Extrapolation of the W7-X magnet system to reactor size

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Abstract

The fusion experiment Wendelstein 7-X (W7-X), presently under construction at the Greifswald branch institute of IPP, shall demonstrate the reactor potential of a HELIAS-type stellarator. HELIAS reactors (HSR) with three, four and five periods have been studied at IPP for many years. Assuming a plasma axis induction of around 5 T, corresponding to about 10 T maximal induction at the coil conductors, it was shown that such reactors are feasible. Taking into account recent developments in superconductor technology, and in particular considering the extensive technical development work performed so far for ITER, the possibility is being investigated to increase the conductor induction up to the 12 T – range corresponding to a plasma axis value >5.5 T. This improves the stellarator confinement properties but would not change the basic physics with respect to the previously analyzed machines. For the study the 5-periodic HELIAS type, HSR5, is taken which evolves from W7-X by linear scaling of the main dimensions by about a factor of four. By coincidence the coil circumference lengths of HSR5 are almost exactly the same as those of the ITER toroidal field coils.

For the presented 12 T reactor version, the HSR50a, also the conductor and structural requirements are comparable to the corresponding ITER specifications. Therefore, advantage is taken of these similarities, and the conceptual HSR50a magnet design is based wherever applicable on ITER solutions.

The input for this engineering study was provided by the new code "MODUCO" which was developed for interactive coil layout. It is based on Bézier curve approximations and includes the computation of magnetic surfaces and forces.

It is shown that such a 12 T HELIAS stellarator magnet system is feasible. The results of this conceptual study could be used as starting point for a further in-depth R&D project.

1. Introduction

The W7-X magnet system is built up of five identical modules where each one consists of two flip-symmetrical half-modules encompassing 5 non-planar and 2 planar superconducting coils of different geometries. The non-planar coils produce the stellarator field proper, whereas the planar ones allow additional field variations and are intended to enhance the experimental flexibility. A W7-X – type fusion reactor, the 5-periodic HSR5, would contain only the 50 non-planar coils [1].

Up to now the industrially available, relatively cheap and highly ductile NbTi, cooled by superfluid helium, was taken as design base for the HSR reactors. With this a maximal induction of ~10 T at the conductor, corresponding to ~5 T at the plasma axis, could be achieved (HSR5 in tab. 1). Nb_3Sn was considered as too brittle for producing the 3D-shaped stellarator coils. However, in the last years the development of the high performance superconductors Nb_3Sn and Nb_3Al progressed considerably. Nb_3Sn will be used already for ITER and is consequently being produced in large quantities. The ITER toroidal field (TF) coils will be manufactured by the "Wind, React, & Transfer technique" [2]. But also Nb_3Al has been brought to a level at the brink of large-scale applications [3-4] and can be considered as a serious option for a Helias reactor.

After all the development work done for ITER it seems to be possible to use Nb_3Sn also for a 3D stellarator coil by adapting the ITER assembly technology. However, Nb_3Al has the decisive advantage of being much more strain resistant than Nb_3Sn, and this fact would significantly ease the production of the more complex HSR coils. Looking somewhat further into the future it is even conceivable that by the time of the design of a demo-reactor high temperature superconductors will be ready to be used at temperatures on the order of 20 K and above [5]. With these prospects in mind one can already now increase the maximal induction at the coils of a HELIAS reactor safely up to ~13 T with a correspondingly higher plasma axis field. Nb_3Sn as well as Nb_3Al conductors entail the additional advantage of a much wider range of design and operational options like higher cooling temperatures with better efficiencies and higher heat capacities of the materials, and/or decreasing the coil cross-sections to gain more space. It can be assumed that the maximal field will not be limited by the superconductor but rather by the structure.

In the present study concerning an HSR5 reactor type, the HSR50a (s. tab. 1), such an advanced superconductor is taken into account, and the plasma axis induction is increased to ~5.8 T, corresponding to ≤12.3 T at the conductor. The aim of the study is to explore the technical limits; for a final design the optimum field maximum concerning physics, technology and costs might well be lower.

The coil system of HSR50a was created using the new code "MODUCO" (MODUlar COils) which also provided the central coil current filament (CCF), fields, and forces as input for the structural development and analyses. MODUCO was developed for interactive magnetic field optimization, parameter studies, and coil layout [6]. The code is based on the representation of the CCF by four to six spatial control points with tangent vectors, and on interpolation of the coil by cubic Bezier curves. This leads to an easy-to-handle analytic description of the coils which allows to modify them within wide limits. The present version of MODUCO operates with five control points per coil and reproduces the classical $\ell = 2$ stellarator as well as the magnetic field of W 7-X. Magnetic surfaces and particle orbits, forces, and magnetic fields inside the coil cross sections can be computed. Several reactor configurations with 3, 4 and 5 periods have been investigated, and the code is well-suited to model future stellarator experiments and reactors.

Tab. 1: Main data of the previous Helias HSR5 and the new HSR50a reactors

	HSR5	HSR50a
Major radius	22 m	
Average minor radius	1.8 m	
Plasma volume	1407 m³	
Iota(0)	0.84	
Iota(a)	1.00	
Average field on axis	4.75 T	5.6 T
Maximum field on coils	10.0 T	12.3 T
Number of field periods	5	
Number of coils	50	
Magnetic energy	100 GJ	152 GJ

Coincidentally, the coil dimensions of HSR50a are very close to those of the ITER TF coils, and all coil centre line lengths of 33.6 m to 34.5 m lie within <3 % only. The maximal conductor induction is similar in both machines around 12 T, and the local maximal 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 toroidal field coil [7] and to try to transfer the extensively developed ITER-technologies wherever applicable.

2. Superconductor

It is conservative to base this reactor design study on the most advanced superconductors Nb_3Sn or Nb_3Al which are produced today already in the km-range, even though the latter are not yet manufactured on industrial scale. State of the art Nb_3Sn strands would in principle be an attractive choice. However, it is quite challenging to build up even the planar ITER winding packs (WP) with them due to their brittleness and strain sensitivity [7, 8]. Therefore, Nb_3Al is the preferable material for a stellarator reactor.

Up to now, higher current densities were achieved with Nb_3Sn as compared to Nb_3Al at relevant operation conditions. With the former, values up to J_c = 3000 A/mm² (non-Cu) at 12 T and 4.2 K are reported for strands [9]. Corresponding values of "only" about 1660 A/mm² [10] were achieved with advanced Nb_3Al produced by the "rapid heating, quenching and transformation annealing" (RHQT) method. However, the Nb_3Al technology is still progressing rapidly and similar J_c-values as with the already mature Nb_3Sn are expected in near future; the direction to go is known [3]. The main point though is not which small sample values are reached under ideal laboratory conditions, but how a real cable for a large coil performs after all the production and assembly stages, and under the enormous electromagnetic loads. In a Nb_3Sn cable with steel jacket the thermal compressive strain of the conductor due to different thermal contraction is around -0.5% to -0.6% [11, 12]. This reduces the critical current at 12 T, 4.2 K by a factor >2 [13], whereas for Nb_3Al the degradation is less than 20% [3, 4]. In addition, the strain during magnet loading decreases the performance of Nb_3Sn further. This was shown with the insert coil tests of the ITER CS model coil whereas there was no degradation of the Nb_3Al coil [4]. Practical conductor characteristics far from ideal laboratory values were also revealed during the ITER cable qualification tests where the critical strand currents ranged from 193 A to 302 A at 12 T, 4.2 K [12], corresponding to 1170 A/mm² non-Cu current density only in the best sample. Due to all these unpredictable degradations, large safety mar-

Tab. 2: Winding pack comparison between ITER and HSR50a

	ITER TF	HSR50a SqC*	HSR50a RP*
Cable current	68 kA	86 kA	
No. of cable turns	134	156	
Max. induction at	11.8 T	12.3 T	
Operation temperature	5 K		
Superconductor material	Nb_3Sn	Nb_3Al	
Strand diameter	0.82mm		
SC strand Cu:non-Cu	1		
No. of sc strands	900	630	
No. of additional Cu	522	792	
Void fraction	29 %	29 %	
Cable Cu:non-Cu ratio	2.2	3.5	
O.D. of central channel	10 mm		
O.D. of cable	40 mm		
O.D. of jacket	44 mm	53x53mm²	44 mm
Conductor insulation	1 mm	1.5 mm	1 mm
RP insulation	1 mm	-	1 mm
DP* insulation	3 mm		
Ground insulation	7 mm		
WP embedding	4 mm		

* SqC: square conductor, RP: radial plate, DP: double pancake

gins were chosen for ITER, and the critical strand current was specified as 190 A at 12 T, 4.2 K corresponding to 737 A/mm² non-Cu-J_c.

With this in mind, and particularly considering the fact that there are many years of superconductor development to come until the first real stellarator reactor will be designed, it is conservative to assume for the present study a conductor with twice the performance of the specified ITER strands. Taking the ITER TF coil cable (left in fig. 1) as the base for a first design iteration one gets cable data as shown in tab. 2. The scaling from the 11.8 T maximal conductor induction in ITER to 12.3 T in HSR50a was done with the scaling law given in ref. [13] (zero external strain assumed). The strand numbers are not optimised yet regarding the cabling layout.

The 86 kA cable current is chosen ~25 % larger than in the ITER TF coil, but this remains within state of the art considering current leads, quench protection, and fast discharge conditions. That such currents are practically achievable was demonstrated with the ITER TF model coil which was successfully tested up to 80 kA with a maximal induction of ~10 T at ~4.5 K [14]. Naturally, cable current and dimensions have to go through many iteration steps for a consistent design taking into account the final superconductor characteristics as well as all electromagnetic, mechanical and thermal requirements.

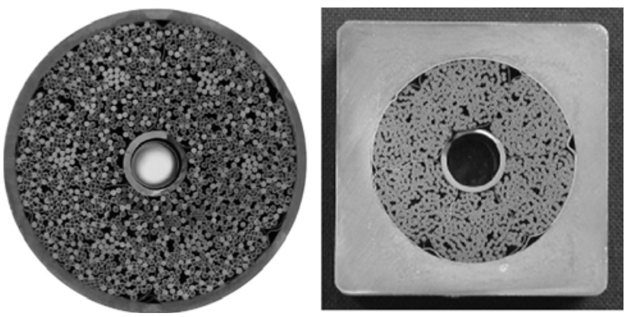

Fig. 1: ITER cable cross sections [2] .
Left – toroidal field (TF) coil conductor; Right - central solenoid (CS) and poloidal field (PF) conductors.

3. Coil winding pack

The ITER TF coil cross section at the inboard leg is shown in fig. 2. It is basically trapezoidal in order to achieve a wedged vault structure. The winding pack is built up from five full double pancakes (DP) with 2x11 turns, and two tapered DP at the sides with 12 turns each. Every DP is embedded within a steel radial plate (RP) which are stacked on top of each other to form the WP. There are several steps of electrical glass-polyimide insulation: the turn insulation on top of the individual round conductors, the insulation around each RP with additional layers in between them, and the ground insulation of the whole WP. The remaining gap to the inner case wall is filled with fibre glass material and vacuum-impregnated with epoxy (cf. tab. 2).

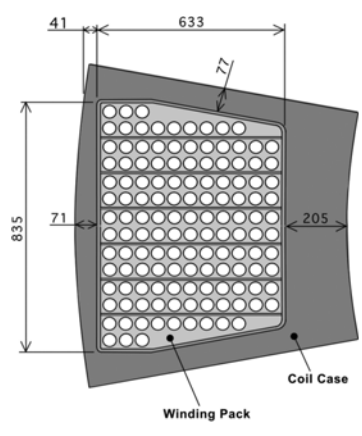

Fig. 2: ITER TF coil inner leg cross section [7]

There was a long discussion within the ITER project whether to take the square conductors (fig. 1 right) also for the TF coils. Finally the radial plate concept was chosen for better structural robustness, electrical insulation redundancy, and easier conductor jacket production [15]. On the other hand, the radial plates are difficult to manufacture to the required tolerances, and WP assembly becomes quite involved [8]. For the 3D-coils of HSR50 the optimization process might lead to a different result as with ITER. In the present study the square conductor option is taken as the preferred solution, but both approaches remain open at this stage.

Both WP concepts for HSR50a are shown in fig. 3 with the conductor data as in tab. 2. The outer coil case dimensions are reference values only. During the structural analysis iterations the casing cross section is adapted to strength requirements individually for each coil and each position around the coil circumference (cf. fig 8). An ITER-like trapezoidal section for HSR50a would slightly improve the space situation at the inboard side, and lead to a small conductor peak field reduction. However, this is believed not to be sufficient to outweigh the increased fabrication effort with respect to a rectangular WP cross section.

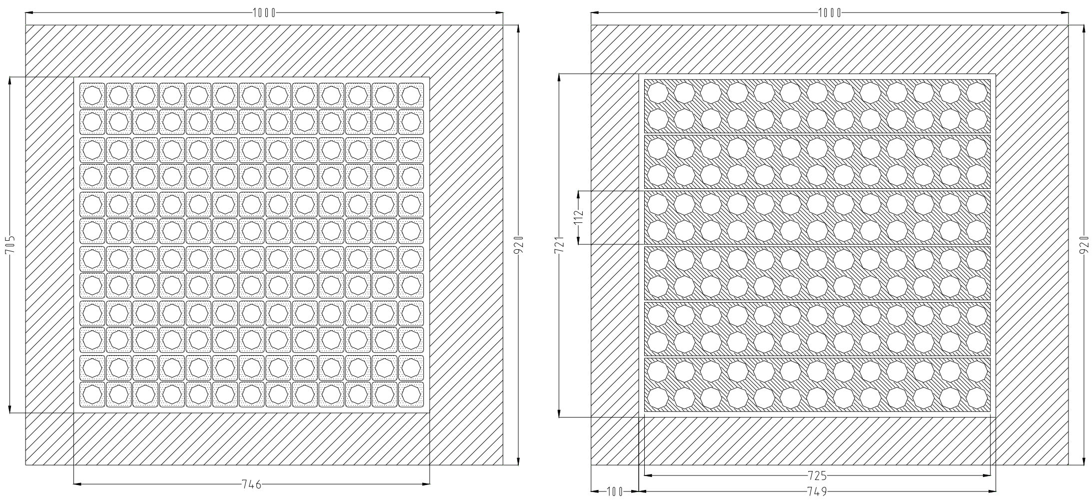

Fig. 3: HSR50a winding pack (WP) options. Left – square conductor concept according to ITER CS and PF coils. Right – radial plate concept according to ITER TF coils; Coil axis is at the left.

The winding pack dimensions and orientation have negligible influence on the plasma confinement field and can thus be chosen according to engineering requirements. The orientation around the CCF was performed with an EXCEL program as interface between MODUCO and the structural analysis code, ANSYS. For the chosen cross section the local field distribution was again determined by MODUCO.

For easier fabrication, the WP cross section is rotated around the CCF such that it is always parallel to a given reference plane in space. This way the conductors, coil case walls and, if applicable the radial plates, are not twisted and need to be bent around two axes only and not around diagonals. The preferred orientation is given by two parallel planes in minimal possible distance confining the CCF. Thus one can define a local coil "minimum coordinate" (MC) system with the centre of gravity located in the origin and y_{mc} parallel to the normal vector of the planes. x_{mc} is the direction of the largest coil extension measured parallel to the planes, and z_{mc} naturally is perpendicular to x_{mc} and y_{mc}. Fig. 4 shows the CCF of the HSR50a coil type 1 (which is at the "triangular" plasma cross section position) in the MC-system including the dimensions parallel to the axes. The CCF alignment was determined with the EXCEL SOLVER program. Tab. 3 gives the corresponding figures for all five coil types of the reactor. The last column contains the maximal angle deflections of the CCFs from the respective reference plane orientation. It is obvious that coil type 1 has the largest deviation from planarity both concerning the coil height as well as angular deflection. (The term "height" implies the coil lying on the floor.)

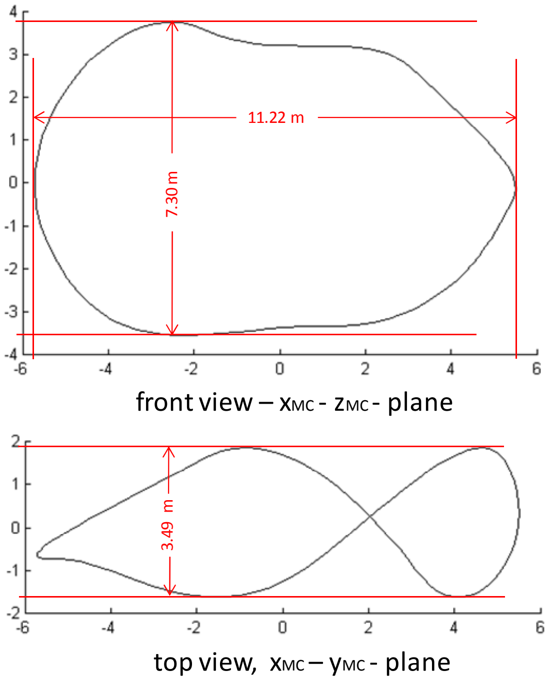

Fig. 4: HSR50a coil type 1 central current filament in the „minimum coordinate“ system. The lower diagram shows the minimal coil extension between parallel planes.

The cross section orientation relative to the MC coordinate system has the advantage that the angle deviations from planarity are minimal. Fig. 5 shows as an example a radial plate of the worst case coil type 1 oriented in this way. In order to avoid a local winding pack collision between both coils type 5 at the module interface, their cross section orientation was chosen parallel to the poloidal plane at the toroidal angle φ = 36°. Since the type 5 coil is the least critical concerning deviation from planarity (cf. tab.3), the suboptimal orientation is acceptable. In future design iterations this narrow can be avoided by a slight local shift of the CCF.

For manufacturing a HSR50a winding pack with Nb_3Sn cables and square jackets one would follow the ITER CS coil concept and react pre-bent conductors, insulate them, tighten, and finally impregnate them to form the solid WP [16]. With Nb_3Al this procedure would be much easier, and even a react-and-wind procedure is conceivable.

Manufacture of 3D radial plates and insertion of the conductor cables is quite difficult already with the planar RPs of ITER [8]. For an HSR5 one could produce such radial plates analogously to ITER in segments with regard to the coil circumference either by complete 3D-machining or by extrusion of segment parts (ribs) and welding them together [17]. For HSR50a, a radial plate concept option is shown in fig. 6 in 2D-representation: The segments are welded together from bent ribs where the latter are staggered at the segment interfaces such that by fitting them together they provide a form lock. Considering a Nb_3Sn cable, the segments could be inserted between the insulated pancakes of a slightly opened conductor double-pancake. After inserting the cable the staggered cover plates would be added and welded such that they overlap the segment interfaces. Finally, also the rib interfaces would be welded at the abutting faces (where possible) for a sound RP segment connection.

Again, with an Nb_3Al cable the assembly would be much simpler. A reacted and pre-bent Nb_3Al double pancake could probably be opened so far as to insert a complete RP.

Tab. 3: HSR50a coil data in the “min. coord.” (MC) system. Coil 1 is at the plasma “triangular” and coil 5 at the “bean” position of the torus, respectively.

Coil type	Min. height [m]	Max. length* [m]	Width† [m]	Pos. dev.‡ [deg]	Neg. dev.‡ [deg]
1	3.49	11.22	7.30	63.8	-47.1
2	3.33	11.21	7.50	58.1	-44.3
3	2,80	11.65	7.58	49.7	-37.1
4	2.49	12.09	7.19	51.1	-31.4
5	2.22	12.02	7.57	40.5	-30.7

*) Perpendicular to minimal height
†) Perpendicular to min. height and max. length
‡) Deviations of tangent vectors from planarity

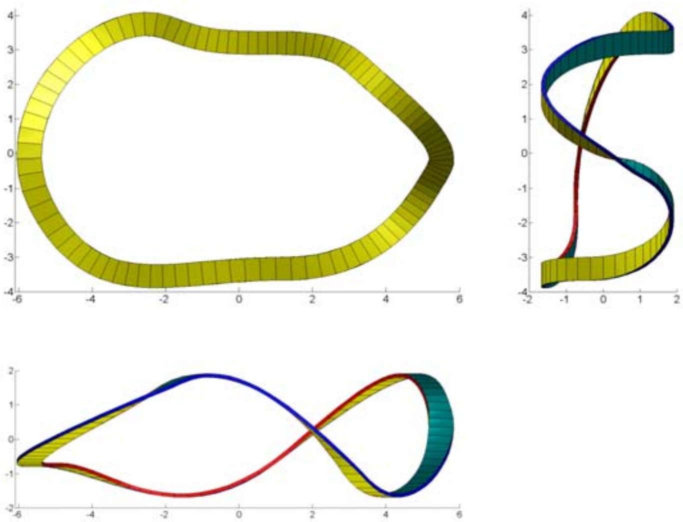

Fig. 5: Radial plate (RP) of coil type 1, oriented wrt. the min. coord. system (cf. fig. 4) in front, top, and side views. NB: The RP element long edges appear in true length in the front view (upper left), and are parallel in the others.

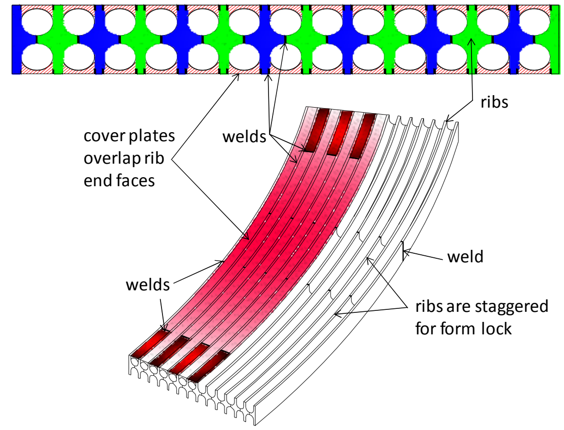

Fig. 6: HSR50a RP concept (2D-representation): Bent ribs are welded together, ribs are staggered at segment interface but not welded (form lock). Cover plates (seven out of 13 are shown) overlap the rib interface and are staggered too. Conductors are omitted for clarity.

4. Magnet system structure

The most delicate design issue of the stellarator reactor, in particular of a 12 T - variant like HSR50a, is concerned with the support structure. Some work was done already on HSR5 [18] and the 4-periodic HSR4 [19] where the requirements were somewhat relaxed due to the lower maximal induction of ~10 T. For HSR50a the conceptual design was started from scratch, however, with the experience of the real W7-X – structure as background. In this study the coil casings are naturally considered as part of the structure, but not the winding pack. The additional strength provided by the heavy square conductor jackets or radial plates, respectively, is thus neglected and in that sense the developed design is conservative. As a first approach the casings were furnished with reinforcement ribs, and for the inter-coil structure double shells were chosen. Most strikingly, it was found that a massive central support ring, as installed in W7-X, is not required. Large port openings are left within each coil interspace at the outboard side, and one weight support per module is attached at the inboard side. The weight supports consist of two sets of seven stacked 120 mm stainless steel plates each which allow movement towards the torus centre for thermal contraction compensation.

Fig. 7 shows the stress plots of both sides of a module: Most of the stress intensity is far below the allowable limits of the envisaged forged steel 1.4429, and only some local stress peaks exist which partly can be accepted, partly are due to rough modelling of component interfaces, and only a few remain to be eliminated in the course of detail design. The allowable limits of 625 MPa and 810 MPa for membrane (Sm) and membrane plus bending stresses (1.3 Sm), respectively, are established on the assumption of a realistic 940 MPa yield limit. It is shown that at no place a steel plate with thickness >150 mm is required. The maximal deformation within the system due to Lorentz forces is 60 mm only which is rather small for such a large system. In this first design iteration it is demonstrated that a reasonable structure for such a reactor is possible.

However, much optimization work still remains, i.e. local stress maxima have to be eliminated, unnecessary material in low stress areas has to be removed, and heavy shells should be replaced by boxed-in or ribbed sections. In addition, the question how to optimally connect all the components has to be solved. Also all the winding packs have to be analyzed locally and as constituents of the structure. However, the first results are very promising.

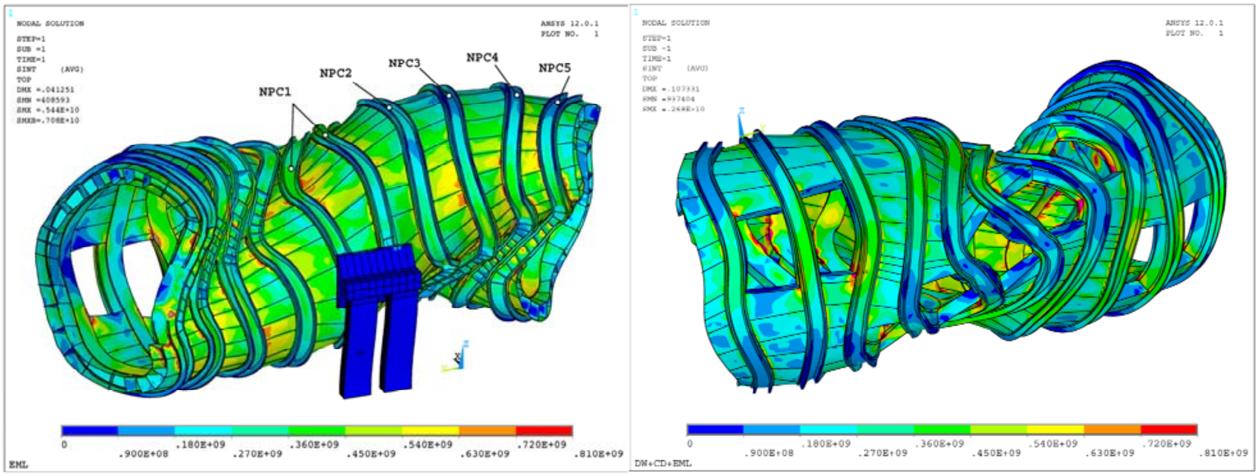

Fig. 7: Tresca stress distribution in HSR50a module; weight support at the inboard (left) side. Most of the stresses are below the allowable limits, all of them are below the yield limits. Only a few stress peaks remain to be reduced during detail design since those between coil housings and inter-coil shells are mainly due to numerical effects, and some local maxima are acceptable.

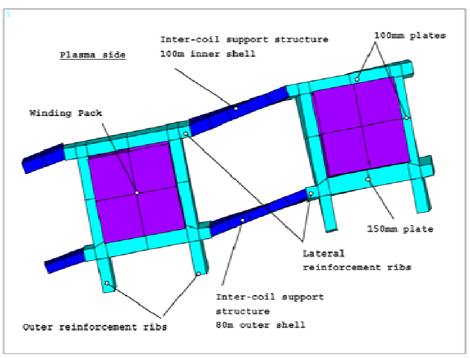

Fig. 8: Cross sections of two coils connected by inter-coil shell structure. The winding pack is not taken into account concerning the strength.

5. Electrical design

The stored magnetic energy of the ITER TF coils is 41 GJ or 2.3 GJ per coil [7], the corresponding value for HSR50a are 152 GJ and 3 GJ, and the inductances are 17.7 H and 41.1 H, respectively. These values indicate that the magnet power supply and coil protection system can be designed analogously to ITER, i.e. one power supply for all 50 coils in series and fast discharge resistors after every other coil [20]. A similar result was also found in an earlier study on the 4-periodic reactor HSR4 [21]. Due to the higher energy as in ITER to be discharged per coil, the copper content of the HSR50a-cable has to be increased (s. tab. 2) in order to limit the hot spot temperature and discharge voltage.

In the course of this study, only a rough comparative estimate was performed using the heat balance $I^2(\rho_{Cu}/A_{Cu})\Delta t=\sum m_i c_i \Delta T$, with ρ_{Cu} and A_{Cu} the resistivity and cross section of the copper, respectively, m_i the individual masses per unit length, and c_i the heat capacities of the copper, superconductor, jacket and helium. For ρ_{Cu} and c_i the temperature dependence is taken into account. The given ITER equivalent current decay time constant of $\tau = 11$ s leads, with the simple estimate $U=L\cdot I/\tau$, to discharge voltages of 110 kV totally or 12.2 kV per coil pair for ITER, and correspondingly to 321 kV and 12.8 kV for HSR50a. The real discharge voltages for ITER, considering the complete electrical network with capacitances, currents in structural components, and variable discharge resistors, are much lower [22]. But the simple estimate shows that the discharge voltages per coil can be assumed to be quite similar in both machines.

With the switch-off delay of 2 s after the quench, as specified for the ITER TF coils, one gets with the above heat balance for the latter a hot spot temperature of ~150 K. Thereby the thermal capacity of the insulation and heat transfer to the RP are not taken into account. For the HSR50a square conductor, having a large jacket mass, the same procedure yields a hot spot temperature of 120 K. However, for a stationary operating stellarator reactor with much less disturbances coming from plasma currents and control fields, a switch-off time delay requirement of 1 s is probably sufficient. With this the hot-spot temperature decreases even further to 85 K.

A worst case estimate for the RP version of the HSR50a coils yields under the same assumptions as above with ITER (no consideration of the RP heat capacity and 2 s delay) a hot spot temperature of ~290 K. With one second switch-off delay one gets 220 K which is not too far from the ITER value and is probably acceptable. In any case these estimates show that the cable layout is reasonable, in particular concerning the square conductor version. However, further in depth studies similar to those done with ITER [e.g. 22, 23] are required for a final design.

6. Conclusion

It is shown that the magnet system of a 5-periodic HELIAS stellarator reactor with 12.3 T maximal induction at the superconductor, HSR50a, is feasible. Since the coils of such a machine are very similar in size as the ITER TF coils, and the electromagnetic loads are not much higher either, one can take advantage of all the development and design activities as well as the prototyping which was invested there. This means that a HSR5, 12 T magnet would not require basically new developments but just an adaption and upgrade of quasi existing technologies.

HSR50a is a straightforward extrapolation from W7-X, therefore, physics and part of the technology can be directly taken over. It is thus the obvious first option to be studied. However, the three- and four- periodic HELIAS versions have to be considered too. The final design decisions will certainly be influenced by the outcome of the W7-X experiments

It is evident that an enormous amount of work still needs to be done on the HELIAS magnet system, besides all the other issues yet to be solved which are particular for stellarator reactors and those which are common to both, tokamaks and stellarators. For such a task a full-time engineering team has to be installed which can build on the results of the presented study.

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