Insulation of The Coil and Bus Bar Ends during Assembly of W7-X

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Abstract—**The superconducting magnet system of the WENDELSTEIN 7-X (W7-X) experiment consists of 50 non-planar and 20 planar coils which are connected by 121 bus bars in series in seven groups of ten coils each. The terminal ends of the coils and bus bars are not insulated by the manufacturers and will be insulated during assembly. The insulation has to withstand a voltage of 13 kV dc for 1 min at Paschen conditions. Furthermore it has to be considered that the quench detection wires which were fed inside the insulation along the coil and bus bar ends have to be fed through the insulation near the joints.**

***Index Terms*— assembly of coil, insulation**

I. Introduction

The terminal ends of the coils and bus bars are not fully insulated by the manufacturers and will be equipped with transition pieces aluminium / stainless steel during coil and bus bar assembly preparation at Greifswald (Fig. 1). The transition pieces are part of the joints which will be assembled after making the electrical connection between coils and bus bars (Fig. 2 a). The superconductor between the end of the insulation of the manufacturer and the transition piece flange have to be insulated during assembly preparation.

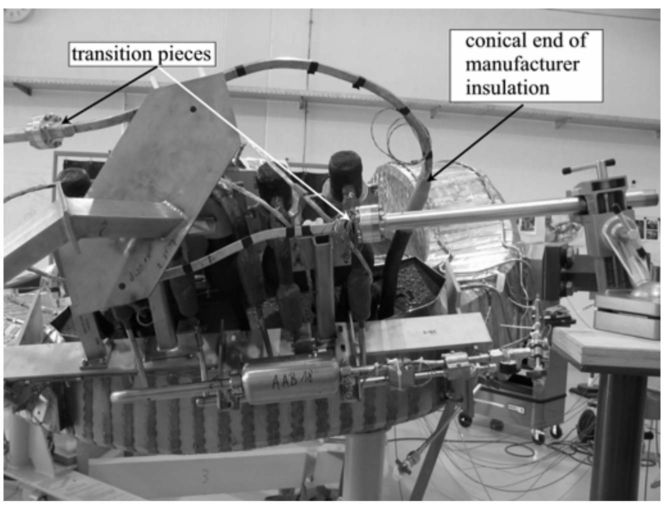

Fig. 1. Coil after arrival at Greifswald and welding transition pieces.

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The main requirements of the insulation are:

- 13 kV dc in helium atmosphere between 10^{-6} and 10^{3} mbar for 1 min [1, 2, 3]
- compatible with coil and bus bar insulation
- low-inductance feeding of QD (Quench Detection) -wires and feedthrough of the wires
- withstand a temperature gradient of 80 K along the insulation of the transition piece during welding of this joint
- easily and reliably mountable in different positions
- compatible with the insulation of the joint housing

Furthermore it has to be considered that the quench detection wires which are fed inside the insulation of the coils and bus bars have to be fed through the insulation near the joints.

II. Quench dtection of The Joints and Bus Bars

In the W7-X it is foreseen to monitor each bus bar length and joint separately. Thus along each conductor length two QD-wires (one for redundancy) are embedded in the insulation. To meet the requirement to distinguish between quench of conductor or joint the voltage taps for quench detection will be arranged as shown in the drawing and schematic in fig. 2. The QD-wire will be soldered to an aluminium stud and then the stud will be welded to the surface of the aluminium jacket by stud welding.

As all coil terminals have to be insulated before threading of coils on the plasma vessel the dedicated bus bars for the coils are not assembled yet. All bus bar ends have to be insulated before installing because of the constrained access for welding and insulating of the transition piece. Therefore the QD-wires of the bus bars and coils respectively must be simulated by short wires which will be connected after installing the bus bars and joints to the dedicated conductors in a so called connection box (Fig. 2 a). The connection box also serves as a feedthrough for the wires which have to be fed through the cryostat to the quench detection system. Outside the insulation the wires must be fed as close as possible to the superconductor to minimize inductance. During energizing the coils up to the operating current and slow and fast discharging a voltage will be induced in the wires. This voltage can generate a quench signal which leads to a rapid shutdown of W7-X.

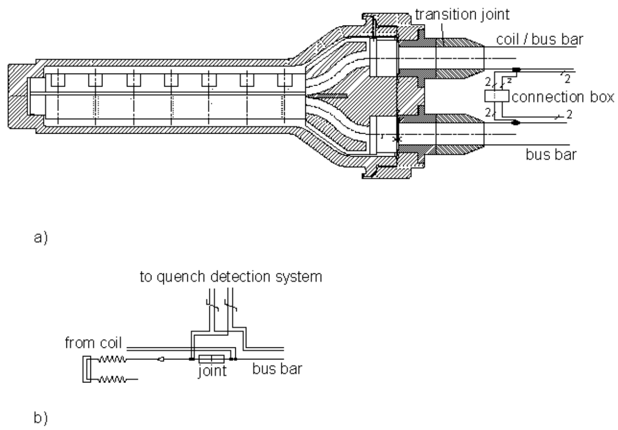

Fig. 2. Drawing and schematic of the QD-wiring.

Taking into account the highest induction of 0.5 T in this area, a fast discharge within 3 s and an allowed noise of the voltage of 5 mV the surrounded area between conductor and wire and wires themselves must be lower than 0.03 m^2 according to the law of induction.

Following this requirement the wires have to exit the insulation close to the joint considering the minimum bending radius which is 35 mm.

III. Design and Qualification Procedure

The insulation of the coil terminals made by the manufacturer consists of wet wrapped overlapping glass fiber tapes up to a thickness of about 5 mm. The insulation of the bus bar is made of 5 wet wrapped overlapping layers: glass, Kapton, glass, Kapton and glass. The two QD-wires are embedded in the insulation of coils and bus bars.

All surfaces which have to be insulated and the end of the insulation of the manufacturer will be abraded. A cap made of Teflon will be mounted to protect the strands and the uninsulated parts of the transition piece against resin and dirt. A glass content of more than 60% is required for the insulation [1, 3].

The insulation to be applied to the terminal ends can be devided in the four parts:

- insulation of the studs (1)
- insulation of the conductor (2)
- insulation of the transition piece (3)
- additional wet wrap (4)

which are shown in Fig. 3. After insulation all surfaces are covered with conductive paint.

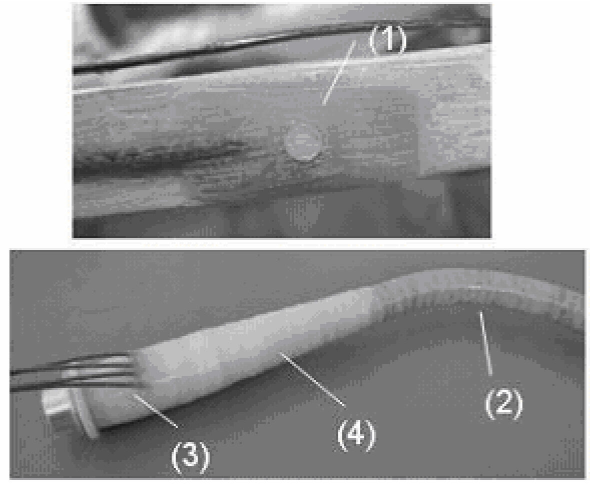

Fig. 3. Parts of the insulation at termination end.

The insulation of the stud is the first step. A glued G10 piece covers the stud to allow for a slight transition while wrapping the tapes, especially the Kapton tapes. To reduce the dielectric stress in the insulation due to spikes and sharp corners the edges of the studs will be rounded.

The insulation of the conductor which overlaps the insulation end of the manufacturer for about 50 mm is similar to the insulation of the coils and bus bars and consists of six wet wrapped overlapping layers: glass, Kapton, glass, Kapton, glass, glass. Between the layers and between the overlapping parts of the layers epoxy is painted by brush to ensure a good wetting and bonding. Clearances between QD-wires or gaps where no glass tape can be applied will be filled with resin filled compound.

The third part of the insulation is the so called insulation cap which is used to insulate the transition piece. The cap made of glass-fiber-reinforced plastics (GRP) consists of two cylindrical half shells as shown in Fig. 4. Inside the cap are four drill holes which are used as feedthroughs for the QD wires. Only wet laminated pressed GRP materials can be used. Standard G10 or G11 prepreg materials are not recommend for cryogenic applications because of risk of delaminations between the stacked or wrapped layers. After machining, delaminations often begin at the flange where the cross section of the glued surface is very small. Samples made of G10 material showed delaminations over the whole length after thermal cycling. The length of the cap depends on the straightness of the superconductor. As the conductor is bent even in the area of the transition piece the cap may not exceed a length of 65 mm.

The flange at the end of the cap is needed to nest the base plate insulation of the joint to the insulation cap. To compensate different weld seam geometries a recess is inside the cap.

The insulator shells are glued together by epoxy seals which are part of the dielectric barrier. To provide an additional barrier inside the cap across the seals of the shells Kapton is applied during mounting.

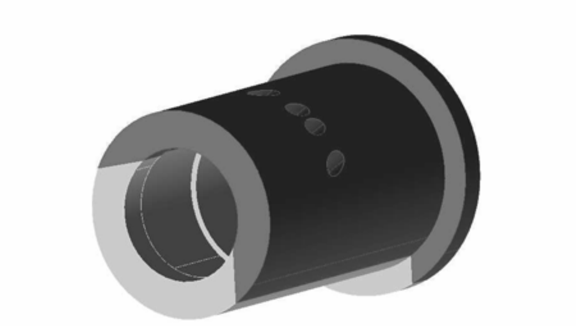

Fig. 4. Insulation cap with the 4 holes for the QD-wires.

The weakest point of the insulation are the feedthroughs of the QD-wires as in all mounting positions voids have to be avoided and the resin must remain in the holes. These conditions are fulfilled by applying resin filled compounds. This compound consisting of epoxy and outgassed Cabosil was qualified for cryogenic temperatures. Compounds with Cabosil are well compressible and pasty. The compound is also used to glue the insulator shells to the transition pieces. Thus it is ensured that the compound will be squeezed through the holes. By using this technology a good bonding is achieved. This is confirmed by cross sections and tests.

The last part of the insulation is an additional wet wrap made of glass tapes. Due to the curvature of conductor in the area of transition piece this wrap is for additional safety and a mechanical support for the cap.

Full size straight and bent samples of the insulation were made to qualify the insulation and the operators.

These samples were tested in the following order:

- 13 kV DC for 1 min in vacuum between 10^{-5} mbar and 10^{+3} mbar at room temperature (RT)
- thermal aging at 50°C for 168 hours
- Heating up the flange of the transition piece directly by flame four times up to 100°C
- 13 kV dc for 1 min in vacuum between 10^{-5} mbar and 10^{+3} mbar at RT
- 50 times thermal cycling between RT and 77 K
- 13 kV dc for 1 min in vacuum between 10^{-5} mbar and 10^{+3} mbar at RT
- 10 kV_{rms} ac for 15 min
- 13 kV dc for 1 min in vacuum between 10^{-5} mbar and 10^{+3} mbar at RT

As the fully insulated transition piece will be welded to the joint housing the influence of welding to the insulation cap was simulated by heating up the flange of the transition four times to 100°C by flame.

The high voltage tests under vacuum, Paschen tests, were carried out in a vacuum chamber at room temperature. The pressure was increased in steps of 10^{+1} from 10^{-5} mbar to 10^{+3} mbar. The allowed leakage current is 1µA. Partial discharges were observed in some samples. Most of these discharges have been detected in the auxiliary insulation which is applied at both ends of each sample. Flashovers or breakdowns were only observed in the first samples in the range of 5×10^{-2} to $5 \times 10^{+2}$ mbar. Partial discharges reduce the life time of the insulation by degradation but the time period of applying the voltage at W7-X is very short. Therefore small voids as a source for partial discharges are not an essential problem of W7-X. But gaps caused by insufficient bonding or large voids could lead to a flashover or breakdown.

The ac test as an accelerated reliability test was made to get information regarding the reliability and life time of the insulation. The duration of 15 minutes is equal to 90,000 rapid shutdowns of W7-X. Although some small partial discharges during the Paschen tests were observed no indication for a failure caused by these discharges were found during and after the ac test.

The insulation developed to meet the electrical and geometry constraints of W7-X was successfully tested.

IV. Tests of The Insulation after Mounting

Electrical tests of the mounted insulation will be carried out at a reduced test voltage of 9.1 kV dc for 1 minute at the non planar coils and bus bars and 6.3 kV for 1 minute at the planar coils [1, 3, 4]. To test the insulation for all conditions of operation of W7-X a Paschen test will be carried out. This requires a vacuum around the mounted insulation. Two types of test equipment which provide a vacuum around the terminal ends was developed and successfully tested. Critical point of both technologies is the vacuum tight transition from the insulation cap to the uninsulated part of transition piece which is at high potential. The first technology is to built up a chamber which consists of membrane bellows and split flanges (Fig. 5). A pressure of about 10^{-3} mbar was achieved. The pressure is set by an inlet valve. The main disadvantage of this chamber is its weight and its dimension.

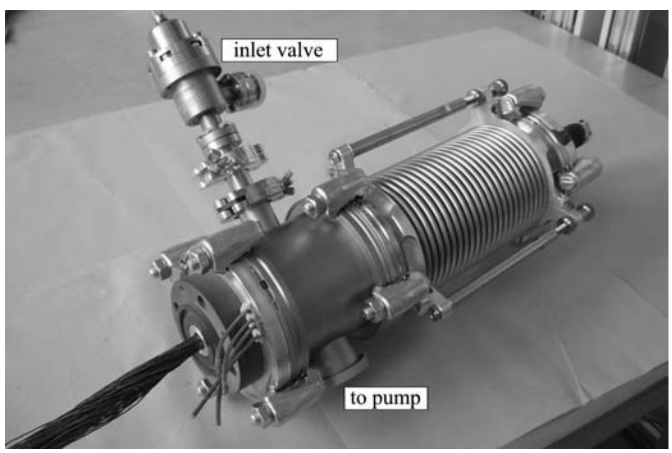

Fig. 5. Equipment for Paschen test consisting of bellows.

The second technology is shown in Fig. 6 is simple and easier to apply in all assembly positions. The insulation is wrapped with a spacer made of stainless steel wire-cloth. The QD-wires are supported by a pipe and fed through a flange to the ambient air. Around the spacer is placed a porous fleece as a mechanical protection. A heat-sealed vacuum tight foil as the last layer allows for the vacuum around the insulation. Paschen tests were carried out with this equipment in the pressure range of 5 x 10^{-2} to 10^{+3} mbar. Disadvantage of this technology is the time-consuming removal of vacuum sealant.

Both technologies allow in the case of pressure dependent flashovers or breakdowns a stepwise testing to find the failure by removal of vacuum parts. By further improvements it is intended to combine the bellow and foil equipment.

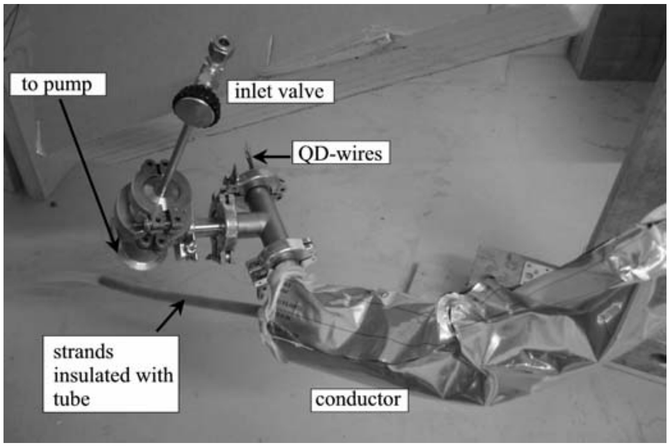

Fig. 6. Equipment for Paschen test consisting of foil.

V. Mounting of Insulation at The First Coil

The insulation work on the first coil was carried out according to detailed working instructions which are part of the quality assurance assembly plan. Only operators passing the training period at comparable mock-ups are assigned to perform this work. Just before the ends were insulated the operators had to insulate short pieces under comparable positions. These work samples were tested at 13 kV dc at Paschen conditions after thermal cycling between RT and 77 K.

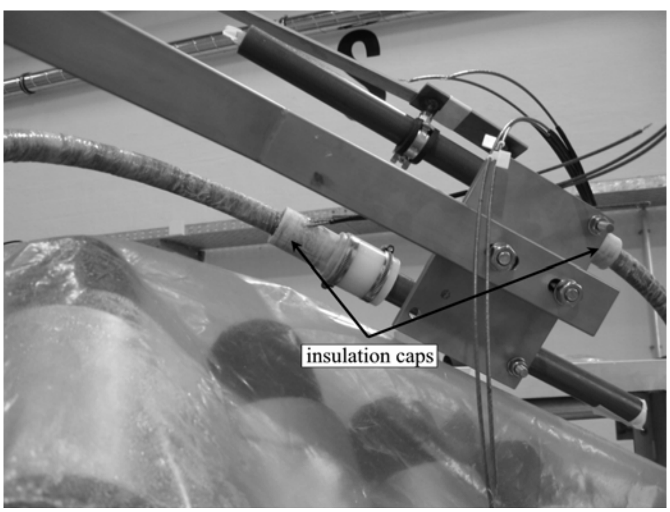

Fig. 7. Finished conductor insulation and glued insulation caps.

The insulation was made and electrically tested (Fig. 7). The Paschen test is still outstanding due to urgent assembly trials with this coil. The test will be performed on the assembled coil.

The experiences taken from the qualification process and the insulation of the first coil are very valuable for the upcoming insulation work on the second coil. The second coil which is already on the plasma vessel has to be insulated under very constrained positions as shown in Fig. 8.

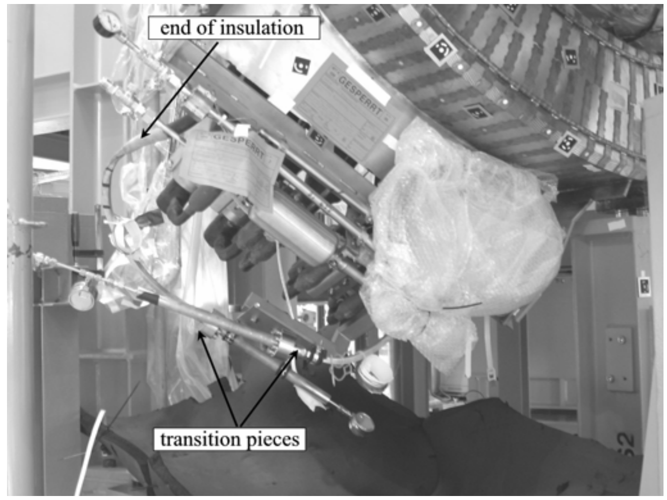

Fig. 8. Position of the second coil for the insulation work.

VI. Conclusion

The insulation of the terminal ends consisting of four parts is optimized with respect to the electrical and thermal parameters and the requirements of the assembly of W7-X. Extensive tests were done to qualify the insulation for 13 kV dc at Paschen conditions after thermal cycling between RT and 77 K. Furthermore the chosen technology ensures a low inductance feeding of QD-wires and allows for detection of quenches in joints or bus bars.

During the insulation of the first coil of W7-X the good performance was demonstrated.

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