Design of Narrow Support Elements for Non Planar Coils of Wendelstein 7-X

B. Heinemann¹, M. Gasparotto², C. Damiani², M. Fröschle¹, B. Giesen³, D. Holtum¹, P. Junghans, F. Koch¹, S. Lindig¹, J. Lingertat², B. Mendelevitch¹, A. Panin³, R. Riedl¹
¹ Max-Planck-Institute für Plasmaphysik, Euratom Association, Boltzmannstr. 2, D-85748 Garching, Germany
² Max-Planck-Institute für Plasmaphysik, Euratom Association, Teilinstitut Greifswald, Wendelsteinstrasse 1, D-17491 Greifswald, Germany
³ Institut für Plasmaphysik, Forschungszentrum Juelich, Association EURATOM/FZJ, Trilateral Euregio Cluster, D-52425 Juelich, Germany

Abstract—The stellarator Wendelstein 7-X is presently under construction and assembly in Greifswald, Germany. One of the main structural elements which have to take the electromagnetic forces of the superconducting coil system are the Narrow Support Elements (NSE). They are placed between the non planar coils and have to take very high compressive forces while relative sliding and tilting of the coils must be allowed. The design has been optimised with regard to a proper load distribution among all support elements taking also into account manufacturing and assembly tolerances. The paper describes the design, analysis and tests which have been carried out for the NSEs.

Keywords: Stellarator; Wendelstein 7-X; mechanical structure; coils; Narrow Support Elements

I. INTRODUCTION

The Wendelstein 7-X (W7-X) is a new steady state stellarator presently under construction at Max-Planck-Institut für Plasmaphysik in Greifswald, Germany. The main parameters of W7-X are: average major radius 5.5 m, average minor radius 0.53 m, maximum magnetic field on the plasma axis 3.0 T [1]

The superconducting magnet system of the W7-X consists of 50 non planar coils and 20 planar coils which are arranged as 5 identical modules in a pentagonal shape. Each module consists of two identical semi-modules, which are flip rotated around a horizontal radial machine vector. One (of ten identical) semi-modules is therefore composed of 5 different non planar coils (NPC) and 2 planar coils (PC).

The concept for the support of the NPCs and the electromagnetic forces generated by the coil currents is the following [2]: All coils are supported on their inner side via two “Central Supports” by the central support ring (Fig. 1). This central support ring has to assure the precise position of the coils, takes their weight and the radial electromagnetic forces. Further wedging and bending forces of the strongly 3-dimensional formed coils are taken by “Narrow Support Elements (NSE)” between the inner legs of two adjacent coils and “Lateral Support Elements (LSE)” between the outer legs. Extensive FE-calculations have been carried out to distribute the electromagnetic loads among all support elements with the objective to minimize the deformations of the coil winding packages and to limit the stresses within acceptable values. While the central support connection and the LSE became bolted, respectively welded connections, the NSE have been designed as moment-free contact elements, only taking compressive loads without restrictions to sliding or tilting of adjacent coils. The coils have to move smoothly during energizing to avoid sudden release of elastic energy (“stick and slip”) which could induce a quench in the superconductor.

Calculations showed that the load distribution among the NSEs is very sensitive to initial contact gaps. To limit the loads to allowable values and to distribute them among the individual NSE, gaps between 0 and 4.5 mm are foreseen at 4 K and zero current, which close during the magnetic field rises.
II. DESIGN OF NSE

Three to seven NSEs (depending on type of coil pair) are placed between two adjacent coils in an area, where the coils come close to each other on the inner side (300 NSEs totally). Specific NSE blocks are cast or welded on both sides of the stainless steel coil casings (Fig 2).

Between those blocks the NSEs are installed in a very limited space and have to satisfy the following requirements:

- to take high compression forces up to 1.5 MN (design value) at full magnetic field (3 T)
- to allow relative sliding of adjacent coils up to 5 mm each direction during energizing the coils
- to allow relative tilting between adjacent coils up to 1°
- smooth sliding and tilting to avoid a quench in the superconductor
- to assure the assembly of the coils with high accuracy
- to operate for the lifetime of the experiment (about 4000 magnetising cycles) without access after assembly
- to operate in high vacuum ($10^{-4}$ Pa) and at cryogenic temperature (4 K)

A. Basic Design

The cross section of a typical NSE with a closed gap is shown in fig. 3. It consists essentially out of the following components:

- A central “pad” made of Al-bronze alloy, 18 mm thick, 60 or 73 mm diameter (depending on compression, see below) The pad is the actual sliding and tilting element for which two alternatives have been investigated and tested: either sliding and tilting only on one spherical pad surface with respect to the counter-side of the adjacent coil, in that case the pad is shrink fit into the pad frame. The second alternative is a loose pad with two spherical surfaces and relative motion on both sides providing redundancy in case of failure. In that design the pad is always centered in a wider pad frame via a special formed spring (“crown spring”) when the coils are not energized. All sliding surfaces of the pad are precisely machined, polished to a roughness of $R_s = 0.7 \mu$m and coated by a 6 µm MoS$_2$ layer in a PVD (physical vapor deposition) process.
- The “pad frame”, which holds the pad in its position. The pad frame is made of stainless steel and shrink fit with its shaft into the NSE block of one coil. In case of a loose pad the inner bottom of the frame is also polished and coated by MoS$_2$ using PVD.
- The “counter-side”, which is the sliding surface on the NSE block of the opposite coil, machined with high accuracy and polished to a roughness of $R_s = 0.7 \mu$m.
- The dust cover, which is a thin walled ring made of Al-bronze, slides onto the counter-side and closes the gap between the two adjacent coils. It protects the polished surfaces and MoS$_2$ layers against dust coming from the super-insulation during operation as well as against dust pollution and humidity during the 5 years of assembly. For the latter a thin copper pipe (3 mm OD, 2 mm ID) is brazed to the dust cover to supply the inner volume with dry air (see below).
- The “wave spring” is made of Inconel 718 and is designed to fit axially between the pad frame and the dust cover in order to press the latter against the counter-side of the adjacent coil.

B. FE calculations

Global model analysis were performed for different plasma scenarios with the aim to optimize the initial gap of NSE’s in order to distribute the loads among the NSEs more homogeneously and to limit the maximum load to 1 MN. As a result of calculation initial gaps between 0 to 4.5 mm will be installed (at 0 current) and two pad sizes were defined: 60 mm diameter for loads below 0.5MN, 73 mm diameter for loads up to 1 MN.

Further detailed FE calculations have been carried out to proof the mechanical integrity of the NSE system, for the loose
pad as well as for the fixed pad design. The cyclic elasto-plastic, non-linear calculations were performed taking into account most important boundary conditions (material properties at RT and 4 K, measured coefficient of friction, shrink fit dimensions, tilting, sliding, etc). The FE model of the NSE design is shown in Fig. 4.

For the loose pad design the worst loading case was assumed to be a pad which leans initially against the frame side wall and whose upper sliding surface is worn (µ = 0.3) while the lower sliding surface (inside frame) is still in good condition (µ = 0.1). High compression aggravated by sliding and tilting exceeds allowable elastic limits and leads to partial plastic deformation of the components at 4 K. Considerations of materials behavior at 4 K necessitates to limit the average plasticity over some critical cross-sections to <1% in steel components and to <6% in the pad material (with certain lack of safety). The acceptable loads (wrt. allowable elastic and plastic limits) are summarized in Table I.

### TABLE I. APPLIED, ACCEPTABLE AND TESTED LOADS FOR DIFFERENT NSE DESIGN AND SIZE

<table>
<thead>
<tr>
<th>Type</th>
<th>Dia. 60 mm</th>
<th>Dia. 73 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Applied load if gap optimised [MN]</td>
<td>0.5</td>
<td>1.0</td>
</tr>
<tr>
<td>Accept. Load (elastic range) [MN]</td>
<td>0.65</td>
<td>0.75 (frame)</td>
</tr>
<tr>
<td>Accept. load (plastic range) [MN]</td>
<td>1.5</td>
<td>1.0 (frame)</td>
</tr>
<tr>
<td>Tested load 77 K, vac. [MN]</td>
<td>-</td>
<td>3.0</td>
</tr>
</tbody>
</table>

Al-bronze alloy (DIN No. 2.0966) has been selected as the pad material. It remains ductile and becomes stronger when deformed even at cryogenic condition (Fig. 5). Furthermore it has still reasonable sliding properties once the lubrication layers are deteriorated.

### TABLE II. MATERIAL LIST AND PROPERTIES FOR NSE COMPONENTS

<table>
<thead>
<tr>
<th>Narrow Support Element Name</th>
<th>Material Name</th>
<th>Material No., DIN/ASTM</th>
<th>Temp. K</th>
<th>Young’s Modulus GPa</th>
<th>Yield Strength MPa</th>
<th>Ultimate Tensile Strength MPa</th>
<th>Unif. Elong. %</th>
<th>Total Elong. %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pad, Dust Cover</td>
<td>Al-Bronze (CuAl10Ni5Fe4)</td>
<td>B150/C63000</td>
<td>295</td>
<td>120</td>
<td>316</td>
<td>737</td>
<td>13</td>
<td>20</td>
</tr>
<tr>
<td>Pad Frame</td>
<td>SS</td>
<td>1.4429/316LN</td>
<td>77</td>
<td>127</td>
<td>448</td>
<td>956</td>
<td>16</td>
<td>12</td>
</tr>
<tr>
<td>Wave Spring, Crown Spring</td>
<td>Inconel 718 0.26% Co</td>
<td>2.4668</td>
<td>77</td>
<td>196</td>
<td>1013</td>
<td>1620</td>
<td>42</td>
<td>50</td>
</tr>
<tr>
<td>Coil Casing (cast)</td>
<td>SS (cast)</td>
<td>1.3960/316LN</td>
<td>77</td>
<td>148</td>
<td>274</td>
<td>538</td>
<td>34</td>
<td>47</td>
</tr>
</tbody>
</table>

All sliding surfaces have to be coated with a lubricant which is suited for cryo-vacuum and will survive during 5 years of assembly and 20 years of operation without maintenance. MoS2 is widely used under similar operating conditions in space industry and has shown the best behavior during tests among all candidates. The best results were reached with a 6 µm thick MoS2 layer on the pad sliding surface applied in a PVD process. Additionally the countersides have been burnished with microfine MoS2 powder.

As MoS2 is sensitive to humidity above 50% at room temperature several protection layers have been applied also by PVD coating and analyzed after exposure to 100% humid air for 4 weeks [3,4,5]:

- Au-MoS2-Au, still oxidation starting from the edges
- MoS2-Ti-TiN, no visible oxidation, but bad sliding properties (stick slip)
- MoS2-Cu, bad sliding properties
- MoS2–SiO2, heavy oxidation, but good sliding
As no adequate protection layer was found in the available time, it was decided to provide a constant flow of dry air inside the NSE volume via a small copper pipe brazed to the dust cover.

III. Tests

In order to validate both designs several test campaigns have been performed and are still in progress mainly to optimize the roughness and lubricants of the sliding surfaces:

A. Tests at room temperature

First screening tests were done at IABG in Munich with a facility able to apply simultaneously 1.5 MN of compression, 2 mm of sliding and 0.5° of tilting. The tests were only done for the “loose pad” design and had the objective to investigate different pad materials, pad shapes and lubricants. To simulate the lifetime of W7-X 500 cycles were performed using a compression force of 150 kN (conditioning phase at 1 T), 3200 cycles at 1 MN (2.5 T) and 400 cycles at 1.5 MN (3 T).

Best results were reached with a PVD coated pad (6µm MoS₂) and surface roughness Rz = 2.5 µm. Stick-slip occurred at around 3800 cycles, the coef. of friction was < 0.25. The redundancy in having two sliding surfaces was clearly visible: sliding started on first pad surface for about 1300 cycles with a continuously increasing friction coefficient. When a certain value was exceeded the second pad side started sliding for about the same number of cycles, then a frequent change in side occurred until both sides have been eroded.

B. Tests under vacuum at 80 K

Further tests were performed at the KRP in Garching under vacuum and at 80 K. The facility uses a big tensile test machine and can apply 1.7 MN compression force, 5 mm sliding but no tilting (Fig 6). The main results compared to RT tests were lower coefficient of friction (as low as 0.02) and higher sensitivity to stick-slip.

The loose pad configuration showed significant improvement by polishing the sliding surfaces (Rz < 1 µm) and by additional MoS₂ powder burnished onto the counter-sides. By that means 3800 cycles could be reached (3200 @ 1 MN, 600 @t 1.5 MN), but stick slip started @ cycle 2330, continuously aggravating.

The fixed pad design yielded with the same surface roughness and lubrication more than 4300 cycles (3200 @ 1 MN, 600 @t 1.5 MN, 200 @ 1.7 MN) without stick-slip and at a very low coefficient of friction µ <0.08. (fig. 7)

IV. Conclusion

The Narrow Support Elements between the inner side of the non planar coils have been designed as flexible contact elements in two different versions. They have to allow sliding up to 5 mm and tilting up to 1° under 1.5 MN compression force. The “fixed pad” solution seems preferable because of lower stresses and plastic strains in the NSE elements and better test results.

Extensive FE calculations have been performed to validate the design. Plastic deformation of the pad is taken into account to compensate assembly errors and to help load distribution.

Several test campaigns at room temperature and in cryo-vacuum have been performed to validate the design and to optimize the sliding behavior. More than 4300 cycles at loads above 1.0 MN have been carried out in cryo-vacuum. The best results were reached with a very low roughness of the sliding surfaces (Rz < 0.7) and with MoS₂ as lubricant, applied to the pad by PVD coating and to the counter-side by burnishing.

REFERENCES