The Quench Detection-Wire-Feedthrough Plug-in of W7-X

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***Abstract*— The stellarator fusion experiment Wendelstein 7-X (W7-X) is presently under assembly at the Greifswald branch of the Max-Planck-Institut für Plasmaphysik (IPP), Germany. To allow the steady-state operation, W7-X has a superconducting magnet system. It consists of 50 non planar coils, 20 planar coils, a superconducting bus bar system and 14 current leads. For continuous on-line monitoring of the superconducting state 1624 Quench Detection-wires (QD-wires) are connected at the joints of the coils and the bus bars. The signals of these wires must be fed through the Outer Vessel (OV) shell to the Quench Detection Units. The electrical feedthroughs, wires and wire connections have been designed and qualified for a test voltage of 13 kV under low gas pressure (Paschen test). Other important requirements are a maximum allowed integral helium leak-rate of 10^{-8} mbar l/s per QD-dome and a maximum allowed total heat load to the thermal shield of the OV of 140 W per QD-dome. The paper describes the design and qualification of the QD-Wire-Feedthrough-Plug-in, the assembly procedure as well as the tests carried out during and after assembly.**

***Index Terms*— QD, feedthrough, assembly**

I. Introduction

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 to form seven electrical circuits of ten coils each. The connection between coils and bus bars will be provided by 184 joints. The magnet system is enclosed in a cryostat with an outer diameter of 16 meters formed by the plasma vessel and the outer vessel and cooled by supercritical helium.

In case of a loss of the superconductivity state of any superconducting section the magnet system must be rapidly discharged. For continuous on-line monitoring of the superconducting state Quench Detection-wires (QD-wires) are connected at the coils, at the joints and at the bus bars. For safety reasons all wires are redundant. The voltage in the range of mV, tapped at the conductors will be permanently measured and compared with a threshold level in the Quench Detection Units [1] outside the cryostat.

The QD-wires of the coils are connected at the interlayer joints and coming out of the coils as twisted pairs in 3 x 6-wire cables for the non-planar coils and 2 x 6-wire cables for the planar coils. The voltages across two adjacent double layers are electrically compensated in a half-bridge arrangement in the Quench Detection Units.

Along each bus bar length two wires (one for redundancy) are embedded in the insulation, crossing the adjacent joints and are connected near the joints to the other superconductor. Thus the voltage drop across each bus bar and adjacent joints will be directly measured [2]. The wires coming from the bus bars are bundled as 2 twisted pairs into a 4-wire cable.

The conductor of the QD-wire is made of silver plated copper strand arranged in the standard gauge AWG24. The conductor is insulated with Kapton® foil. The wires are shielded outside the insulation of coils, bus bars and joints.

In total 190 6-wire cables and 121 4-wire cables are installed to monitor all superconducting parts. The signals of these wires must be fed through the Outer Vessel (OV) shell of the cryostat to the Quench Detection Units. Therefore, 10 QD-domes, i.e. two per module are provided on the OV. The QD-domes are differently located and oriented. The Fig. 1 shows, as an example, the QD-domes for the QD-feedthroughs of module 1. Such QD-dome has an inner diameter of 800 mm and average height of 500 mm.

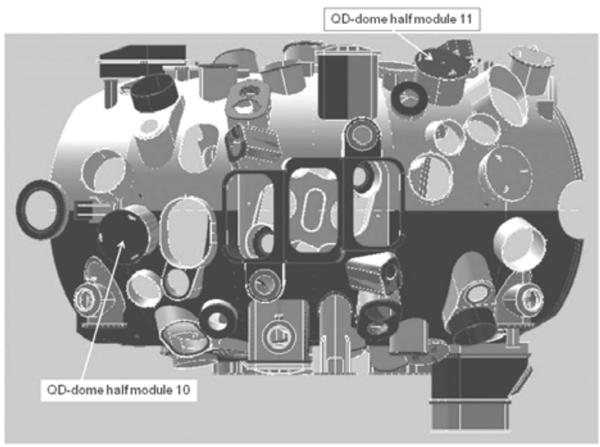

Fig. 1. OV of module 1 with the two domes for the QD-feedthroughs

Several constraints require a complex feedthrough system design. The maximum allowed integral helium leak-rate of one QD-dome is 10^{-8} mbar l/s. The total heat load to the thermal shield of the OV must not exceed 140 W. The electrical insulation of the electrical feedthroughs has to be designed for a nominal voltage to ground of 6 kV DC and a related test voltage of 13 kV DC under conditions close to the Paschen minimum (Paschen test) [2]. The complete system

Manuscript received 9 September 2011.
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must fit into the available space of the dome, and must be replaceable for maintenance.

II. Design of the Quench-Detection-Wire-Feedthrough Plug-in

The design of the Quench-detection–wire-feedthrough plug-in (QD-plug-in) is presented in Fig. 2. The QD-dome on the OV is extended by a remountable dome extension. The QD-plug-in is installed inside this dome extension. The QD-plug-in consists of the plug-in-tube with an inner diameter of 700 mm and a length of 612 mm. In order to allow an access to the inner parts there are 5 openings of 100 x 400 mm in the plug-in-tube.

The plug-in–tube is connected at its warm side with the lid of the dome extension and at its cold side to the thermal shield of the OV.

Thirty-one and 32 leak-tight electrical sockets are arranged in the lid of the dome extension, respectively. From these sockets the Quench-Detection-Dome cables (QDD-cables) inside the plug-in-tube pass the radiation shield and go to the cold copper base plate. At the base plate the cables are thermally isolated and fixed by a conical strain relief. The connection of each QDD-cable to the dedicated QD-cable is made in a connector outside the QD-plug-in.

To protect the QD-plug-in against gas heat conduction and thermal radiation 20 layers of multi-layer insulation (MLI) are wrapped around the plug-in-tube. The MLI from the OV overlaps the MLI from the plug-in tube to improve the thermal resistance of the gap.

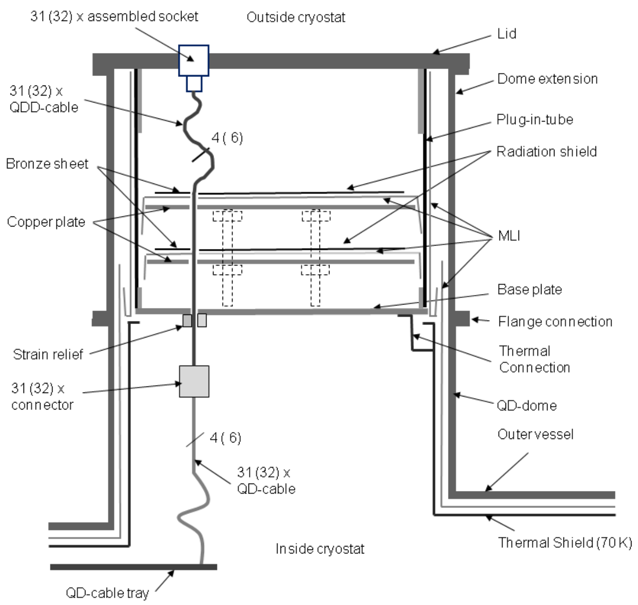

Fig. 2. Schematic view of the QD-plug-in

The design of the QD-plug-in was mainly driven by the thermal losses to the thermal shield of the cryostat. The OV wall is covered by an actively cooled thermal shield and MLI as shown in Fig. 2. The operational temperature range of the plug-in goes from 70 K at the thermal shield to about 293 K outside the cryostat.

The contribution of the thermal radiation depends on the surfaces, emissivity and the temperature distribution along the plug-in-tube. Taking into account the specific losses of 6 W/m^2 for the MLI between 80 and 300 K [3] the radiation losses are about 30 W for all plug-ins.

The heat load to the shield caused by thermal conduction depends on the cross section of conductor and shield of the 1.4 long QD-wires and on the 600 mm long stainless steel tube. With the approximate conductivity integral of 1033 W/cm [4] for copper between 76 and 300 K the heat losses caused by the wires are about 102 W. The stainless steel plug-in-tube with a wall thickness of 1 mm contributes 100 W for all plug-ins.

To lower significantly the heat loads it is necessary to use other material for the conductor and shield of the wires. Thus the copper of the conductor was replaced by Constantan®. The higher resistance of Constantan® will be compensated in the Quench Detection Unit. Thermo-electric voltages are negligible because of the very low temperature gradient. Additional the copper of the shield was replaced by stainless steel. Electromagnetic interferences into the plug-in will be mainly shielded by the steel of the lid and the dome extension as well as the aluminized Kapton® foil of the MLI around the tube. Due to these modifications the thermal losses could be reduced by 98 W to 134 W which is lower as required.

Furthermore the design considers electromagnetically forces of about 200 N caused by eddy currents in the copper plate during the rapid shut down of the magnet system.

III. Main Components of the QD-Plug-in

A. The Electrical Feedthroughs

Essential components of the plug-in are the electrical feedthroughs in the lid of the plug-in. Nineteen 6-wire cables and twelve 4-wire cables respectively thirteen 4-wire for one dome, e.g. in total 166 wires are to feed through the lid of one QD-dome. The electrical feedthroughs have to meet the same electrical characteristics as the wires, and their function as leak tight interfaces. For commonly used weldable ceramic feedthroughs with 1 or 2 pins there is not enough available space on the lid. Thus, several commercial types of multi-pin feedthroughs were tested for possible application. After these tests the 7- and 4-pin female sockets from the company LEMO were chosen (Fig. 3). In order to avoid floating potentials the seventh pin will be connected in the plug outside the cryostat to one of the other pins. As the use of an O-ring is disadvantageous relating to long term tightness the design of the QD-plug-in allows a replacement of O-rings. To replace the O-ring without cutting the connection of the QD- and QDD-wires the sockets will be inserted in the lid from the vacuum side. If weldable sockets are used there would be the risk of destroying internal parts by high temperature.

The sockets were assembled with 1.4 m long QDD-cables by the company Lemo. To obtain the high voltage characteristics at different pressures the soldered pins to the QDD-wires are potted in Stycast®.

After mounting the sockets in the lid Paschen tests and leak tests are performed to guarantee the high voltage withstand capability. It was found that the electrical as well as the vacuum requirements were met.

Fig. 3. 7-pin electrical socket

B. Radiation Shield

The radiation shield consists of two platforms with MLI. The MLI is located between a copper plate and a sheet of bronze to keep the MLI in position. The holes in the platforms where the cables pass the MLI are shifted against each other to avoid a free optical view from the lid to the cold base plate.

C. Connection between QD-and QDD-wires

In addition to the required electrical features the QD-connector has to be small, reliable, applicable for 4 and 6-wire cables and easy to install. The solution which fulfills all these requirements is shown in Fig. 4.

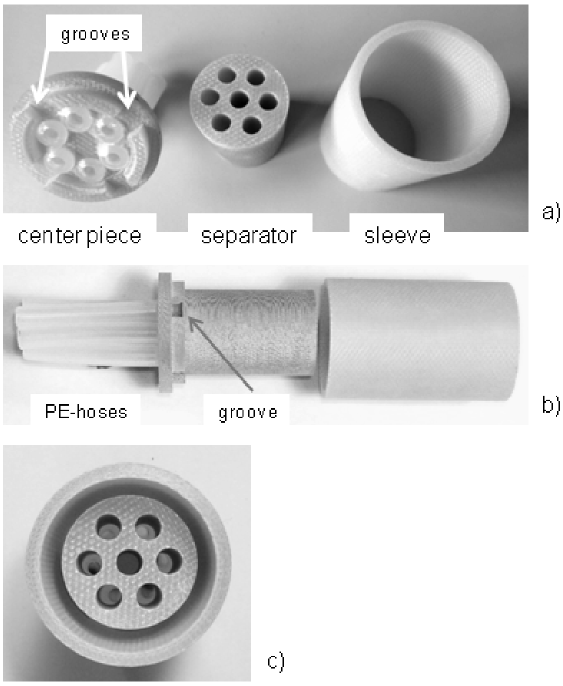

Fig. 4. Connector
a) Parts of the connector
b) Assembly of the connector
b) Connector

It consists of three pieces made of G10 and hoses of polyethylene (PE). The hoses of PE protect the wires against too strong bending. Experiences gained from the insulation of the joints have shown that the Kapton® insulation of QD-wires can be easily break at edges of G10 if there is some cured epoxy resin on the surface of the wire. Therefore, hoses of PE will be inserted in the center piece and then plastic deformed at its end to be fixed in the center piece.

For the 4-wire cables two holes in the center piece will be closed by 5 minutes epoxy.

The pieces will be combined and glued with epoxy and then put over the wires. After soldering the wires the soldering point will be placed in the middle of the separator and the connector will be vertically fixed. Stycast® will be filled in the seventh hole in the center. The four grooves in the center piece guarantee the flow of Stycast® to the other holes. The level of Stycast® in all seven holes and between the separator and sleeve rise uniformly.

Finally the screen against electrical noise and for grounding will be mounted. For that the screens of both cables have to be connected by a screen which covers the QD-connector. This screen connection provides also a certain mechanical stiffness and serves as a strain relief.

The connector has to withstand the electrical field corresponding to a test voltage of 13 kV DC at Paschen conditions even after multiple mechanical as well as thermal load cycles between 70 K and room temperature. Numerous connectors were mechanically overstressed by bending the wires and afterwards thermal cycled. All qualification tests have been passed successfully.

IV. Assembly of QD-Plug-in

A test installation at the OV with a full-size prototype of a QD-plug-in including making and testing the connection of QDD-wires to QD-wires was successfully carried out to qualify the assembly procedure and train the assembly team.

Special attention during this test was given to the support and handling of the 424 kg dome extension including QD-plug-in as well as the controlled overlap of MLI during alignment of the dome extension to the dome. The problem here is that the MLI from the OV must be carefully fed between the plug-in-insulation and the dome extension. Therefore, the insulation from the OV is held by a sheet of bronze.

Furthermore in order to proof the electrical characteristic small chambers were designed to make a Paschen-test for each single QD-connector. The structure of such chamber is shown in Fig. 5. It makes it possible to perform high voltage test under different air and Helium pressures on-site. The achieved vacuum is about 10^{-2} mbar and sufficiently low to perform proper Paschen tests. The gas pressure starts at about 0.05 mbar and will be increased in 10 steps until the ambient pressure. At each pressure level a high voltage test of 5 kV for one minute will be performed. The test is considered as successful if the leak current is not exceeding 5 µA.

Because of safety regulations for high voltages these tests can be performed during breaks or in the night only. Thus, due to the high number of QD-connectors simultaneously tests of much as possible QD-connectors are required. To minimize the number of tests several chambers are needed. Tests will be done at the same time always at connectors of the same electrical circuits. With that strategy the number of tests can be reduced to 7 instead of 64 by using of one chamber.

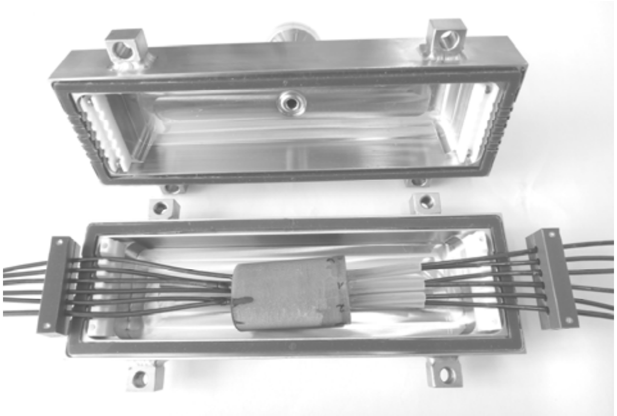

Fig. 5. Chamber for the Paschen test of QD-connector

The assembly of the two QD-plug-ins for module 5 has been started in May 2011. Two QD-plug-ins were pre-assembled, wrapped with MLI and inserted in the dome extension. The sockets and wires were electrical tested at 10.4 kV.

Presently the assembly of the QD-Plug-ins on the QD-domes is underway (Fig. 6). All QD-connectors of one QD-plug-in are installed. Before starting the electrical test of these QD-connectors the QD-connectors of the second QD-plug-in will be completed.

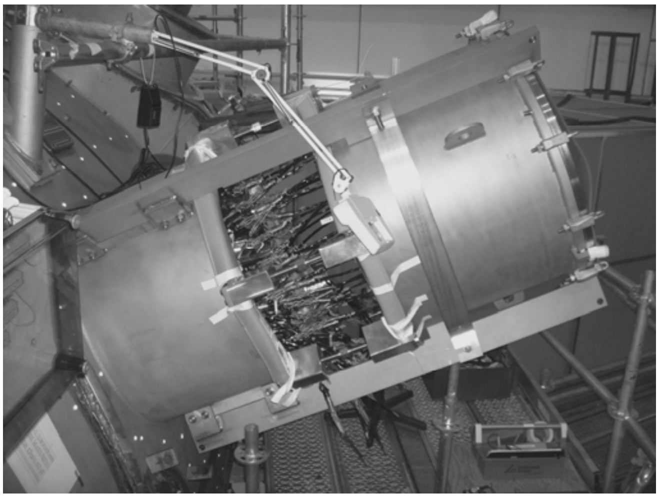

Fig. 6. QD-Plug-in on the QD-dome of module 5

V. Conclusion

A Quench-detection–wire-feedthrough plug-in for W7-X was designed and tested. During the qualification tests the required voltage strength of 13 kV was achieved. The design limits the heat load to the thermal shield of the outer vessel to 14 W only. Also the other requirements regarding Helium leak-rate, mechanical stiffness against electromagnetic forces and mountability in the very restricted space were met. The installation of the first plug-ins at the Outer Vessel of Wendelstein 7-X has been started in May 2011.

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