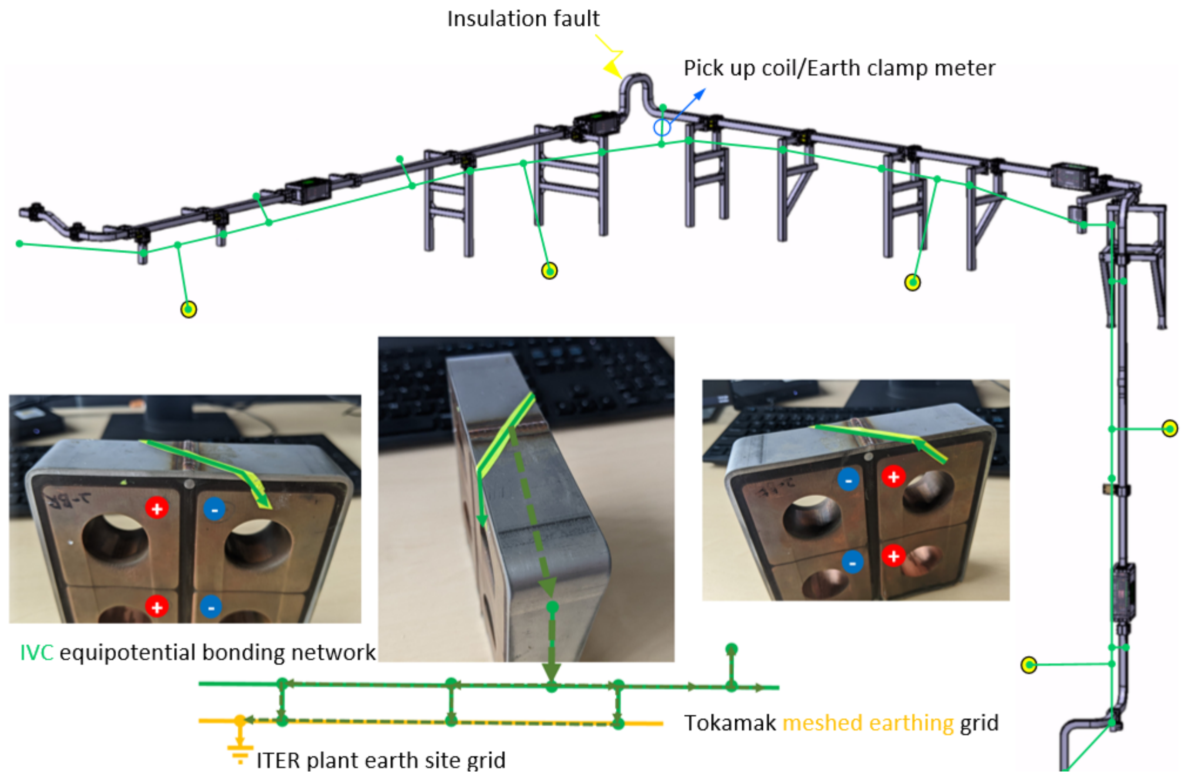


Figure 22 : IVC busbar cross-section & IVC bonding network proposal