Extraction of instrumentation wires through the high-voltage insulation of the ITER magnet feeder system

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Abstract. The ITER magnet quench detection system relies on voltage taps to detect the development of resistive voltages across the coils and busbars. These voltage taps may be at high voltage, up to 30 kV during high voltage tests, and the signals from them must be led from the coils and feeders to the quench detection electronics, requiring that they must penetrate the ground insulation on the coils and feeders. This paper describes the R&D effort to develop and qualify the technology to extract these wires through the feeder busbar ground insulation. The voltage tap wires are 3 mm in diameter, and are a significant perturbation to the 6 mm thick glass/Kapton ground insulation. Techniques to fill the void between wire and ground insulation are presented, as well as techniques to inhibit unwanted resin flow and locally reinforce the wires. Specimens have been thermally cycled and qualified through high-voltage Paschen tests.

1. Introduction
The superconducting magnets of the ITER tokamak, and the superconducting busbars which supply them with current, are protected by a quench detection system [1]. This system monitors the development of resistive voltages across a quenched coil or busbar, and initiates a fast discharge of the affected coil. The superconducting busbars are located in 29 so-called ‘feeders’ and form the connection between the superconducting magnets and the room-temperature electrical supply system [2]. High voltages of the order 10 kV will be developed across the pulsed superconducting magnets in normal operation (Central Solenoid and Poloidal Field Magnets), and voltages up to 4 kV will be developed across the Toroidal Field Magnets during fast discharge [3]. Therefore the superconducting magnets and busbars are enveloped in high voltage ground insulation, which is typically tested at a voltage of 30 kV.
The three major elements of the quench detection system are the voltage taps, which directly connect to the coils and busbars and detect the resistive voltage; high voltage insulated wires and cables, which lead these signals away from the coil or feeder; and the quench detection electronics, which are located some distance away from the magnet system. This arrangement requires that the voltage tap wires penetrate the ground insulation of the coil or feeder, and this must be accomplished without any loss in performance of this insulation, which is typically a 6 mm thick glass/Kapton structure. The voltage tap wires consist of a 1 mm diameter multi-strand copper core, enveloped by 1 mm thick polyimide insulation, and are rated to withstand 30 kV; these 3 mm diameter wires represent a significant perturbation to the ground insulation.

This paper describes the R&D effort to develop the techniques, and define the materials, to perform the voltage tap wire (also known as high-voltage – HV– wire) extraction through the ground insulation on the feeders. A concept which was trialed but not eventually selected is also reported. The selected technology has been qualified on several mock-ups, which have been thermally cycled and have successfully passed high voltage tests, including Paschen tests.

2. Feeder Insulation Architecture
The feeder insulation architecture is shown in Figure 1. The main ground insulation is shown as item (D) in that figure, and consists of 7 half-overlapped layers of glass pre-preg/Kapton (GK) combined tapes; the materials used, and techniques employed, to make this insulation are reported in [4]. Underneath this ground insulation are the co-wound tapes, which are connected to one end of a busbar segment and may therefore be at high-voltage. Voltage tap wires are connected to these co-wound tapes, and also directly to the busbar conductor surface. Above the ground insulation is the ground screen (F) which consists of a non-woven conductive fabric and serves to define a zero potential surface [5]. Electrical connection to the ground screen is made through a copper electrode with a soldered copper wire (H), and both the electrode and groundscreen are overlapped with two half-lapped layers of pre-preg (G) for mechanical protection.

![Figure 1: Ground insulation architecture of the feeder busbars, including co-wound tapes and ground screen](image-url)
The entire insulation structure presented in Figure 1 is ~6 mm thick, and it is through this that the 3 mm diameter HV wires must be extracted. A further constraint is the busbar mechanical support structure, which consists of a series of discrete supports which allow the busbar to slide [6]; the HV wire extraction positions must be selected such that the clamps cannot damage these wires during the busbar sliding process. The HV wire extraction solution must be able to withstand thermal cycling to low temperature, and must not degrade the electrical insulation properties of the busbar insulation, including under Paschen conditions. The technology must be robust and be maintenance-free for the lifetime of ITER (20 years), as access for repair would require a stop and warm-up of the ITER machine.

3. Initial Trial – Use of Epoxy Putty as a Filler
An initial trial to extract a HV wire from ground insulation was performed at Rockwood Composites Ltd. The ground insulation consisted of 9 half over-lapped layers of GK insulation, using the materials defined in [4], and was wound on an aluminum tube. The HV wire was stepped 9 times through the layers of insulation over a length of 300 mm, and in practice this was accomplished by stepping the wire after approximately every 3rd GK wrap, or 37.5 mm. An epoxy putty (Huntsman AV/HV 1580) was used as the filler on the sides of the wire to eliminate voids, as shown in Figure 2a (left) which shows the specimen partway through manufacture. The specimen was cured using silicone rubber strips to apply consolidation pressure [4], and was then sectioned to inspect the embedded HV wire as shown in Figure 2a (right).

The advantages of this approach are that epoxy putty is malleable, and so can flow to fill the ‘cusp’ shaped volume between the wire and ground insulation and furthermore, the implementation of this process is relatively simple. Some local voids in the cusp area could be identified in other section cuts, but they did not extend along the entire 300 mm long HV wire extraction path, which is key to achieving a Paschen tight insulation structure.

Cracks in the HV wire insulation were observed in a later specimen which was trialing the extraction of 4 HV wires with this technology. Two possible reasons were considered for this failure. Firstly, the thermal contraction of the epoxy putty on cooling is similar to that of stainless steel, and so is not matched to the surrounding GK materials or the HV wire insulation; the concern is that this will impose a strain on the HV wire insulation. The second concern is the repeated bending and handling of the wire which is required as the filler is applied. It is not possible to say which of these failure modes dominates. Ultimately this approach was not adopted mainly due to the two reasons outlined.
4. Use of Pre-Preg as the Filler

Two main strategies were adopted to overcome the limitations of the approach discussed above, and both of them were inspired by the team responsible for the manufacturer of the ITER Central Solenoid magnets [7]. The first was to use pre-preg as the filler between wire(s) and ground insulation, and the second was to prepare a taper in the ground insulation and lay the wires onto it, in order to minimize wire handling. These are discussed in detail below.

4.1. Pre-Preg Filler

The advantage of using pre-preg as the filler is that it is thermally compatible with the GK insulation, which itself incorporates the same pre-preg material. Due to the need for redundant voltage taps in the feeders, each wire extraction position entails 4 wires to be extracted. It was decided to extract these wires in a bundle, with the wires lying side-by-side, in order to minimise the number of penetrations through the ground insulation. The pre-preg filler was applied by wrapping each HV wire in a half-lapped layer of pre-preg tape, and then the 4 wire bundle was itself overwrapped with a half-lapped layer of pre-preg, as shown in Figure 3a (left). This was prepared ‘off-line’, which minimised the risk associated with wire handling.

In order to make the HV wire extraction more robust, two separate wire reinforcements were implemented. The first one consists of a shrink tube made of polyethylene (PE), which is applied on a local area of each wire where it exits the ground insulation; this is the darker material shown in Figure 3a (left). This shrink tube is applied before the pre-preg wraps, and provides some strain relief to the wire. It is important that the shrink tube does not extend down the whole length of the HV wire, as the gap between it and the wire could lead to breakdown in Paschen conditions.

![Figure 3a](left): Wrapping pre-preg around a bundle of 4 HV wires. Figure 3b (Right) Showing the bulky PE reinforcing tube, and detail of the HV wire groundscreen.

The feeder ground insulation was prepared with a 200 mm long taper, which was accomplished by offsetting subsequent layers of GK material. The pre-preg wrapped bundle of HV wires was then laid along the taper, and additional strips of pre-preg were applied longitudinally along the bundle to further fill the ‘cusp’ volume. GK tapes were then wrapped ‘into’ the taper in a mirror image of the first application, so as to finalise the insulation. During the curing process, it was found useful to use a temporary barrier material at the HV wire exit position to inhibit resin flow (from the pre-preg) up the wires. If this resin flows onto the exposed HV wire insulation and cures, it can cause cracks in the latter. Silcoset 101 was used as the temporary barrier material.

The second wire-reinforcement is applied after the ground insulation has been cured. This consists of a second ‘bulky’ PE tube which has a 1 mm wall thickness. This bulky PE tube is not close fitting to the HV wire; it is secured in place by a room-temperature setting resin system. This strategy was developed at Wendelstein W7X to reinforce the HV wires on that machine. Figure 3b (right) shows the application of the bulky PE tube (white colour) prior to it being encapsulated onto the underlying structure.
4.2. **Wire Groundscreen**
A further complexity involves the application of the groundscreen on each HV wire. Each wire is fitted with its own metallic groundscreen sheath, which must extend up to the busbar groundscreen but not connect electrically to it; the latter is required to avoid ground loops. In practice this was implemented by threading the bulky PE tube over the HV wire groundscreen sheath, as shown in Figure 3b (right). A thin square of fine copper mesh was then applied in contact with the end of the HV wire groundscreen sheath, which was bonded onto the underlying structure along with the bulky PE tube. The capping layers of pre-preg on the busbar groundscreen (part G in Figure 1) provide the electrical separation between the HV wire groundscreen and busbar groundscreen.

5. **Qualification Tests**
Multiple specimens incorporating the technology described in Section 4 have been prepared by the feeder manufacturer, ASIPP, and also at the ITER Organization workshop hosted by the CEA (known as Magnet Infrastructure Facilities for ITER [8]). Specimens are subjected to a DC hi-pot test at 30 kV, followed by a Paschen test up to 15 kV in dedicated vacuum chambers. The specimens are then thermally cycled to 77 K, and the tests repeated.

The predominant failure mode which early specimens suffered was breakdown in Paschen conditions after the thermal cycle; such a failure mode requires a path for the helium gas along the length of the extracted HV wire, and for this path to open up after the thermal cycle. This was attributed to the inadequate application of the pre-preg filler, and highlights the criticality of this operation. This failure mode is mitigated by the multiple wraps of pre-preg which are now applied on the HV wires, as well as the secondary longitudinal strips. Specimens are now routinely made which pass all the HV tests after thermal cycle.

6. **Conclusions**
A dedicated and thorough R&D programme was required to develop the technology to extract HV wires from ground insulation, in a reliable and robust way. Guiding principles include using thermally compatible materials, minimising wire handling, and implementing strain relief to the wires where they exit the ground insulation. The technology is now considered to be mature, and specimens are Paschen tight after thermal cycles. Nonetheless, the high level of ‘craft’ required in this process will require a comprehensive Quality Control plan to ensure its success on the ITER machine.

**Disclaimer**
The views and opinions expressed herein do not necessarily reflect those of the ITER Organization.

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