Bolted coil support at the W7-X module interface

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An overview of the design, FE analysis results, tests, and assembly strategy of the bolted connection between the coils of neighboring W7-X modules is presented. This connection, based on an accurately machined bridge, allows the accommodation of expected misalignments of the coil positions up to ±23 mm and 1 deg which might be due to assembly tolerances and module adjustments. The joint is capable to cope with forces up to 1.3 MN and moments up to 0.2 MNm. Loads are transmitted by a combination of form lock provided by tapered coil block shoulders, and by friction on the bottom of the blocks. A special friction-enhancing foils inserted between the bridge and coil block bottom surfaces ensure a friction factor >0.5. Non-linear FE analyses, based on elastic-plastic material models, show that local plastification and even slippage in spite of the initial high friction are unavoidable but stay within an acceptable margin. In parallel, machining and assembly tests were carried out to check and simplify the design further, and to develop the manufacturing strategy.

Keywords: W7-X, stellarator, magnet system, support elements, bolted connection, friction foil

1. Introduction

The W7-X stellarator [1] is being constructed in a modular fashion and consists of 5 identical modules. The W7-X superconducting coil system and central support structure (CSS) follows this modular concept. At the final assembly stage of the magnet structure, the CSS sections and non planar coils (of type 5, NPC5) of the neighboring modules are to be joined together by bolted connections. Those between the coils are identical flip rotated joints, the so called Lateral Support Elements D06 (LSE D06) (Fig.1). Additional support at this module interface is also provided by one pair of sliding contacts between the coils [2].

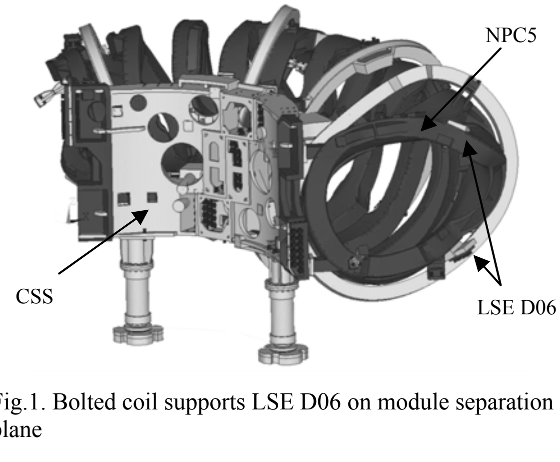

Fig.1. Bolted coil supports LSE D06 on module separation plane

The connection has to transmit operational loads up to 1.3 MN in axial and lateral (shear force) directions, and moments up to 0.2 MNm [3]. A non-welded design is required due to difficult accessibility at that state of assembly, and the large weld seam size required for coping with such enormous loads. In this paper a short overview of the functional requirements, design, finite element (FE) analysis results, tests, and assembly strategy of the LSE D06 is presented.

2. LSE D06 design

2.1 Layout and functional requirements

The LSE D06 consists of a steel piece, the so called "bridge". This is bolted on both sides to the steel coil "blocks" which are welded to both adjacent NPC5. The coil blocks (Fig.2) have an U-shaped recess for the

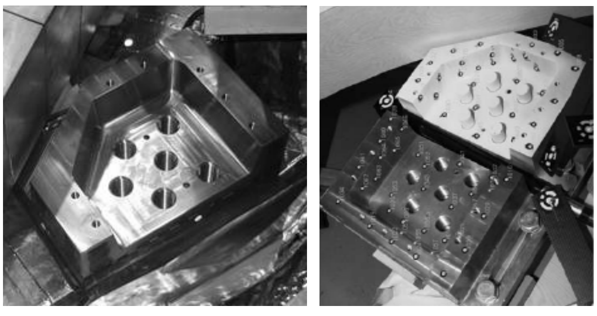

Fig.2. Coil block welded to NPC5 (left). Coil blocks of a test mock-up simulating assembly conditions (right) with reference marks for photogrammetric scanning.

bridge installation in order to provide form locking in addition to force transfer by friction. Only the relatively small separating forces between the modules which are expected at some special operation conditions are supported solely by friction.

The initial design of LSE D06 [4] included an Inconel straight bridge, shim plates, wedges and jack bolts (Fig.3). The wedges and shim plates were foreseen to be tailor-made in order to accommodate for the necessary position adjustments between modules, and to

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take care of possible misalignments. This solution was able to compensate the misalignments of coil blocks up to ±10 mm in each direction. However, accurate estimations of maximal possible misalignments, mainly due to individual positioning of each module in order to optimise the W7-X magnet field and in addition due to the sum of all manufacturing and assembly inaccuracies, showed that up to ±23 mm in all directions have to be compensated by the LSE D06 design.

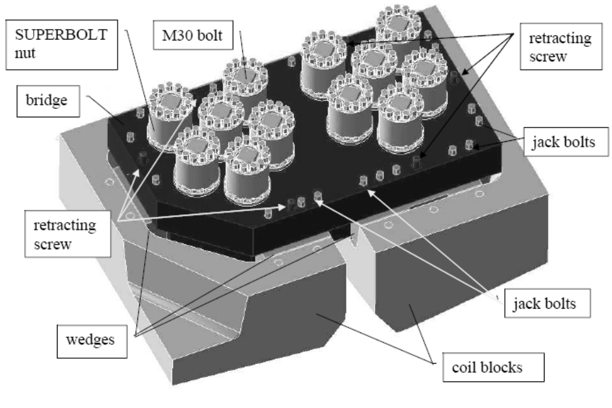

Fig.3. Initial LSE D06 design [4]

Furthermore, a lot of small components and complicated tightening procedures of this design would have made assembly difficult and time consuming considering the limited space. Therefore, an alternative joint with a kinked “mono-block” bridge (Fig.4) without shims, wedges and jack bolts was developed.

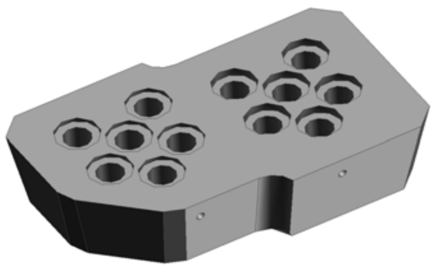

Fig.4. CAD model of the mono-block bridge for the maximal expected shift of adjacent coil blocks.

In Fig.5 the mono-block LSE D06 FE model, implemented into the global model of the W7-X support structure [2], is shown.

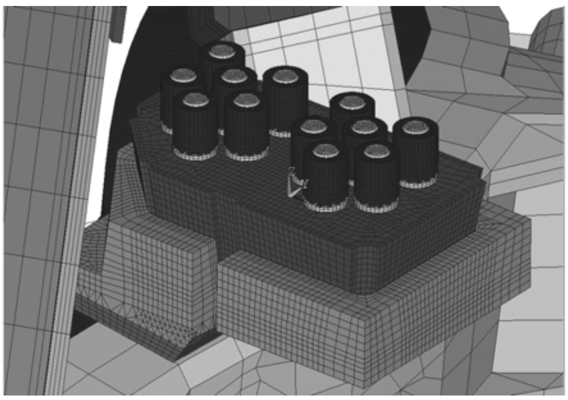

Fig.5. FE model of mono-block LSE D06 introduced in the magnet system FE global model.

The mono-block bridge solution requires highly accurate measurements and machining of the bridge to get its contact surfaces aligned with the corresponding surfaces of the coil blocks. FE calculations showed that for a safe transfer of the operational loads a compressive preload between bridge and coil block shoulders is required [2]. This is achieved by pressing a slightly oversized bridge (cf. Fig.9) with a pre-tension of 430 kN into the coil block shoulders using six M30 bolts per coil block. MoS_2 coated bridge side faces shall guarantee smooth bridge installation. In assembled position, after bolt pre-loading, the bottom surfaces of the bridge and the coil blocks must be in contact. Special friction-enhancing foils inserted between these contact surfaces increase the frictional capacity of the connection. Intensive FE analyses confirmed that austenitic stainless steel (EN 1.4429) can be used as bridge material even though it is loaded locally to the plastic limit. Use of Inconel 718 (EN 2.4668), as envisaged for the original straight bridge, could thus be avoided. It would have been difficult to machine to required accuracy.

2.2 FE analysis results

The LSE D06 design was preliminary investigated using a local FE model [4]. More detailed results were later obtained from the FE global model of the magnet system with an integrated local FE model of the LSE DO6. Static analyses including bolt preload at RT, cool-down to 4K, and operation were carried out. Geometrical and material parameters were investigated in detail:

- An initial contact gap between bottom of the oversized bridge and the coil blocks (cf.Fig.9); this influences the distribution between frictional load capacity and form locking within the shoulders on the one hand, and the stiffness of the connection on the other hand. Displacements and distribution of forces and moments within all coil support structure (e.g. module flanges, sliding contacts) depend to some extend on the stiffness of the LSE D06.
- The shape of mono-block bridge must be adapted to module adjustment and assembly inaccuracies; extremely kinked bridge shapes varying up to ±23 mm in each direction were studied.
- Three modes of FE simulations were carried out: 1) Conventional static analysis with the EN 1.4429 steel bridge 2) Classical limit analysis where the nominal load is increased until full plastic yielding takes place in the most loaded cross section, and 3) Limit analysis with consideration of the serration effect on the yield curve [5, 6].

Main conclusions from the FE analyses can be formulated as follows:

- Local plastification of the bridge and the coil block shoulders is unavoidable.
- The coil block shoulders do not yield during bolt preload at room temperature even for an initial gap of 500 μm at the bottom surfaces.

- The contact pressure after preload and cool down at the bottom of the bridge is nearly independent of the initial gap settings within the investigated range of 30-500 µm for the bottom surface.
- With an assumed 500 µm initial gap at the bottom and friction factor of µ=0.05 on MoS_2 coated shoulders, the bottom contact is closed at only 20 % of the bolt preload. Even for the extreme initial gap of 700 µm at the bottom and 0.1 friction between shoulders and the bridge, the bottom gap already closes at about 45% of the preload.
- The plastic collapse of LSE D06 is determined predominantly by the persistency of the coil block shoulders (cf. Fig.6), and secondly by the M30 bolts. The steel bridge of EN 1.4429 is not the critical component regarding failure of the connection.
- In all considered cases using limit analyses, the connection reaches the required safety factor of 1.5 defined as the failure load divided by the design load.

The tensile stresses on the EN 1.4429 steel bridge are not critical.

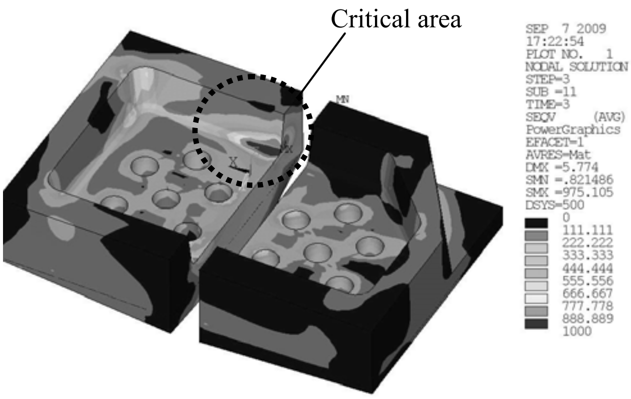

Fig.6. Critical area on coil block shoulder (von Mises stresses in coil blocks at 120% of operational design load at 4K shown)

The cyclic analysis performed using bi-linear elastic-plastic material with hardening and a conservative assumption that friction factor drops down to 0.3 at the bottom shows that the plastic strains in the shoulder and the sliding of the bridge converge to a stable value within 10 load cycles. The maximum equivalent plastic strain is less than 1% and the relative local movement between the bridge and shoulders stabilizes at less than 0.5 mm.

3. Tests on friction enhancing foil

FE simulations show, that the condition for the coil block shoulders is less critical when the bigger part of the loads in operation is transferred by friction between the bridge and the coil blocks, instead of via the shoulders. Therefore a coefficient of friction of ≥ 0.5 is required which can be achieved by installing a special friction enhancing foil. EKagrip® friction sheet (ESK comp., Kempten/Germany) is a steel foil with a friction-enhancing coating based on electroless nickel plated with embedded diamond particles of defined size. After coating, the foil is heat-treated to relieve inherent tensile stresses and to impart sufficient diamond retention strength. The foil is characterized by a micro-scale interlocking with the joint surfaces achieving static friction increase by up to 300%. Key parameters are the counterpart material, the counterpart surface roughness and the applied surface pressure.

To select and qualify the right EKagrip® product a series of tests has been performed (Fig. 7) at RT and 77 K. As standard test parameters for the friction tests machined stainless steel (EN 1.4429) surfaces with a typical roughness of the coil block surface R_z = 4 µm were used. Where no pressure or particle size is indicated in the diagram, compressive stresses of 45 MPa were studied using EKagrip25 PLUS foils with embedded diamond particles having an average diameter of 25 µm. At the LSE D06 a nominal surface pressure of ~75 MPa after bolt preload is expected. The coil blocks are machined from EN 1.4429 but it could be shown that there is no significant difference to EN 1.3960 (applied for module flange) with respect to the coefficient of friction.

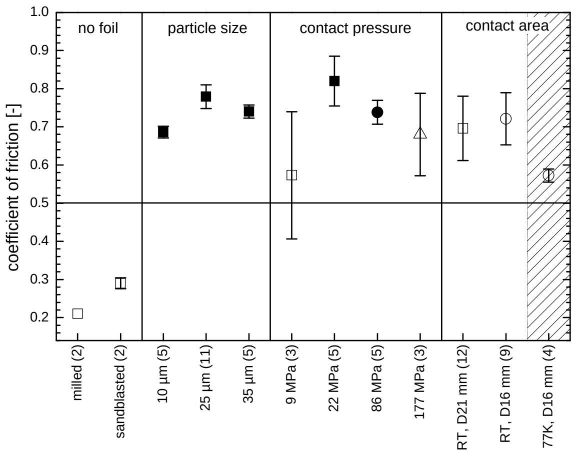

Fig.7. Measured coefficient of frictions versus different parameters using friction enhancing foils. Gray shaded area: cold tests; squares: diameter of circular contact area 21 mm, circles: 16 mm, and triangles: 10 mm; open symbols: updated test set-up to allow cyclic loads. Error bars are standard deviations of the average values. The numbers of performed tests are given in brackets.

Figure 7 shows that the static coefficient of friction μ is clearly increased once a friction enhancing foil is used. $\mu > 0.5$ was verified under cold conditions by immersing the experimental set-up in a LN_2 bath. After up to 4000 cyclic loads of about 80% of the fictional limit (i. e. without sliding) no degradation of μ was observed. The EKagrip® foil was tested once in liquid helium, the coefficient of friction was similar to the one in LN_2.

4. Assembly tests and strategy

A series of tests was performed to check the feasibility of the required measurement and machining accuracy for the mono-block bridge, the fitting accuracy of the mounted connection, and to develop the assembly strategy. Assembly tests were performed using LSE D06 mock-ups under realistic conditions simulating also the limited space on site.

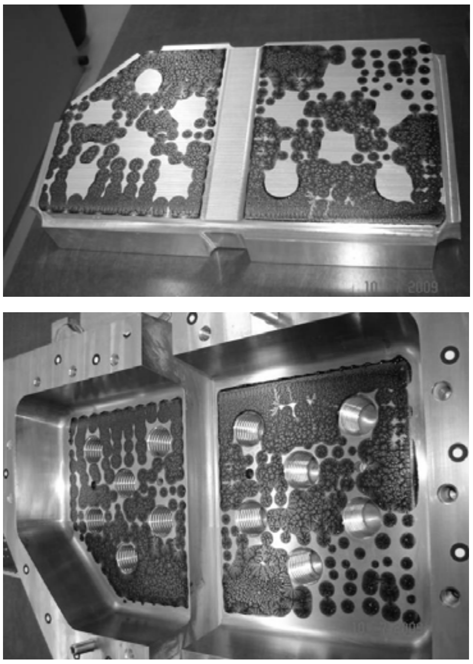

Fig.8. Feasibility test: check of matching of contact surfaces at the bottom of the mono-block bridge.

The developed manufacturing procedure for the mono-block LSE D06, based on 3D and photogrammetric scanning (company Padelt 3DSysteme GmbH, Strausberg /Germany), can be summarized as follows:

- The coil block shoulders are measured individually for each coil using 3D laser scan before final positioning of the module.
- The relative position between two adjacent coil blocks after final module installation and alignment is determined using photogrammetric scanning of reference points marked on the blocks (cf. Fig.2).
- The design shape of the mono-block is constructed by CAD from the measurements obtained in the previous steps, and corrected for specified oversize at the sides of 25 µm and gaps at the bottom of 200 µm (Fig.9).
- During manufacturing the shape of the mono-block is monitored using laser scan until the measured values are within the specified tolerance bands which are ±50 µm for the bottom contact surface and ±25 µm for the side contact surfaces.

It is important to avoid any separation of adjacent coil blocks during the time between the measurements and the final LSE D06 assembly. FE simulations show that relative coil block displacements (<0.5mm) in other directions than moving apart, for instance caused by temperature differences or assembly activities, are "automatically" resolved during assembly of the connection due to the tapered side contact surfaces.

Instrumentation of coil blocks is ongoing. Stresses in highly loaded regions of coil blocks and the bridge will be monitored during operation using strain gauges [7].

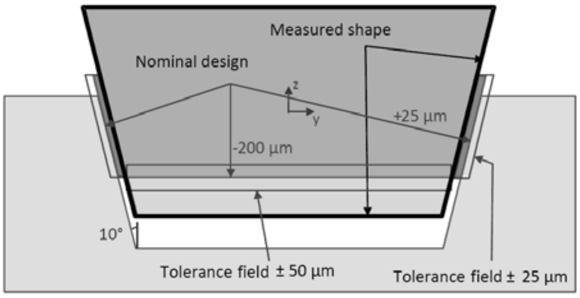

Fig.9. Measured and nominal design shape of mono-block with tolerances

5. Conclusions

The W7-X coil support structure includes ten highly loaded LSE D06 connections. The functional requirements for these bolted elements at the W7-X module interfaces can be realized by kinked stainless steel mono-block bridges. Due to individual positioning of W7-X modules and individual tolerance chains, each of these connections is unique. Proper function of the connection relies on high friction between the bottom surface of the bridge and the coil block. This is achieved by inserting EKagrip® foils which were qualified by extensive tests. Nonlinear FE analyses based on elastic-plastic material models show that local plastification and even slippage are unavoidable in spite of the high friction, but stay within acceptable margins. Trials demonstrated that the tight manufacturing tolerances required for the press-fit of the bridge within the coil blocks can be realized. The installation of the first two LSE D06 connections is planned for end of 2010.

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