Design and test of the support elements of the W7-X magnet system


Abstract— The Wendelstein 7-X stellarator is presently under construction and assembly in Greifswald, Germany. Its ultimate goal is to verify that such stellarator magnetic confinement concept is a viable option for a demonstration power-plant.

The superconducting magnet system, capable to generate a average magnetic field up to 3 Tesla at the magnetic axis, is basically composed of non-planar and planar coils, and of a central support structure to which they are connected. This system is a complex mechanical structure which has to fulfill demanding requirements in terms of accuracy of the magnetic field, capability to take the operational loads, suitability of the manufacturing tolerances and assembly scheme, interfaces.

The magnet system is interconnected by support elements which have been conceived and designed in such a way to react to the loads in a “balanced way”, while complying with the other requirements mentioned above. Given the unprecedented complexity of such mechanical scheme, an integrated programme of design, FE analyses, tests, assembly trials has been undertaken.

This paper gives an overview of the way this structure is conceived, of its key support elements, and of the results of the analyses and tests carried out so far.

W7-X, stellarator, magnet system, support elements

I. INTRODUCTION

The main objective of WENDELSTEIN 7-X (W7-X), now under manufacturing [1] and assembly [2], is the demonstration of the inherent steady state capability of a stellarator at reactor relevant plasma parameters [3].

Fig. 1 shows a 3-D view of the basic components of the stellarator. The superconducting magnet system consists of 50 Non-Planar-Coils (NPC) and 20 Planar-Coils (PC), connected between them and to a Central Support Structure (CSS). Each coil consists of a winding pack of Cu-stabilized Nb-Ti strands into an Aluminium jacket, embedded and enclosed into a stainless steel casing (DIN 1.3960, i.e. AISI 316 LN), the last one providing the structural stiffness to the coil itself. The CSS is also made of stainless steel (AISI 316 LN).

70 super conducting coils (50 non planar coils 5 types, 20 planar coils 2 types), weight 3600 kN, Cryostat, 10⁻⁵ mbar, 4 K
Machine base Central support structure (CSS), weight 600 kN

Plasma vessel Divertor
Helically wound plasma axis, B_average_max = 3T, R=5.5m, a=0.53m, V=30m³
299 Ports

Figure 1. 3-D view of the W7-X basic device.

From the mechanical point of view, the magnet system has to fulfil a series of stringent requirements:

- high positional accuracy, in order to generate a very precise magnetic field (B), where deviations from stellarator-symmetry should be ~10⁻⁴ times smaller than the magnetic field itself at the plasma axis. This, in turn, reflects on manufacturing and assembly tolerances and sequences.
- intricate 3-D geometry and interfaces with many other surrounding components (ports, thermal shields, etc.).
• capability to take the high Electromagnetic (EM) forces during operation, with limited stresses (for a safe structural response) and deformations (mainly to avoid collisions with the other components).

The magnet system is laid out in a pentagonal scheme, see Fig. 2 where only the NPC are shown: each of the five identical modules is composed of 2 identical half modules, one flip-rotated with respect to the other. The half module consists of 5 different types of NPC and 2 of PC, as shown in Fig. 3.

Figure 2. Top and side view of the W7-X pentagonal magnet system, with also the EM forces shown (horizontal and vertical forces, not in scale). Note that the number close to each vector corresponds to the coil type.

To generate the required magnetic field, various current profiles (depending on the plasma scenario) can be run into the coils, which induce high EM forces and moments (one example is given in Table I, see also caption of Fig. 4).

TABLE I. EXAMPLE OF CURRENTS [MA] AND EM FORCES [MN, MN•MM] ON THE COILS

<table>
<thead>
<tr>
<th>Coil</th>
<th>Current</th>
<th>Fx</th>
<th>Fy</th>
<th>Fz</th>
<th>Mx</th>
<th>My</th>
<th>Mz</th>
</tr>
</thead>
<tbody>
<tr>
<td>NPC1</td>
<td>1.97</td>
<td>-2.56</td>
<td>-0.04</td>
<td>-0.86</td>
<td>-0.20</td>
<td>0.33</td>
<td>0.09</td>
</tr>
<tr>
<td>NPC2</td>
<td>1.93</td>
<td>-3.83</td>
<td>-0.82</td>
<td>-1.26</td>
<td>1.31</td>
<td>-1.62</td>
<td>-1.88</td>
</tr>
<tr>
<td>NPC3</td>
<td>1.83</td>
<td>-2.61</td>
<td>-1.71</td>
<td>-2.12</td>
<td>0.57</td>
<td>0.83</td>
<td>-0.05</td>
</tr>
<tr>
<td>NPC4</td>
<td>1.48</td>
<td>-1.16</td>
<td>-0.60</td>
<td>-2.37</td>
<td>-1.32</td>
<td>1.14</td>
<td>0.33</td>
</tr>
<tr>
<td>NPC5</td>
<td>1.46</td>
<td>1.21</td>
<td>-0.81</td>
<td>-0.77</td>
<td>-0.11</td>
<td>2.43</td>
<td>-0.19</td>
</tr>
<tr>
<td>PCA</td>
<td>-0.42</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>PCB</td>
<td>0.44</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

a. Forces on the planar coils are omitted

From the plan view in figure 2 it can be seen that there is a net inward force from the coils to the central support structure, coil type 5 though, which lies in the central part of the pentagon, deeper inside the high B region, for this reason sees a net outward force. The vertical forces (side view of Fig. 2) are downwards in one half module, and upwards in the flip-rotated one. Overall, we can say the CSS (Fig. 3) is compressed, rounded and twisted by the coils.

In order these forces are reacted properly, the way the magnet system is interconnected plays a vital role.

The connection scheme which has been selected is the following. The coils are:

• bolted to the CSS by the Central Support Elements (CSE).
• welded (or bolted, § II-D) to the adjacent coils on the outboard side by the Lateral Support Elements (LSE).
• in contact with the adjacent coils in the inboard side with the Narrow Support Elements (NSE).
• The PC, furthermore, are in contact with the NPC by means of the Planar Support Elements (PSE).

The NSE, and the conceptually similar PSE, are actually both sliding contacts that enter into action only when the coils are energized and therefore deformed; otherwise there is a gap between these elements, ranging from 0 to ~5 mm.

Some of these support elements are illustrated in Fig. 4.

Figure 3. Coils types in a module (left), where the flip-symmetry can be recognized; CSS (right).

II. DESIGN AND TEST ACTIVITIES

A. Magnet system structural response

When the coils are energized, the way the magnet system responds to the EM forces is rather complex.

First of all, Fig. 5 shows a typical plot of EM volumetric forces, as calculated for NPC3 which is also shown in Fig. 4: the radial forces, which are basically a result of the interaction between the poloidal component the coil current density and the toroidal magnetic field, tend to “inflate” the coil and push it towards the CSS (“Fx” in Table I). The lateral forces, which are the effect of the attraction of the adjacent coils to eachother
(depending on vicinity and current of the adjacent coils), generate bending and twisting effects.

Figure 5. Example of EM volumetric forces on NPC 3.

The CSE are meant to firmly connect NPC and PC to the central ring, and to provide the basic response of the CSS to the EM forces. The NSE and LSE (and PSE) which interconnect the coils, have mostly to limit deformations and stresses originating from the lateral forces to acceptable values. For this reason in particular, NSE and LSE are located in areas where the two adjacent coils are closer in the inboard and outboard side, respectively (Fig. 4). The benefits from interconnecting the coils can be recognized in Fig. 6, which shows the displacement plots for NPC type 1 only bolted with the CSE to the CSS, compared with the displacement plots for a fully interconnected magnet system (half module) when subjected to the same EM forces, as calculated by Finite Elements (FE) models. In fact, thanks to the NSE and LSE, the level of maximum displacement, which occurs at the outboard side, is decreased by a factor ten on NPC1. Furthermore, a significant decrease of stress levels, at the inboard side, is also achieved: by connecting all the 50 NPC’s on the inboard side, the reactive NSE forces basically self-balance.

Figure 6. FE model showing displacement (in m) on NPC1 (left) only bolted to the CSS, and on a fully interconnected magnet system (right).

These constraints, however, results in large reactive forces, in particular at the inboard side where the NSE are located, due to the vicinity of the coils as it can be seen in Fig. 4. Because of this, the magnet system is also very sensitive to small changes in the initial gaps (i.e. the gaps with zero current) of the various NSE located between two adjacent coils. Table II shows an example of such variations for those NSE which are located between NPC2 and 3: millimetric variations induce changes in the pattern of forces in the order of tens of kN. This force redistribution also affects, in some amount, CSE and LSE. This sensitivity implies that the manufacturing and assembly tolerances must be kept under strict control.

All these analyses have been done by using FE models of the magnet system [4], like the one shown in Fig. 6.

B. Narrow Support Elements

The Narrow Support Elements [5] have been designed to be able to sustain contact forces up to 1.5 MN, contact sliding up to 5 mm, and tilting between the two coils up to 1 deg., as predicted by the FE model.

Up to 7 NSE are located between each pair of coils (see also Fig. 4). In total, there are ~ 300 of these contact elements in the complete magnet system (and ~ 150 planar supports contact elements).

The basic design is illustrated in Fig. 7. The NSE consists of a sliding pad (1) shrink fitted into a pad frame (2), in turn shrink fitted into the coil casing (3); the pad has got a spherical surface that is meant to slide and tilt against the adjacent coil casing (4).

Figure 7. NSE cross section (pad diameter 73 mm).

The basic feature of the NSE is that thick, low friction pads are able to sustain contact forces, tilting and sliding during magnet energization. Furthermore, pad plastic deformations, induced by the high stresses during contact on its spherical part, self limit the force peaks values and re-distribute them among adjacent pads (“learning” process): this gives some resilience to assembly errors and other uncertainties. Low friction is another desired feature, as it decreases transversal forces and also avoids sudden release, during sliding, of elastic energy (“stick and slip”) which could induce quenching of the coils. Therefore the pads and their sliding counter-faces are coated by MoS2. The NSE are equipped with a cap (5) which protects the coating from dust (e.g. thermal insulation flakes) which could settle during operation and degrade frictional properties.

Accompanied by literature survey, the selection of the best combination of materials, surface roughness and coating, has been performed by means of an extensive test programme.
Initially full scale friction tests on NSE mock-ups at room temperature (RT) in air were performed, complemented by laboratory tests on various pad coatings. This was followed by full scale friction tests in cryo-vacuum (77K), with the selected combination of materials: Al Bronze pads (DIN 2.0966), with Physical Vapour Deposited (PVD) MoS2 coating on the pad surface, and burnished MoS2 powder on the sliding counterface, roughness of the sliding surfaces Rz<1 [5].

The way to install the NSE, and protect their coating against humidity during assembly has been carefully considered, too [2], [5].

Fig. 8 shows the test device for cryogenic friction tests, with the push piston applying the contact force, and the stroke piston applying the sliding force, so simulating force transfer between coils on a pair of NSE.

More than 4000 coil energization cycles, at various B, are expected during the operational life of W7-X, therefore tests with similar load cycles are performed. Fig. 9 shows the pad mock-ups. The picture on the right was taken after a test where smooth sliding (i.e. no stick and slip) of the NSE pad mock-ups was experienced, with coefficient of frictions always well below 0.1 [5]. The NSE mock-ups were able to take the loads without damages (the pad was plastically deformed as expected), therefore we can consider that the basic NSE concept is being experimentally validated.

In combination with this test programme, assembly trials are on going to verify feasibility and accuracy [2], and FE models have also been developed and calibrated with the tests in order to make predictions for the real magnet system with different geometries and load conditions, Fig. 10 and [5].

C. Central Support Elements

The CSE (2 on each coil, 14 in total on each magnet system half-module) have to transmit huge forces and moments to the CSS, up to ~ 4MN and ~ 350MN•mm, respectively.

The basic design of this connection is shown in Fig. 11. A matrix of long studs (3x3 M30 in most cases, see also Fig. 4) is tightened (with “super-bolt” nuts) between the coil and the CSS. This joint is able to take shear force and torque by friction, and axial force and bending moment by pre-compression. The CSS interface flange is equipped with wedged shoulders able to react in case shear forces and torque would exceed the reactive friction forces. Shims are installed between the coil and CSS flanges, to compensate manufacturing and assembly errors. These long studs are provided with sleeves and both are made of high-strength Inconel 718 (the other main components are made of AISI 316 LN).

The rationale for this design is:

- bolted instead of welded connections limit distortions and simplify the assembly process, and in general decrease the CSE reaction bending moments during operation (“flexible joints”).
- Long (~500 mm) and slender bolts better adsorb deformations, and sleeves made of the same material limit the loss of pre-load (typically to ~7%) during cool-down from RT to 4K.

On the other hand, according to the calculations carried out so far, during operation some of these flanges will “open”
(~1mm) despite the high pre-load during tightening, therefore it had to be experimentally verified that the CSE components can work in this “unusual” way.

A first series of tests have been carried out on full scale single-bolt mock-ups [6], to verify the maximum achievable pre-load (up to 570 kN) and the way this pre-load is lost during cool-down to 77K. Other laboratory single-bolt tests are under way to verify other design features (like spherical washers to accommodate sleeve-stud manufacturing and assembly errors) and assembly sequences (like the control of the pre-load which is essential for the way the CSE reacts during operation). An example is given in Fig. 12.

Another test programme under execution is the so called 3-bolts tests, where a full scale CSE mock-up (1x3 matrix of M30 bolts) is subjected to the operational “nominal” loads (as calculated by FE models) at 77K, see Fig. 13, left.

The test consisted of cyclic and proportional application of Fx and Fz from zero to various load levels. The forces were progressively increased up to the “nominal” values, 455 for Fx and 270 kN for Fz, and higher, until significant plastic effects on the “coil” side were found at 120% of these values (Fig. 14) and the test was stopped. The mock-up, however, was able to keep the original bolt pre-tightening and was still dismantle-able after the test (Fig. 15, left).

In parallel, an FE model of the 3-bolts mock-up has been calibrated with the test and is now used to benchmark other FE models of the real CSE’s, to predict the behaviour of such connections in the W7-X conditions [4].

The next step will be to perform a second test where the machine lifetime will be simulated (more than 4000 cycles) at loads between 70 and 100% of the nominal ones. After this test we will be able to consider the concept basically validated.

D. Lateral Support Elements

The LSE (Fig. 4) have to limit the lateral displacements of the NPC, and therefore are subject to forces and moment up to 1.5 MN and 200 MN\(\text{mm}\), respectively.

Given the assembly constraints, the only viable solution for those LSE connecting the coils within the half-module is to use welded connections.

A bolted solution is currently under study for those lateral supports connecting coils at the boundary of half-modules (i.e.
two flip-rotated NPC1) and modules (i.e. two flip-rotated NPC5) and will not be described here.

The welded LSE consists of two half boxes which are inserted and welded each other and to the coils (Fig. 16). It is essential to limit and control the deformation due to weld shrinkage in order not to cause excessive perturbation to the very sensitive NSE gaps (e.g. Table II).

Therefore, a wide experimental programme has been undertaken, in order to define boxes lay-out, weld seam patterns, number of passes and other welding parameters, and to identify shrinkage predictability and control, Fig. 17 and [2].

It has been found that the “parallel” weld shrinkage (mostly driven by the long welds on the two coil sides, seam size from 15 to 25 mm) ranges between 0.5 and 1.5 mm. This shrinkage in principle can be neutralized by inserting oversized LSE boxes in between the coils. The repeatability of such values have been found to be ~0.5 mm, therefore this is the real uncertainty to be taken into account during assembly.

In parallel, a specific FE model of the magnet system has been developed in order to predict how it will deform during assembly, in particular during LSE welding by imposing shrinkage errors as those mentioned above. Fig. 18 gives an example.

This model will now be used to study other assembly steps of the magnet system, and also will utilize the results of the weld test (Fig. 17, right) to predict how the LSE box welding process will be affected by the coil stiffness. This can then be benchmarked with a real assembly test under preparation, Fig. 19 and [2].

III. CONCLUSIONS

The W7-X magnet system is a complex mechanical structure, with challenging requirements in terms of operational loads, interfaces, manufacturing and assembly accuracy to limit the magnetic field errors.

The way this system is interconnected has a great influence on its structural response. Thorough optimisation is required to make sure that the magnets can be operated at acceptable levels of stress and deformation.

A wide programme of design and FE analysis has been undertaken. In parallel, tests on full scale mock-ups and assembly trials are being carried out to validate the design and to calibrate the FE models. Such an integrated programme has to ensure that the magnet system will be able to perform reliably during the entire life of the stellarator.

REFERENCES