Qualification of the TIC conductor for the in-vessel coils in ASDEX Upgrade

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ASDEX Upgrade will be evolved by installing a new upper divertor with two in-vessel coils allowing the investigation of alternative magnetic configurations. The in-vessel coils will be bended inside the torus. The co-axial conductor consists of a Tefzel insulated water cooled copper core embedded into a stainless steel protection shield. To test the conductor concept and to qualify the electrical and thermal properties of the Tefzel insulated conductor (TIC), prototype conductors of 3 and 8 m length were used. These conductors undergo electrical and thermal tests accompanied by FEM calculations. The electrical tests include high voltage and partial discharge tests. For thermo-mechanical tests the prototype conductors were fed with up to 13 kA for 5 s. During the test the copper conductor was heated up by 60 K. The Tefzel cladding and the protection tube are warmed up with a delay given by the thermal heat conduction and capacity. The thermo-mechanical behaviour of the TIC during the heating and cooling phase could be confirmed by the FEM-models. As part of the qualification, the conductor was thermally overloaded by a factor of 3, without degradation.

The paper presents the electrical and thermal tests as well as the results of the related FEM calculations.

Keywords: ASDEX Upgrade, in-vessel coils, Tefzel insulated conductor, qualification

1. Introduction

ASDEX Upgrade (AUG) is a tokamak that can be operated with strike lines in the upper and/or the lower divertor. In 2016 a project was started to develop and install a new upper divertor with internal coils and an in-vessel cryo-pump. The aim is to investigate alternative magnetic configurations that may facilitate the access to detachment via an enhanced flux tube expansion and/or connection length[1]. To realize the envisaged magnetic configurations two internal coils operated with up to 52 kAt will be installed. A critical component is the conductor for the two in-vessel coils. It has to be compact due to the limited space available. It has to be compatible to the magnetic forces and last not least it has to withstand the high voltage induced during disruptions of up to 1 kV/turn. The realized concept for the conductor is comparable to the ITER in-vessel coils [2]. Whereas the maximum baking temperature of 155°C of AUG allows to replace the hygroscopic MgO insulation of the ITER concept by a Tefzel (ETFE polymer) cladding suitable for an extrusion process. In terms of electrical safety this solution with a complete screening around the copper conductor is preferred, because it is inherently safe against a winding short-circuit, that would lead to high forces on the conductor and would restrict the operation of the coil and the experiment [3]. In addition, the stainless steel protection tube acts as the vacuum barrier.

In the present design each coil consists of four windings with a radius of about 1.5 m; the connection to the feeding port is done by several bends of a radius of 180 mm and various bending angles. In order to perform electrical and thermal tests a prototype conductor with a length of 35 m was produced and qualified. The qualification of the conductor comprises the electrical qualification, bending properties and possible deforming as well as the thermo-mechanical behaviour. The thermo-mechanical behaviour was investigated by a combination of realistic loading (13 kA) accompanied with FEM interpretation of the results. This is a critical issue, because the copper core warms up by 60 K during the 5 s operation and the conductor itself is not in a thermal equilibrium. The different steps of the conductor qualification and the results of it are presented in the following sections.

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2. Composition and layer properties of the TIC conductor

The setup of the Tefzel insulated conductor is shown in Fig. 1: A copper tube with an outer diameter of 18 mm and a cooling channel diameter of 8 mm acts as the electric conductor. The oxygen-free copper grade CW008A is used; the examined prototype conductor was made of a hard tempered copper with a measured Vickers hardness of 115 HV.

The 2.5 mm thick insulation layer is made of the ETFE-polymer Tefzel HT-2183 (DuPont™). Due to the manufacturer's data this fluoroplastic resin provides a high mechanical toughness, a good creep resistance as well as an improved stress crack resistance. The ultimate elongation is 150% at room temperature and 280% at 150°C. With a recommended upper service temperature of 155°C, the material complies with the baking procedure of the AUG vessel. For FEM calculations the temperature dependent material properties of comparable Tefzel types were used, as not all of these data were available for HT-2183. The specified dielectric strength of Tefzel is 70 kV/mm, so a layer thickness of 0.16 mm would be sufficient to insulate a maximum voltage of 11 kV.

The 1.5 mm thick protection tube with an outer diameter of 26 mm is made of stainless steel (SS) grade 1.4404 (316L).

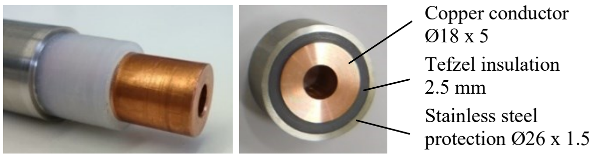


Fig. 1: Setup of TIC conductor

Table 1 displays the main properties of the conductor layers, as used for thermo-mechanical calculations.

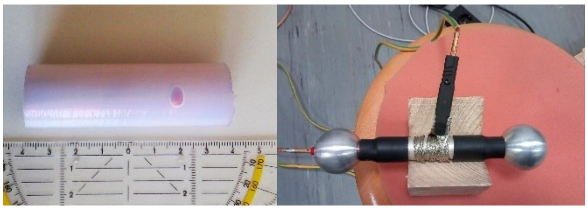
	Copper	Tefzel	SS
Density [kg/m3]	8900	1740	7900
E [GPa]	110	1.3 (at RT)	200
Poisson Ratio	0.33	0.42	0.3
K [W/m/K]	400	0.25	60.5
c [J/kg/K]	385	1045	434
CTE [1/K] x 1e-6	17.7	133 (up to 100°C)	16.26

Table 1: Material properties of conductor materials

3. Electrical qualification

The intention of the electrical tests was to learn more about the behaviour of the TIC cable related to different kind of loads due to bending, baking and high-current operation. An electrical arrangement to automatically perform partial discharge (PD) measurements at a high range of 50 Hz AC voltage (0...15 kV_p) was applied between the stainless steel tube and the copper core before and after each load cycle. The difference in PD activity is related to the total gas volume trapped between/inside the different layers of the compound TIC cable.

To test and calibrate the method, short pieces of the cable (150...190 mm) with and without known gas-bubbles in the ETFE were prepared for the PD test (see Fig. 2). Of special importance is the preparation of the cable ends. Corona discharges were suppressed by so called "stress control shrinking tubes". Electric field hot spots at the open copper end edges were shielded by polished aluminum balls at copper potential. Finally, it was possible to detect a change of trapped gas volume with a sensitivity down to approx. a few 10 mm³.



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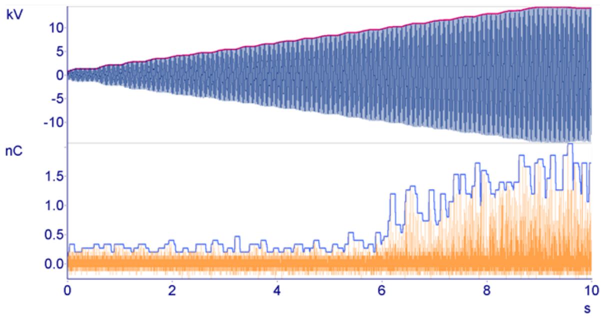

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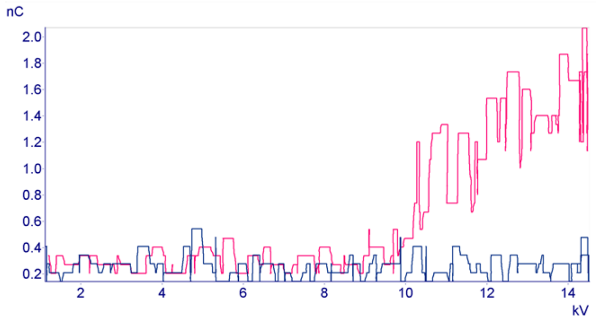

d)

Fig. 2: (a) Sample of a TIC conductor without the SS-protection - with a bubble in the ETFE insulation. (b) Connection and preparation of the test piece for the PD measurement. (c) Sweep of the high AC voltage (blue), processing of the peak voltage (red), synchronized measurement of the PD activity (orange) and processing of the PD peak values (light blue). (d) The curves are showing the PD activity for two samples with bubble in red and without bubble in the ETFE insulation in blue.

In total, there were performed about 20 PD tests on 14 different test pieces of the TIC cable of different length between 0.3 and 8.5 m before and after a wide range of treatments:

1. DC high-current tests up to 13kA/10sec for up to 60 cycles, each.
2. Different bending tests down to minimum radius of 100 mm.
3. Homogeneous baking at temperature up to 160 °C for 8 hours...12 days.

In Fig. 3 there is a summary of all PD measurements shown. For smoothening the curves, the PD-activity was averaged over 10 cycles of measurement voltage (= 200ms @50 Hz). Due to different length of the samples, the PD activity per length is given.

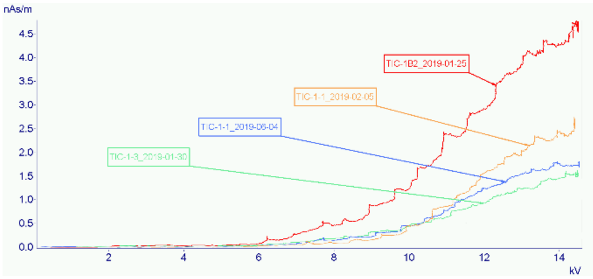

Fig. 3: Comparison of all results with respect to the sample length. The 4 cables with highest PD activity are red: after bending small radius and first short baking (8 hours), orange: straight cable after 5 days of baking, blue: after 12 days of baking and 7.5kA HC-test, green: after small radius bending and 3 days baking

The conclusions with respect to the electrical behaviour of the TIC conductor are as follows:

- Baking typically increases the PD activity on a low level basis. After baking for at least 1 day, the PD activity typically does not further change.
- Bending in all relevant radii only slightly modifies the PD activity.
- No relevant change of PD activity was found by high current tests, even at highest current (13kA) and highest thermal stress (180 K temperature difference between outer SST shield and inner copper conductor) after first baking! For an un-baked cable the high current test can cause a significant increase in PD activity (gaps due to inner stress).
- Highly modified PD activity can be seen in some cases after first baking (Fig. 3, red curve). Here, the first baking dramatically increased PD activity which relaxed after second (longer) baking.
- Electrical weakening of the cable (breakdown of the ETFE layer) was never observed up to 15 kV_p test voltage.

4. Bending behaviour

During installation of the in-vessel coils two different bending methods will be applied: The large radius of the coil winding is made by Cluster Roll bending, whereas the various bends of the coil terminations with a small radius are formed by Punch-/Draw bending.

To investigate the effect of bending on the dimensional stability of the conductor compound, both bending methods were applied to TIC samples with a radius between 100 and 170 mm. All samples were baked at a temperature of 150 °C, to simulate the thermal conditioning of the plasma vessel of AUG.

For examination of the bending samples, section profiles were measured and metallurgical inspected. As a result no severe deformation of the conductor compound, especially of the Tefzel insulation layer could be observed. Furthermore the polished micrograph sections did not show any critical changes in the metal structure of copper and steel due to cold forming (Fig. 4).

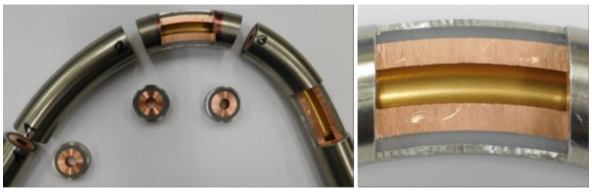

Fig.4: Examination of bended samples

In the present design the minimum bending radius is set to 180 mm, which is nearly two times of the Punch-/Draw sample radius; therefore a degradation of the conductor by the bending process can be excluded.

5. Friction behaviour of the Tefzel interlayer

Contact and friction conditions of the Tefzel interlayer to copper and steel have to be considered as a result of the production process of the prototype conductor.

The application of Tefzel onto the copper tube by extrusion moulding causes a good adhesion on the inside of the Tefzel layer. On the outside the forming of a wavelike surface structure could be observed during the moulding process. In the following manufacturing step the SS-tube is compressed by drawing it together with the Tefzel/copper-unit through a calibrated die. This results in an inhomogeneous contact between Tefzel and Steel: areas of contact and pressure are alternating with areas of a layer gap. Polished section specimen showed gaps in the range of 15 … 35 µm. During tests with samples of the prototype conductor a change in the friction behaviour could be observed after a baking conditioning at 150°C; this effect can be explained by the thermal expansion and the subsequent plastic deformation of the Tefzel layer, which lead to a modified contact condition.

In order to determine the friction coefficient between Tefzel and stainless steel, a friction test with an extruded Tefzel sample and SS-bushing was performed; with a contact pressure in the range of 0.7 to 1.6 MPa, coefficients for static friction of around 0.23 and coefficients for sliding friction of around 0.17 were measured. To simplify the mechanical modelling a uniform friction coefficient of 0.2 was applied to the thermo-mechanical calculations.

6. Calculation of thermo-mechanical behaviour

During operation of the coil the copper conductor is heated up due to ohmic losses. As the Tefzel layer is also acting as a thermal insulation, the stainless steel cladding is warmed up only with a strong delay. Differences in the thermal expansion of the conductor layers lead to a thermo-mechanical loading of the TIC compound. Another loadcase to be investigated is the behaviour under baking conditioning at 150°C.

With respect to the contact condition between the layers the entire length of the conductor can be divided into sections with a sticking and a sliding contact (s. Fig. 5): In the almost overall length the conductor layers are linked together, because in this section the internal shear stresses on the layer surfaces are not sufficient to overcome the adhesion. In this length section all conductor layers show the same total expansion in the longitudinal direction. On the other hand in the sections close to the free ends of the conductor a sliding contact is possible, dependant on the friction and pressure conditions in the Tefzel interlayer. Here the conductor layers show a different expansion in the longitudinal direction. These effects are modelled with FE-calculations as presented in the following subsections.

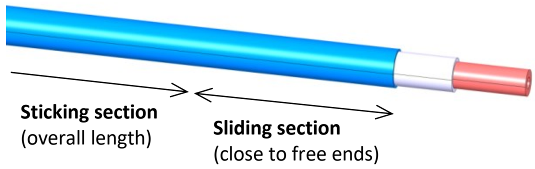

Fig.5: Conductor length with respect to contact condition

For the thermo-mechanical calculations the FEA-Software MSC MARC/Mentat was used (contact analysis, 20-node hexahedral elements with 0.5 mm radial length in outer conductor-layers).

6.1 Straight conductor with loadcase high-current

A finite element analysis on a 20 mm long segment of the TIC conductor was performed to investigate the stress-strain behaviour in the section of a sticking contact due to Ohmic heating; this was done by defining an initial temperature of 20°C and a temperature rise of 60 K in the copper within 4 s. For the total expansion of the conductor in the sticking section a longitudinal strain ε_z= 0.58 ‰ was determined.

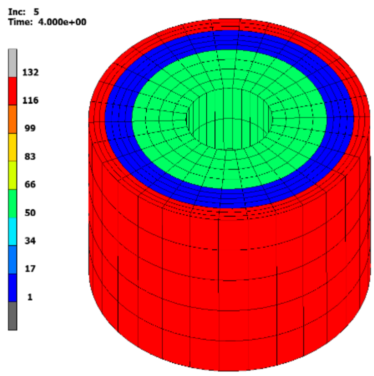

Fig.6: TIC segment with VM-stresses (MPa) due to Ohmic heating

Fig.6 shows the resulting von-Mises stresses of 132 MPa in steel, 4 MPa in Tefzel and 63 MPa in copper; these stresses are well below the allowable strength values R_{p1} of 235 MPa, 40 MPa and 380 MPa respectively.

To estimate the sliding length at the coil terminations an analytical calculation was performed by considering the forces in longitudinal direction: As the copper is subjected to the thermal expansion, it is retained by the cold steel jacket. In the cross section the resulting tensile force on the steel area is balanced by the pressure force on the copper area. Sliding between copper and steel will occur, when this force exceeds the friction force, which is defined by the product of the peripheral area up to the conductor end, the contact pressure and the friction coefficient on the Tefzel layer. For the prototype conductor with an assumed friction coefficient of 0.2 a sliding length of 260 mm to the conductor end is calculated; as the balancing forces are straight proportional to the temperature in this analytical approach, the sliding length is independent of the temperature rise of copper.

The corresponding FE-analysis for a 500 mm long segment with a free end confirmed the assumptions of the analytical calculation: Due to sliding on a length of about 250 mm, the stresses in the layers are relaxing towards the free end and the copper moves out of the steel protection by 0.14 mm.

6.2 Bended conductor with loadcase high-current

To investigate the thermo-mechanical behaviour in the numerous R180 bends of the coil´s feeding section three-dimensional FE-calculations were performed on a 90 deg. bend with an adjoining straight length of 100 mm on both sides; the loadcase conditions of high current, as specified before, were applied. As expected, also in the curvature of the conductor the thermal expansion of copper is restricted by the cold SS-jacket. With a maximum compression in the Tefzel layer of ε= 0.6 % in the middle of the bend the stresses are well within the elastic region of this polymer.

6.3 Behaviour under baking condition

For the sticking section a short TIC segment was subjected to a temperature rise up to 150 °C. The FE-calculation was performed with temperature-dependent values for the tensile modulus and the stress-strain relation without considering the creeping effect. As a result the total strain in longitudinal direction amounts to ε = 0.22 %. The maximum von-Mises stresses are reached at a temperature of 90 °C: 140 MPa in steel, 1.6 MPa in Tefzel and 37 MPa in copper.

The sliding section at the conductor free ends near the vacuum feed-trough was investigated with a straight 3D FE-model and repeated baking as loadcase. As a result an offset of Tefzel at the end in the range of 1 mm was found in addition a gap between Tefzel and steel occurs; the gap size is limited to about 0.4 mm, as this corresponds to the free thermal expansion of Tefzel. In respect to the electric insulation a gap on the atmosphere side of the conductor has no effect and a degradation of the conductor due to baking can be excluded.

7. Thermo-mechanical qualification

To test the behaviour under the heating and cooling condition of the envisaged coil operation straight conductor samples of 3 m and 8 m length were subjected to a cyclic loading (45 and 200 cycles). Both ends of the sample were equipped with position encoders (s. Fig. 7). to measure the expansion of copper conductor and steel jacket.

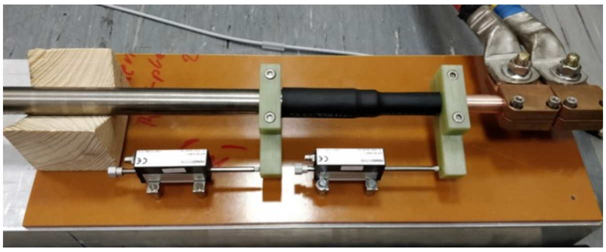

Fig.7: Termination of 3m sample with electrical connection and measuring devices

The cyclic testing was also performed with the modified 8m sample, where the ends were bended with R180 and R100 deg., respectively.

Corresponding calculations for individual cycles with typical conditions were performed.

7.1 Ohmic heating of straight conductor

Both straight samples were heated by a current of 7.5 kA for 10 s. The copper conductor was cooled by water with a flow rate of 1.6 and 9 l/min and showed a temperature rise in the range of 45 to 55 K.

The measured expansion of the steel jacket resulted in an expansion rate of ε_{SS}= 0.05…0.06 %, which was 10 to 15 % higher than calculated.

For the 3m sample cycles were performed before and after baking at 150 °C. It reveals that the offset between SS and copper at the ends increased from 0.1 mm to 0.36 mm corresponding to an increase of the sliding length at the conductor ends by about a factor of 3 from 195 to 635 mm. This effect at the terminations however does not lead to a mechanical or electrical degradation of the conductor.

7.2 Ohmic heating of conductor with bended ends

After a baking procedure the sample was again subjected to a cycling test with a current of 13 kA for 4 s. To simulate the cooling condition in the 40 m long conductor of the whole coil, a time-delayed cooling with a water flow rate of 9 l/min in-between the cycles was provided.

The measure temperature rise of copper was 58 K. The expansion rate of the steel jacket in the straight section was determined to ε_{SS}= 0.058 %, which was slightly above the calculated rate. The measured expansions of SS and copper around the bending areas confirmed the calculated behaviour of the conductor, as sliding between SS and copper is blocked by the bends.

As part of the qualification, by increasing the load period from 4 to 10 s, the 8m sample was thermally overloaded up to a factor of 3. The subsequent electrical examinations did not show any degradation of the conductor.

Cut-out probes in the bending region did not reveal a compression of the Tefzel layer, caused by the cycling tests and the overload.

8. Conclusion

To qualify the electrical and thermal properties of the chosen TIC conductor, cycling tests with high current were performed; the corresponding FEM calculations of these thermo-mechanical tests were in good agreement with the measured expansions of the conductor. In addition the electrical examinations were done by high voltage and partial discharge tests. In all of these qualification activities no severe issues concerning the envisaged coil operation were detected.

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