# Bolted coil support at the W7-X module interface

Andrzej Dudek[a], Andre Benndorf[a], Victor Bykov[a], Paul van Eeten[b], Joris Fellinger[a],
Dag Hathiramani[a], Klaus Höchel[a], Dieter Kuse[a], Frank Meisel[a], Steffen Padelt[b], Dirk Pilopp[a],
Mathias Schülke[a], Lars Sonnerup[a], Felix Schauer[a]

*[a]Max Planck Institut für Plasmaphysik, D-17491 Greifswald, Germany*
*[b]Padelt 3D Systeme GmbH, D-15344 Strausberg, Germany*

The paper presents an overview of the design, finite element (FE) analysis results, tests, and assembly strategy of the bolted connection between the coils of neighboring W7-X modules. The design is based on an accurately machined bridge and allows the accommodation of expected misalignments of the coil positions up to ±23 mm and 1 deg. 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. Special friction-enhancing foils are inserted between the bridge bottom surfaces and coil blocks to ensure a friction factor above 0.5. Non-linear FE analyses with 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 have been 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 sectors 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].

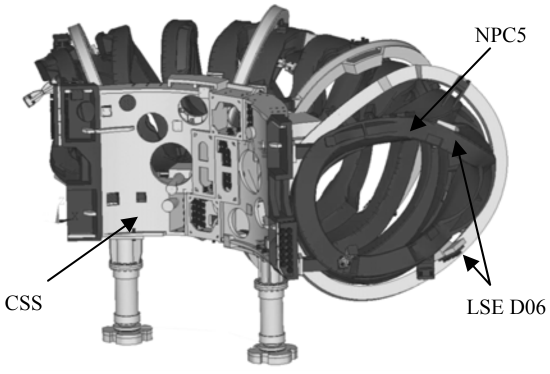

Fig.1. Bolted coil supports LSE D06 on module separation plane.

The LSE D06 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 due to requirements for the large weld seam size to cope with such enormous loads. A short overview of the functional requirements, design, finite element (FE) analysis results, tests, and assembly strategy of the LSE D06 is presented below.

## 2. LSE D06 design

### 2.1 Layout and functional requirements

The LSE D06 consists of a massive stainless steel "bridge", which is bolted on both sides to the steel coil "blocks". The coil blocks (Fig.2) are welded to both adjacent NPC5 and have an U-shaped recess for the bridge installation in order to provide form locking in addition to force transfer by friction. Only the relatively small separating forces between the coils which are expected at some special operation conditions are supported solely by friction.

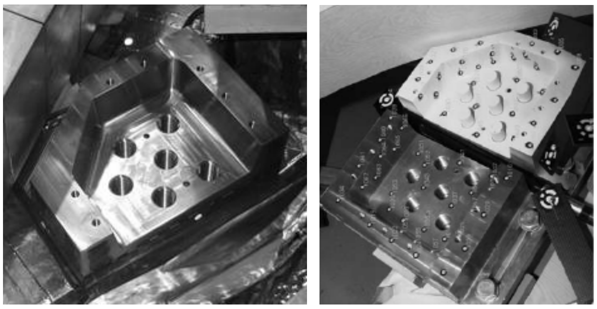

Fig.2. Coil block welded to NPC5 (left). Coil blocks of a test mock-up simulating assembly conditions (right) with reference marks for photogrammetric scanning.

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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*Corresponding author's email: Andrzej.Dudek@ipp.mpg.de*

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.

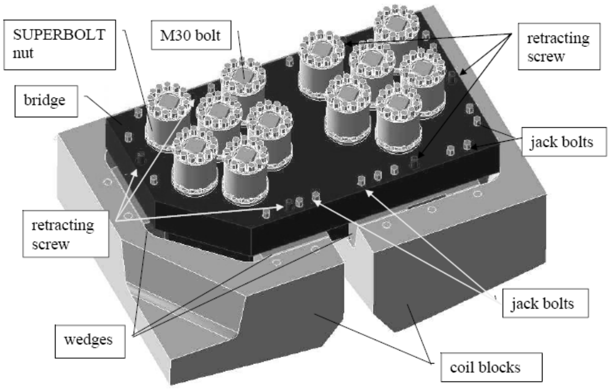

Fig.3. Initial LSE D06 design [4].

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.

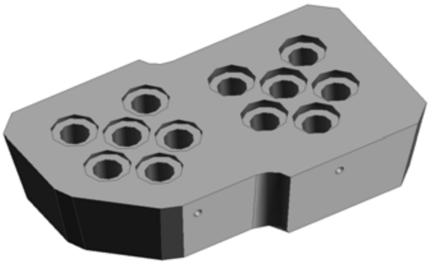

Fig.4. CAD model of the mono-block bridge for the maximal expected shift of adjacent coil blocks.

The mono-block LSE D06 FE model implemented into the global model of the W7-X magnet system [2] is shown in Fig. 5.

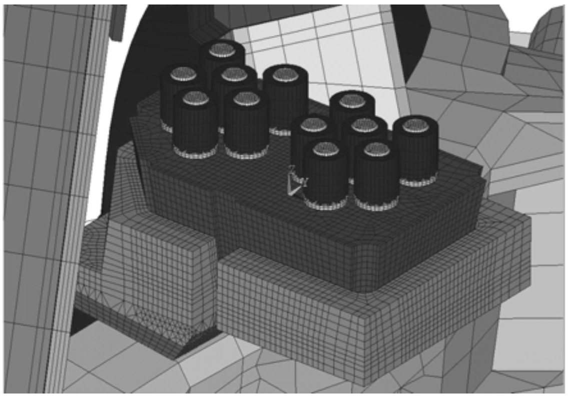

Fig.5. FE model of mono-block LSE D06 introduced in magnet system FE global model.

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 show 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) into the coil block shoulders. Six Inconel M30 bolts per coil block with a pre-tension of 430 kN ensure that the bottom surfaces of the bridge and the coil blocks are in contact. Special friction-enhancing foils inserted between these contact surfaces increase the frictional capacity of the connection. $MoS_2$ coated bridge side faces shall guarantee smooth bridge installation. 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 obtained later from the FE global model of the magnet system with an integrated local detail 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 as follows:

- 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, which 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 at the bottom of the bridge after preload and cool down is nearly independent of the initial gap there within the investigated range of 30-500 μm.
- With an assumed 500 μm initial gap at the bottom and friction factor of $\mu$=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 and secondly by the M30 bolts. The most critical area is shown in Fig.6. The steel bridge of EN 1.4429 is not the critical component regarding failure of the connection.
- Limit analyses show that in all considered cases the connection reaches the required safety factor of 1.5 defined as the failure load divided by the design load.

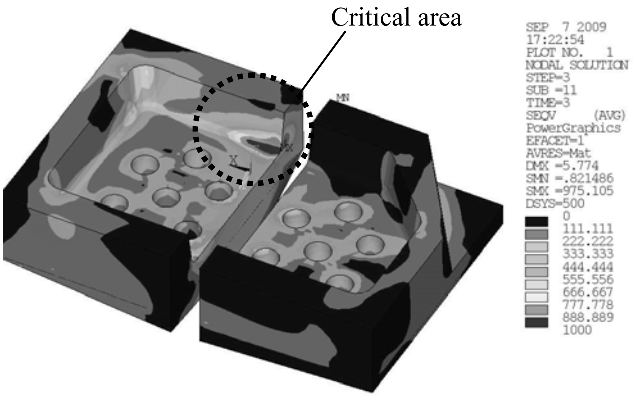

Fig.6. Critical area on coil block shoulder (von Mises stresses in coil blocks at120% of operational design load at 4K shown).

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 plating 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.

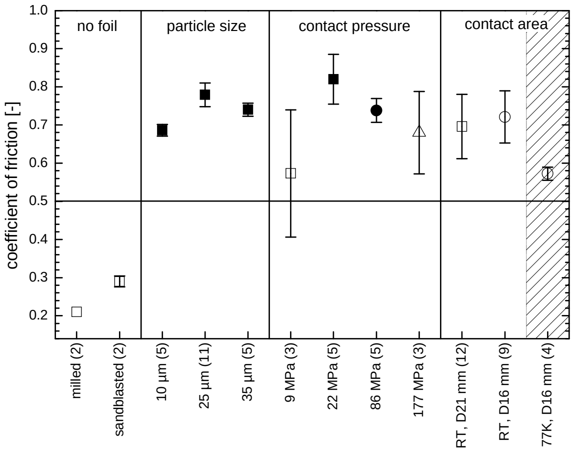

Fig.7. Measured coefficient of frictions versus different parameters using friction enhancing foils. Gray shaded area: cold tests; squares: diameter of circular contact area 21 mm, circles: 16 mm, and triangles: 10 mm; open symbols: updated test set-up to allow cyclic loads. Error bars are standard deviations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

Figure 7 shows that the static coefficient of friction $\mu$ 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 $\mu$ 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.

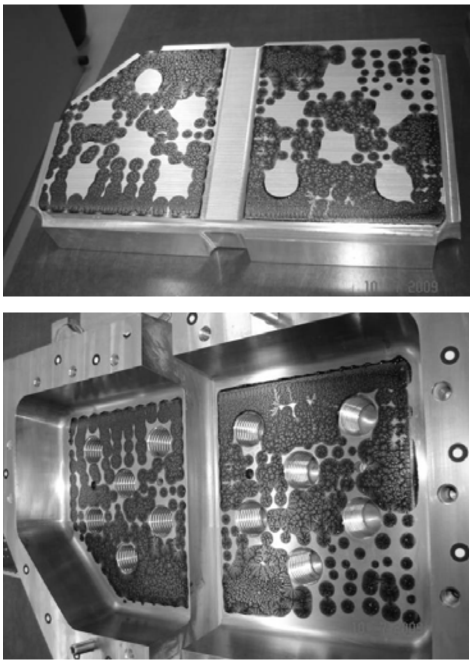

Fig.8. Feasibility test: check of matching of contact surfaces at the bottom of the mono-block bridge.

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].

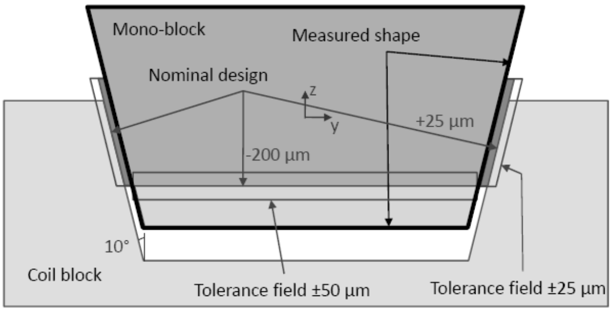

Fig.9. Measured and nominal design shape of mono-block with tolerances (bolts not presented).

## 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 with elastic-plastic material models show that local plastification (less than 1%) and even slippage (relative local movement less than 0.5 mm) is unavoidable in spite of the high friction and is acceptable for the present design. 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.

## References

[1] L. Wegener, Status of Wendelstein 7-X construction. Fusion Engineering and Design, 84 (2009) 106-112

[2] V. Bykov , et al., Structural analysis of W7-X: from design to assembly and operation. Paper presented on this conference

[3] V. Bykov, F. Schauer, K. Egorov, P. Van Eeten, C. Damiani, A. Dübner, et al., "Structural analysis of W7-X: main results and critical issues", Fusion Engineering and Design 82 (2007) 1538–1548

[4] P. van Eeten, D. Hathiramani, V. Bykov, A. Cardella, A. Dudek, J. Holluba, et al., Design and test of the support element of the W7-X superconducting magnets, in: 22nd SOFE Symposium on Fusion Engineering 2007, IEEE 2007, ISBN: 978-1-4244-1194-8

[5] L. Ciupinski , et al., Limit analysis of W7-X critical magnest system components with consideration of material serration effect. Paper presented on this conference

[6] E. Briani , et al, Limit analysis of narrow support elements in W7-X considering the serration effect of the stress-strain relation at 4K, Paper presented on this conference

J.P.Kallmeyer , et al., Mechanical instrumentation of the Wendelstein 7-X cryogenic structure. Paper presented on this conference