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Title: **Verification tests of critical bolted connections of the W7-X coils.**

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Abstract

The functionality of the most critical bolted connection between a coil and the central support structure of the Wendelstein 7-X (W7-X) magnet system was mechanically tested on full scale mock-ups. The object of the test campaign was to verify the final design, in particular the load capability of the connection. Special attention was drawn to its individual components (bolts, sleeves, and spherical washers) and the assembly steps, here especially the positioning and welding of wedges. Furthermore, the instrumentation foreseen for bolts on W7-X was studied.

A consecutive series of tests was performed using mock-ups equipped with modified components. Each test sequence included activities at ambient temperature (assembly, bolt preload, and check of the measurement system) and load tests in liquid nitrogen. To simulate the expected life time of W7-X, several thousand load cycles were executed. Additionally, high load tests were performed to investigate the limits of the connection. It was shown that the connection could take the nominal loads with a safety margin of about 1.2. Above this the bolts starts to deform plastically. A MoS_2 lubricant layer introduced between the relevant sliding surfaces of the bolted connection significantly reduced stick-slip which was detected during previous test campaigns.

This paper gives an overview on the functionality test and main conclusions of the experimental test campaign.

1. Introduction

The most critical components of the central support structure of the Wendelstein 7-X (W7-X) magnet system are their bolted connections to the coils [4]. This so-called Central Support Elements (CSEs) have to transfer high forces during stellerator operation. Analyses on CSEs using complex FE models [1], [2] predict axial loads from ca. -3.2 MN (compression) up to ca.1.5 MN (tension), shear forces up to 1.4 MN, and bending moments up to 350 kNm at 3 Tesla (100% load) axial magnetic field during operation. The most critical bolted connection (called NPC1Z1, Fig.1) shows in addition to high loads on the bolts a significant opening of the interface flange. To check the functionality of this connection test campaigns were performed on full scale mock-ups in order to verify that the connection will be able to take the loads expected during W7-X operation at 4K. Three mock-ups representing the CSE NPC1Z1 were prepared, using the same materials as in the real W7-X, and subjected to the tests. Due to symmetry, for the test mock-ups arrangements with only 3 instead of matrix of 3x3 bolts (see Fig.1b) were used. Pulling forces Fx, oriented along the bolts axes and transversal forces Fz, generated bending moments and shear stresses acting in the 3-bolts plane (Fig. 2b) corresponding to nominal loads in the magnet system, were applied on mock-ups during the tests. To simulate the expected life time of W7-X, several thousand load cycles were executed. Subsequently, high load tests were performed to investigate the limits of this bolted connection. Previous test campaigns [3] have shown that it was able to sustain cyclic loads for the entire W7-X lifetime, but undesirable effects - like stick-slip on the sliding surfaces of the connection - have been observed.

2. Experimental procedure

Based on previous test results, additional FE calculations, and optimized CSE components as well as assembly procedures, the CSE connection was significantly modified. To verify the final design of the CSE and procedures, a consecutive series of tests was performed with a third mock-up (mock-up C). The design of mock-up C includes the following main modifications in relation to previous tested mock-ups [3]:

- Modified design of SUPERBOLT ®nuts; qualified technology of jack bolts manufacturing and coating of jack bolts threads increased their load capability and reduced significantly friction during tightening. Consequently, a new tightening procedure of nuts was developed - required bolt preload could be achieved using reduced torque and in shorter time.
- To compensate the influence of machining and assembly tolerances on bending of the bolts, spherical washers and centring sleeves were introduced.
- During the test sequence, especially with mock-ups B [3], fretting marks associated to stick-slip were observed on the sliding surfaces between wedges and shoulders. In W7-X, mechanical disturbances related to such stick-slip events have to be avoided since they may induce quenches of the superconducting magnets. Therefore, on mock-up C a MoS_2 lubricant layer was introduced between the relevant sliding surfaces.
- Special attention was drawn to positioning and welding of wedges. A new design of welds (“double welds”) and improved welding procedures – wedges welded before coil and ring assembly - reduces wedge deformations due to the welding process. Using the improved positioning procedure of wedges it is possible to keep the required gap tolerances between wedges and shoulders.
- The instrumentation foreseen for CSE bolts on W7-X was tested.

The test sequence with mock-up C included activities at ambient temperature (wedge welding, coating of shoulders with dry MoS_2, mock-up assembly, bolt preload) and the cyclic load test at 77 K. Finally, high load test on the mock-up were performed. During the load tests mock-up C was immersed in LN_2. To apply axial and shear forces the mock-up was connected to two hydraulic pistons and to the base frame (Fig. 3).

Data acquisition was similar to the previous test and is described in [3]. Acoustic monitoring based on accelerometer and piezo-sensors was applied on different places of the mock-up to record the expected stick-slip events during tests [5]. Furthermore, the instrumentation foreseen for the CSE bolts on W7-X was applied.

Executed test activities can be divided into following steps:

- Assembly of the mock-up and bolt preload (up to 490 kN/bolt) at RT; installation into the base frame.
- To check consistency of the mechanical response of the mock-ups A, B and C at 77 K, five load cycles at different load levels were performed.
- The cycle test: 3200 load cycles at 80% of the nominal load (i.e Fx = 387.2 kN, Fz = 268.8 kN) and 400 cycles at 100% of nominal load level (Fx = 484 kN, Fz =336 kN) corresponding to a the load level expected at B~3T operation of W7-X. The loads Fx and Fz were always applied simultaneously to the mock-up.
- Thermal cycle: after completion of the cycle test campaign, the mock-up C was warmed up to RT and cooled down again to 77 K. The thermal cycle was realised within approx. 72 h.
- The high load test included tree main sequences:
    - Stepwise increasing of the loads from 40% up to 100% of nominal load level; at each load step 10 load cycles were performed.

- Starting from 100% of the nominal load level only the horizontal force (Fz) was stepwise increased (from Fz = 336 kN to 440 kN, Fx = 484 kN = const).
- Starting from Fz =440 kN and Fx = 484 kN, both loads were simultaneously and stepwise increased to investigate the limits of the connection. Due to limitations of the test device, the maximal achieved loads were Fx = 653 kN (vertical force) and Fz = 594 kN (horizontal force).

An overview on the cycle and high load tests is shown in Fig. 4.

3. Summary of main results

The assembly of the mock-up was done without serious complication. A common problem of all mock-ups was the integration of sleeves and the SUPERBOLT® due to limited space. Additionally, for mock-up C, an increased number of sensors reduced the available space further.

Bolt preload was applied successfully. In comparison to the previous tests, the improved tightening procedure reduced the bolt tightening time by about a factor of 2. Contrary to before, no plastic deformation on jack bolts of the SUPERBOLT® nuts with modified design was detected after test.

Good agreement to previous tests could be shown by the consistency checks.

During the tests campaign special interest was drawn to the observation and investigation of stick-slip events. During the cyclic test with mock-up B [3] first acoustic signals were detected after ~1000 cycles at 80% of the nominal load. Based on signal analyses, the most probable origin for the stick-slip was sliding of the wedge surface on the support block. Throughout the tests with mock-up C, piezo-sensors were

positioned close to the potential location of stick-slip, i. e. near the wedges, two sensors on both sides of the mock-up and additional two sensors - near the connection to the vertical hydraulic cylinder. High sampling rates were used to be able to localize the source of stick-slip events. Recorded data were analysed with respect to time differences of the acoustic signals at the different sensor locations for triangulation. The first stick-slip event on the wedge surfaces was observed after 3050 cycles during cycle test at 80% of the nominal load. The next events appeared at a load level of 90% (single events), and after 3500 cycles at 100% of the nominal load level. During the high load test, starting from 80% load level, during each load step an increasing numbers of stick-slip events occurred.

The stresses and opening of about 1 mm of the interface flange was in the same range as observed in the previous tests [3]. No major plastification (except < 2 kN loss of preload on bolts) occurred during the cycle test. At high load test, beginning from a vertical load of Fx =484 kN (100%) and a horizontal load of Fz=414 kN (~123%) significant loss of bolt preload started (>5%), and increased with each load cycle. The largest plastic deformation occurred on the bolts, which is in agreement with previous experiences. No indication of fracture was observed. The maximal applied forces during the high load test were limited by the load device.

The disassembly of the mock-up after the test was performed without any complications.

4. Conclusions

The most critical CSE connection NPC1Z1 was simulated in a full scale cyclic load test campaign. The performed tests have shown that the bolted connection can take loads corresponding to a magnetic field of 2.5 T on the stellarator axis. The expected life time

of W7-X was simulated by more than 3000 load cycles without mechanical defects. Load levels corresponding to ~ 3T in W7-X brings the bolted connection close to its plastic limit. In contradiction to the real operating temperature of the CSEs at about 5 K, the tests were performed at 77 K. The increase of the material strength from 77 K to 5 K will give some safety margin.

A MoS_2 lubricant layer between the relevant sliding surfaces of the bolted connection is able to avoid stick-slip during the W7-X life expectancy.

The instrumentation foreseen for the CSE bolts on W7-X were tested successfully and will be installed into the W7-X magnet system.

5. References

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