Coil winding pack FE-analysis for a HELIAS reactor

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At the Max-Planck-Institut für Plasmaphysik (IPP) a reference design is being created of an upgraded five-periodic HELIAS type stellarator reactor which evolves from Wendelstein 7-X (W7-X) by scaling of the coil centre line geometries by a factor of four. This reactor type was extensively investigated at IPP with regard to physical characteristics and to some extent also to engineering issues. The upgrade concerns an increase of the induction at the plasma axis and correspondingly at the superconductor.

The aim is to develop the reactor concept to a stage and such detail that major engineering problems are unveiled, and relevant comparisons with other concepts, including tokamaks, can be drawn in view of upcoming decisions concerning a DEMO reactor. Even though progress in plasma physics, and in particular future results of W7-X and other machines - particularly of ITER - will probably lead to somewhat different coil shapes, no principal changes of the reference design are expected.

In this paper the option of a roll-formed square coil cable jacket is investigated. Detailed structural FE analysis of the coil winding pack demonstrates the feasibility of such a conductor which appears to be the most economical option. It also allows sufficient space for a cable current density very similar to that of the ITER TF coil with a similar overall winding pack cross section of \( \approx 0.5 \text{ m}^2 \). Already existing Nb\(_3\)Sn conductors could thus be safely applied in such a HELIAS reactor. Obvious progress of superconductor technology, particularly concerning Nb\(_3\)Al, will be beneficial concerning savings of conductor material, ease of manufacture, higher operation temperature, etc.

Keywords: stellarator, reactor, HELIAS, magnet, superconductor, winding pack, Wendelstein 7-X

1. Introduction

Based on previous studies on helical advanced stellarator (HELIAS) reactors (HSR) at IPP [1-7], activities have started regarding the further development of this conceptual design. The chosen type, HSR5/22 (5 periods, 22 m torus radius; also known as "HSR5" or "HSR22") is derived from the currently built W7-X experiment by scaling the coil centre line geometry and thus the main dimensions by a factor of four. Consequently, the stellarator field configuration and thus the basic plasma physics remain the same. The upgrade from HSR5/22 to the new "HSR50a" concerns the increase of induction from \( \approx 5 \text{ T} \) to \( \approx 5.6 \text{ T} \) at the plasma axis corresponding to \( \approx 10 \text{ T} \) and \( \approx 12 \text{ T} \), respectively, at the maximally loaded coil conductor [8].

The five-periodic machine configuration was found to be most promising concerning plasma performance, and consequently the consecutive IPP modular stellarator experiments W7-AS and W7-X were designed this way. The highly successful W7-AS [9] confirmed the concept. Even though previous investigations on HSRs showed the potential of three and four periodic reactors for better economy [5,7], we decided to stick to the five periods for this reference design as the safest solution, keeping in mind that results from W7-X as an intermediate step on the road to such a reactor will be available in a few years. These and later achievements of ITER and other machines will lead to a final optimization of the coil shapes, and then one can decide whether to go for a smaller four- or even three-periodic machine. Since the coil types and sizes remain the same, the reference design could be adapted with relatively low effort.

In order to allow for a fair comparison with the more advanced tokamak designs, particularly in view of upcoming strategic decisions concerning the DEMO-reactor, it is indispensable to update the previous HSR5 work and to develop a more detailed machine concept. Meanwhile one can greatly benefit from advanced technologies as well as physical and engineering experiences gained with W7-X and other projects worldwide, particularly with ITER.

HSR5/22 was planned for 3 GW of fusion power with 10 T at the coil conductor. This would allow to use a NbTi superconductor cable with superfluid He cooling at 1.8 K. However, already available advanced Nb\(_3\)Sn and Nb\(_3\)Al conductors - or possibly future high temperature superconductors – allow to create stronger magnetic fields with significantly reduced cooling requirements. The maximal field of such a reactor would then be limited mainly by structural integrity. Around 12 T at the conductor of HSR50a is a reasonable choice for a basic design. It provides a comfortable safety margin concerning the confinement time which roughly scales with \( B^{0.8} \) [4], and future results of W7-X will show whether one has really to exploit 12 T or whether one could save on conductor and structure mass, cooling requirements, etc., in trade-off with fusion power.

The size of HSR5/22 is mainly enforced by space requirements for the blanket and neutron shield. The minimal distance between plasma boundary and coils is, similarly to tokamaks [10], about 1.5 m which leaves \( \approx 1 \text{ m} \) for the blanket and neutron shield, and the rest for the vacuum vessel as well as the thermal shield [3]. Due to its large plasma surface, the HSR22 renders relatively
low average and peak neutron wall loads of 1 MW/m²
and 1.7 MW/m², respectively [2]. This has to be compared
to ≈2 MW/m² and 3 MW/m², respectively, in
tokamaks [10] which means that the stellarator first wall
and blanket replacement intervals can be increased, or
the reactor size correspondingly reduced.

HSR50a is intended as an engineering study which
later can be adapted to W7-X and ITER results. The
"basic machine", consisting of the magnet system
including the mechanical structure and cryostat, shall be
designed first. The cryostat encompasses the plasma
vessel (PV), outer vessel (OV), ports, and thermal
insulation built up of the shield and possibly multilayer
insulation. The components within the PV can then be
adapted from available designs, and concepts for remote
handling, maintenance, and first wall as well as blanket
replacement can be worked out. Most of these topics
were considered already in the previous HELIAS
studies, but need to be updated and substantiated.

The magnet system of HSR50a consists of 50 non-
planar coils, evenly distributed throughout five identical
modules. Each module consists of two flip-symmetrical
half-modules encompassing 5 non-planar coils of
different geometries.

Coincidentally, all coil centre line lengths of HSR5
and thus HSR50a are maximally 3 % below the corre-
sponding ITER toroidal field coil (TFC) circumference
of 34.5 m [11]. The maximal conductor induction is
similar in both machines around 12 T, and the local peak
forces per coil unit length are only ≈20 % larger in
HSR50a. This comparison suggests itself to base a first
HSR5 coil design iteration upon the ITER TFC and to
transfer the extensively developed ITER-technologies
wherever applicable. It was demonstrated that ITER’s
superconductor and winding pack concept, including
electrical insulation, can be adapted to HSR50a, as well
as the electrical design concerning power supply, voltage
levels and quench protection [8].

In this paper further mechanical analyses are
presented which confirm the first results that HSR50a
can be built with a reasonable structure. In addition, it is
now shown that a cheaper roll-formed square cable
jacket, as in most of the JT-60SA EF coils [12], can be
used instead of the previously assumed round-in-square
radius of 1.11 m (Fig. 2), a react-and-wind technique
produce the coil with a similar wind-and-react and
conductors not acceptable. Therefore, one would
introduce additional compressive strain on the
radius of 1.11 m (Fig. 2) , a react and wind technique
conductors section could thus be saved with Nb3Al.

2. Coil cable and winding pack

It was shown [8] that Nb3Sn or preferably Nb3Al
cables with a diameter of 44 mm and a central channel of
10 mm would be suitable for HSR50a. With the new
cable design (Fig. 1) one gains an additional section
factor of 1.26 which is coincidentally the same as the
HSR50a to ITER TFC current ratio 86/68 kA/kA. With
the somewhat higher induction in HSR50a (s. table 1),
the critical current decreases by ≈15 % at operation
conditions T = 4.7 K and intrinsic strain εi = -0.7 % [13, 14].
The ITER strand (diam. 0.82 mm, Cu/non-Cu ratio 1:1)

specification requires a critical current Ic ≥ 190 A at
4.22 K, 12 T, assuming εi = -0.2 % [11]. This value
contains some safety margin since the prototype strands
described in ref. [13] reach under these conditions
currents between 237 A and 265 A. The Jc-decrease of
15 % due to the higher field at the conductor is thus
comfortably covered already by the ITER safety margin
for strand manufacture. Since even better Nb3Sn-strands
are available already today and further improvements are
expected [15,16], one can safely assume that the
stellarator coils can be built with an ITER-like Nb3Sn
cable. In addition, a HSR is a steady state machine
without plasma disruptions and reduced AC and stability
requirements, i.e. reduced corresponding safety margin
demands.

A “state of the art” Nb3Al strand with the same non-
Cu cross section as the ITER wire exhibits a critical strand current of 380 A at 4.22 K, 12 T and εi = -0.2 %. With an operational εi = -0.7 %, the Ic decreases only by 15 % [17]. Contrary to that, the Ic of a Nb3Sn strand
grades by ≈50 % at the same strain. Much super-
conductor cross section could thus be saved with Nb3Al.

Considering the smallest HSR50a coil curvature
radius of 1.11 m (Fig. 2), a react-and-wind technique
would introduce additional compressive strain on the
order of 2 % which is with present-day Nb3Sn or Nb3Al
conductors not acceptable. Therefore, one would
produce the coil with a similar wind-and-react and
transfer technique as the ITER TFC and react the
conductor in an oven of similar size. Insulation appli-

Table 1: Main data of ITER and HSR50a

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<tr>
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<th>ITER</th>
<th>HSR50a</th>
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<tbody>
<tr>
<td>Major radius, m</td>
<td>6.2</td>
<td>22</td>
</tr>
<tr>
<td>Av. minor radius, m</td>
<td>2.0</td>
<td>1.8</td>
</tr>
<tr>
<td>Plasma volume, m³</td>
<td>837</td>
<td>1407</td>
</tr>
<tr>
<td>No. of coils</td>
<td>18</td>
<td>50</td>
</tr>
<tr>
<td>Av. field plasma axis, T</td>
<td>5.3</td>
<td>5.6</td>
</tr>
<tr>
<td>Max. field on coils, T</td>
<td>11.8</td>
<td>12.3</td>
</tr>
<tr>
<td>Superconductor</td>
<td>Nb3Sn</td>
<td>Nb3AL, Nb3Sn</td>
</tr>
<tr>
<td>Stored energy, GJ</td>
<td>41</td>
<td>152</td>
</tr>
<tr>
<td>Fusion power, MW</td>
<td>500</td>
<td>3000</td>
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4) ITER TF coil system
cution and handling of the 3D double pancakes should correspond to the ITER TFC procedure without works associated with the radial plates. However, progress is being made in developing less strain sensitive Nb$_3$Sn as well as Nb$_3$Al strands for better handling at room temperature [15-18], so assembly of future winding packs should become much easier anyway.

3D cable jacket bending for the stellarator coils is certainly more difficult than for the planar ITER TFCs. The bending effort also depends on the winding pack (WP) cross section orientation which is free to rotate around the central current filament (CCF) without significantly influencing the stellarator field and structure. The WP orientation has to be optimized regarding space requirements and ease of manufacture.

For W7-X each coil segment was adjusted individually; for HSR50a more general rules to orientate the cross sections are being investigated. For instance, one could align the section normal vectors $\mathbf{n}$ of a coil parallel to a plane from which the 3D-deflections are minimal [8], or parallel to one which contains the torus axis and the coil centre of gravity (CG). This would allow conductor bending around axes parallel and perpendicular to $\mathbf{n}$ only, and yield rather smooth coils of the Types 3, 4, and 5 which have moderate curvatures. For the time being the latter WP section orientation was chosen with few exceptions for the FE analysis. Another option providing a smooth run of the WP along the coil would be to align the normal vectors parallel to the connecting lines from a certain point (pole) near the CG. Fig. 3 shows the corresponding deformation of a 313 mm long cable jacket piece within coil 2 at the maximal curvature region (indicated by the circle segment in figure 2). The bending angle is $16.1^\circ$, twist around the conductor axis $3.5^\circ$, the maximal total bending moment is 4.1 kN·m, and max. plastic strain is $\approx 2.8\%$ (no over-bending considered). Other options are also under consideration, but final decisions can be taken only when a more detailed design and results of practical bending tests are available.

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<tr>
<th>No. of superior strands</th>
<th>800</th>
<th>900</th>
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3. Magnet system structure

Fig. 4 shows the double shell structure [8] with improvements and larger port windows. The stress intensity is low within most of the structure with only some local maxima exceeding the standard allowable membrane plus bending stress limits of typically 750 MPa for steel 316 LN which is acceptable. Detailing and optimization with massive reduction of material will be performed in a next step.

Based on this structure and the above cable layout (fig. 1) the coil winding packs were analysed in more detail. Fig. 5 shows the longitudinal strain within the winding packs which stay everywhere below 0.3 %. Fig. 6 indicates the stress intensity of the conductor jackets in one of the highly loaded coil cross sections (in coil 5). The maximum of 630 MPa is well below the allowable limit for 316 LN. Fig. 7 shows the moderate stress intensities within the conductor, double pancake (DP), and ground insulations on the assumption that sliding is allowed on both sides of the DP and ground insulations, respectively. This can be achieved by applying separating foils before impregnation to avoid dangerous shear and tension stresses during operation.

4. Conclusion and outlook

Structural analysis of the coil winding packs showed that a cost-efficient roll-formed square cable jacket is feasible for the 5-periodic HELIAS reactor HSR50a. In addition, this jacket type yields sufficient space for a cable current density very similar to that of the ITER TF coil. Therefore, Nb$_3$Sn conductors of ITER quality could be safely applied without the necessity to increase the coil cross section, or to rely upon future conductor improvements. However, conductors with better quality than ITER specification are already available, and considerable improvements are to be expected in the medium term. Particularly the developments concerning Nb$_3$Al conductors are progressing quickly, and this material would be much better suited for reactor coils due to its relative insensitivity regarding strain. The expected increase of conductor qualities will allow for reduction of superconductor mass, easier manufacture, and/or increased operation temperature.

In a next step the shell structure mass will be reduced and interfaces to the coil casings developed.
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Fig. 4 Stress intensity (MPa) in magnet system and maximally possible port windows (mm); structure not yet optimized.

Fig. 5 Longitudinal strain within winding packs.

Fig. 6 Stress intensity in conductor jacket (MPa).

Fig. 7 Stress intensity in WP insulation (MPa).

References