HELIAS 5-B magnet system structure and maintenance concept

Felix Schauer, Konstantin Egorov, Victor Bykov

Max Planck Institute for Plasma Physics, EURATOM Association, Wendelsteinstr. 1, 17491 Greifswald, Germany

Work has been continued on the design study of a 5-fold symmetric HELIAS reactor with increased field. The coil shapes were slightly changed from the straightforwardly upscaled W7-X coils to a better suited reactor configuration providing improved plasma confinement and more space for the blanket. This reactor version is now called "HELIAS 5-B". The previously presented building block structure was adapted to the new shapes and forces, and was further optimized for better load distribution and reduced number of joints. Simplified panels with only one or two plates each are now used.

In addition to the previously presented option to separate the whole torus for good access to the in-vessel components, a blanket maintenance concept based on exchange of 400 large blanket segments simultaneously through five vertical ports was devised. Even though this concept is still at an initial state it can be shown that also in a complex stellarator geometry it is possible to have robots running on rails inside the plasma vessel to transport heavy loads.

Keywords: Stellarator, HELIAS, Magnet, Structure, Blanket, Maintenance

1. Introduction

A design study for an upgraded five-periodic HELIAS stellarator reactor is being performed at the Max Planck Institute for Plasma Physics (IPP) in Greifswald. The original HELIAS concept [1, 2] was upgraded concerning an increase of the plasma confinement field [3-5]. This means higher fields >12 T at the superconducting coils and consequently a switch from the previously presupposed NbTi superconductor to Nb_3Sn with the obvious option to replace it with a better one, if available, in future. The superconductor material, maximal field, coil sizes, current densities, forces, stored energy per coil, and other parameters are comparable to corresponding ITER TF magnet system characteristics. Many of the ITER technologies can thus be directly applied to this type of stellarator reactor in spite of the 3D-shape of the coils.

One of the technical challenges of any large fusion machine is the design of a structure to stand the huge electromagnetic forces. One feasible solution for a HELIAS reactor is a building block structure whose parts can be mass-produced, bolted between the coils, and dismounted in case of maintenance requirements [5]. This structure is now being further optimized as demonstrated in section 2. It was adapted to the slight change of the coil shapes from the purely up-scaled W7-X coils to the better suited shapes for a reactor [6]. In addition, it now allows for horizontal and vertical positions of the large ports. To this stellarator (see Fig. 1; not all of the shown large horizontal ports might be required) the name HELIAS 5-B was given. In table 1 some main technical data are collected, together with the corresponding values for ITER.

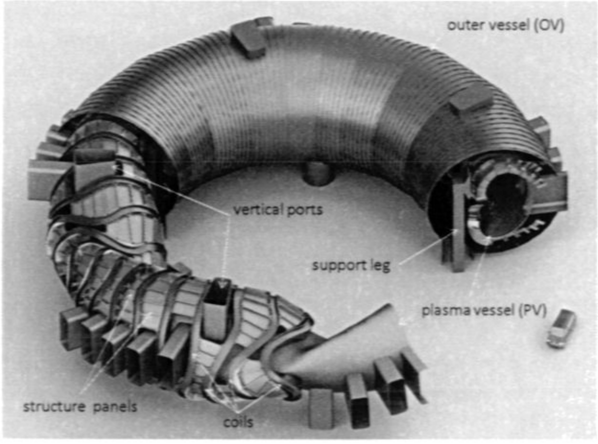

Fig. 1 HELIAS 5-B overview.

Table 1: Main data of HELIAS 5-B and ITER

	HELIAS 5-B	ITER
Major radius, m	22	6.2
Average minor radius, m	1.8	2.0
Plasma volume, m^3	1407	837
Number of coils	50	18^a
Average field on axis, T	5.9	5.3
Max. field at coils, T	12.5	11.8^a
Cable current, kA	86	68
Sc. strand current, A	76	76
Superconductor	Nb_3Sn, Nb_3Al	Nb_3Sn
Stored energy, GJ	160	41^a
Stored energy/coil, GJ	3.2	2.3
Fusion Power, MW	3000^b	500

a) ITER TF coil system

b) Estimated for a plasma axis field of 5 T

---

author's email: felix.schauer@ipp.mpg.de

Section 3 describes a maintenance concept based on exchange of large blanket segments through vertical ports. No neutronic aspects or other blanket details except segment geometry are evaluated. Divertor layout and maintenance are not considered.

2. HELIAS 5-B magnet system structure

The primary structural component is the jacket of the superconducting cable, a quadratic steel pipe with outer dimensions 53x53 mm^2, and 6 mm wall thickness [4]. The coil winding pack (750x709 mm^2 incl. ground insulation) is enclosed by the casing (outer dimension 1000x920 mm^2) which is reinforced with ribs. The inter-coil structure consists of bolted panels [5]. This design allows to omit the central support ring as required in W7-X. Each of the five support legs is attached directly to one coil in a module (see Fig. 1).

The panels have been updated in several iteration steps, taking into account the change of coil shapes and port positions. The panel number was reduced by increasing their poloidal widths from roughly 1 m to 1.5 m on the average which also reduces the number of flange connections. The panels are now split in the minor torus radius direction such that there are two panels on top of each other, each one having one or two plates (Fig. 2). This allows for a better bolted contact distribution along the coil height since in many places assembly and bolting only from the outside is possible.

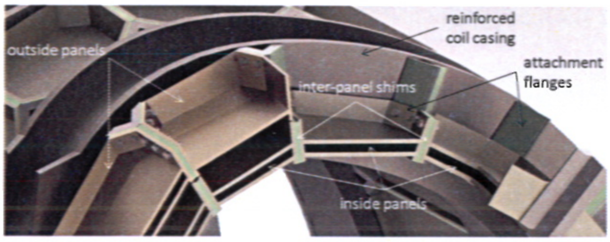

Fig. 2 Cross section of structure panels between coils.

Depending on the load distribution, one or two panels with one or two plates each are inserted at a certain location. Fig. 3 shows the equivalent stress distribut-ion for this structure at the outboard side of the magnet system. The general membrane and membrane plus bending stresses are within allowable limits for stainless steel grade 316 LN. Peak stresses are very localized and can be reduced in the course of further optimization.

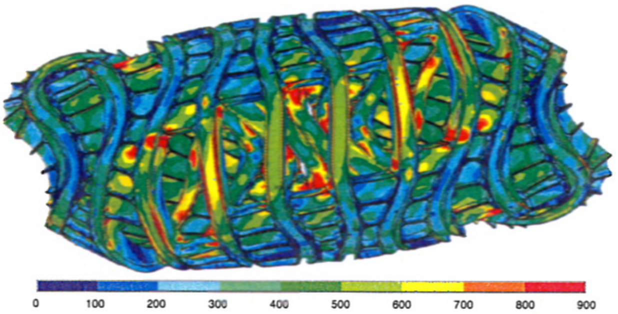

Fig. 3 V. Mises stress distribution at the magnet system outboard side, MPa.

3. Maintenance concept

Many ideas for maintenance of the complex 3-D – shaped stellarator blankets have already been discussed. The most obvious option is to exchange blanket modules through sufficiently large ports which is also the only solution for tokamaks. A HELIAS reactor also offers the option to shift one or several coil subsets [7] or even complete modules radially out of the torus to get access to the plasma vessel (PV) interior via its full cross section. For 5-fold symmetrical HELIAS reactors, subsets of four or six adjacent coils or a complete module can be shifted without being blocked by adjacent coils. These possibilities were recently extended to separation of the torus into two parts (i.e. radial shift of two connected modules) for simultaneous access to four full PV cross sections [5].

Additional approaches are to simplify and/or reduce modular stellarator coils such as to provide more space between them to allow movement of large components radially through wide openings between the coils [8]. One such proposal to simplify coils while keeping the stellarator field intact is passive field shaping using high temperature superconductor tiles aligned on a suitable surface inside the plasma vessel (PV). Another is to straighten the coil outboard legs and move them radially outward. The corresponding field change then has to be compensated by small saddle coils which would have to be removed for maintenance access.

All the methods relying on magnet system configuration changes to get better access to the PV interior require much effort before and after the blanket (and divertor) exchange, particularly since opening of the cryostat is involved. Careful and detailed investigation is needed in all these cases to assess whether the gain in in-vessel component exchange time is not offset by the time for warming up and cooling down the magnet system, opening and closing the PV and outer vessel (OV) with all the contamination and vacuum problems, detaching and re-joining coil coolant lines and power supplies, etc. At this state all options are kept open and thus previous rather rudimentary considerations [6, 7] concerning blanket exchange through ports have been continued.

The HELIAS 5-B structure allows for one large vertical port per module having a slightly trapezoidal cross section with usable clearance dimensions of >4300x(2500, 1800) mm^2 (Fig. 1). The blanket was divided into 16 rings per module with widths matching the port size. Fig. 4 shows 1/5 of the torus blanket reaching from the toroidal angle $\varphi \approx -47°$ at the vertical port of one module to $\varphi \approx +25°$ at the corresponding port of the adjacent module. Corresponding to the 5-fold stellarator symmetry, this blanket arrangement of a "shifted module" recurs five times around the torus. (The five stellarator modules extend from 0° to 72°, etc.) Each ring consist of five segments with average volumes of 5.5 m^3 or roughly 16.5 tons, assuming $\approx$3t/m^3 for a He-cooled solid breeder blanket [9]. Typical dimensions of a segment are 5x1.6x0.8 m^3. In total there are 400 of them which is comparable to the 300 – 400 large modules according to the Large Module Segmentation of a 3300 MW_{therm} tokamak reactor [10]. All port openings other than the large vertical ones are ignored at this stage. The segments might be subdivided as in the tokamak Multi Module Segment concept, but this is left to further studies. Only basic blanket geometries and maintenance principles are considered here, manifold cutting and welding issues are taken into account neither.

Fig. 4 also shows the blanket gaps behind the top and bottom divertor sections. Both extend only over half a module, each one from $\varphi = -18°$ to $\varphi = +18°$ [7]. The gaps in the blanket rings are presently in no way adapted to a real divertor which still needs to be designed.

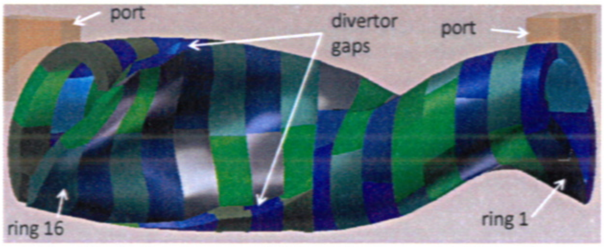

Fig. 4 Blanket rings of 1/5 of the torus ($-47° \leq \varphi \leq 25°$).

The segments of the first and second blanket ring (right side in Fig. 4) can be accessed from the hot cell at top with a vertical handling device as conceived for Multi Module Segments of a tokamak [11]. This device must allow also horizontal movements of its lower end within the PV. Fig. 5 shows the paths of the first two segments of ring 1 out of the port; these are shifts only without rotation. The heaviest and lightest segments of this ring and of the whole blanket are segments 4 and 2 with $\approx$22 and $\approx$9.5 tons, respectively, based on the present preliminary ring divisions. Also the segments of ring 2 - as well as of ring 16 at the other side of the port from the adjacent "shifted blanket module" - can be reached by the same vertical handling device and be removed without rotation.

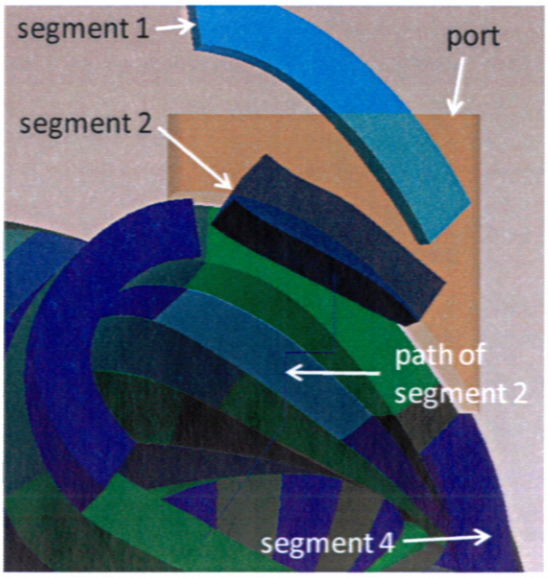

Fig. 5 Segment removal from blanket ring 1.

After removal of the first three blanket rings, the in-vessel crane can be inserted to transport the remaining blanket segments towards the ports to be reached by the vertical handling device. Fig. 6 shows the crane rails attached to the inner surface of the PV, extending from one vertical port to the next and beyond. The top rail is interrupted below each vertical port. The crane has to be driven simultaneously at the top and bottom rails, e.g. via tooth bars, in order to keep it always vertical. The distance between the rails varies which has to be compensated by telescopic columns. The latter rest on a carriage which follows the ups and downs of the bottom rail; a hinge-joint right on top of the carriage allows the columns to stay vertical.

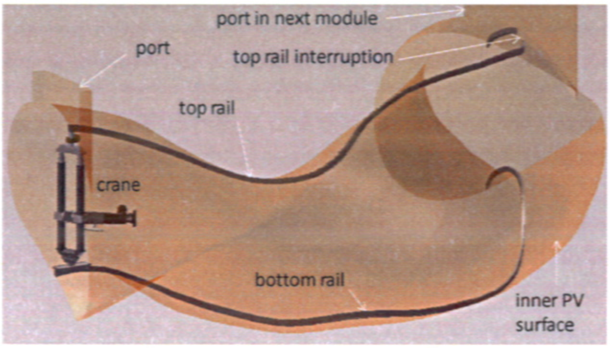

Fig. 6 In-vessel crane on rails.

The blanket segments are reached via a boom which consists of the swivel and shiftable parts, with the latter sliding within the former (Fig. 7). The boom swivel slides on the lower, outer tubes of the telescopic columns. An interface device to hold the blanket segment ("attachment plate") is mounted at the boom end via two hinges with vertical and horizontal axes, respectively. The boom is lifted by cables running on pulleys (better visible in Fig. 8 left; the cables are not drawn). The crane can also rotate around its central vertical axis. With these degrees of freedom the attachment plate can reach any blanket segment and move it along any path.

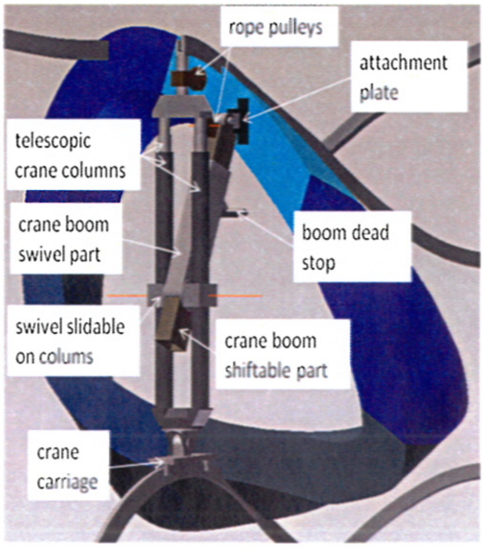

Fig. 7 In-vessel crane removing segment 1 of ring 3.

Fig. 8 shows the crane boom in different positions: On the left attached to segment 2 of blanket ring 8 (at $\varphi \approx -20°$), and on the right side attached to segment 2 of blanket ring 12 (near $\varphi = 0°$, here with divertor gaps on top and bottom). In the latter figure the boom is at its lowest angular position with the dead stop (cf. Fig. 7) touching the columns. This relieves the cables which otherwise are loaded most when the boom points downwards.

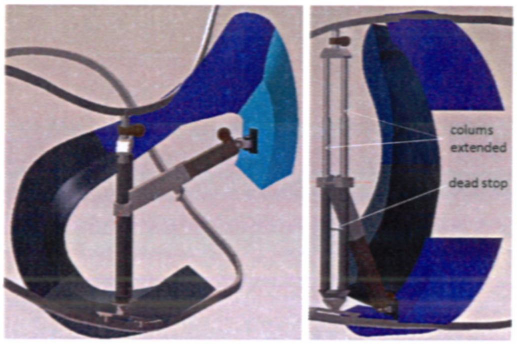

Fig. 8 Crane removing segments of blanket rings 8 (left) and 12 (right), resp.

The shown crane dimensions roughly comply with the segment weights of up to ≈20 tons, the steel cable diameter is around 15 mm (on 2x4 pulleys, 8 cable legs). For each degree of freedom a drive system is necessary. The drives for the cables, the crane rotation, the sliding boom part, and the boom swivel height need to work synchronously in a controlled manner to move the segments on the required paths. The hinges of the attachment plate can be fixed after joining the segment to the crane, their drives need thus to work only in unloaded condition. As soon as a segment is clear of its blanket ring it is moved close to the crane axis to relieve the rail interfaces during the travel toward the port.

No attempt was made to design the fixation between the crane and the blanket segments ("attachment plate"). For the time being it is not clear yet whether it is more advantageous to grip the segments from the side, as shown in the figures, or to have some sunk-in interfaces at their front sides. From a static point of view the latter would be preferable.

Basically, ten in-vessel cranes could work simultaneously to feed five vertical handling devices at the five vertical ports. Since 3 blanket rings or 15 segments per port are removed directly from top, 325 blankets would be left for the cranes, i.e. 32 or 33 pieces for each of them. Obviously, it would be quite an investment to keep all this equipment and the corresponding skilled personnel ready for maintenance which might be performed only once in every 10 years. However, it is imaginable that in a future ideal HELIAS fusion-reactor-world a separate maintenance team is installed with corresponding mobile facilities, i.e. ten in-vessel cranes and five vertical handling devices as well as other necessary equipment. This team could move in a round robin scheme from one reactor to the next to perform the maintenance work.

4. Conclusion

The optimization of the building block structure of HELIAS 5-B has been continued. Results are simpler panels having only one or two plates each, better force distributions at the interfaces between the coils and panels, and a reduced number of bolted joints. Two panels can be assembled on top of each other, and they can be easily distributed according to the loads to be supported.

In addition, a blanket maintenance concept based on exchange of ≈400 large blanket segments simultaneously through five vertical ports was devised. It could be shown that also with a complex stellarator geometry it is possible to have robots running on rails inside the plasma vessel to transport heavy loads. However, the blanket layout is still at a very initial state and its development has to be left to future work.

Acknowledgements

The authors would like to thank their colleagues Th. Bergmann for help with dimensioning the crane, and C. D. Beidler for proof reading the article. The work was partly supported by EFDA.

References

[1] C. D. Beidler et al., Proc. 16th Fus. Energy. Conf. 1996 Montreal, Vol. 3, IAEA, Vienna 1997, p. 407.

[2] H. Wobig, F. Wagner, Landolt-Boernstein—Group VIII Adv. Mat. and Technol., Vol. 3B Energy Technologies, Nucl. Energy (2005) 418–452 (Chapt. 7).

[3] F. Schauer et al., Contributions to Plasma Physics 50, No. 8, (2010) 750 – 755

[4] F. Schauer, K. Egorov, and V. Bykov, Fusion Engineering and Design 86, Issues 6-8 (2011) 636-639

[5] F. Schauer, K. Egorov, V. Bykov, A. Dudek, IEEE/INPSS 24th Symp. Fus. Eng. (SOFE), SP1-18, 2011

[6] T. Amano, et al., 12th Int. Stellarator Workshop, Madison, Wisconsin, Sept. 29 – Oct. 1, 1999

[7] C. D. Beidler et al., Helias Reactor Studies, IPP Report IPP 2/330, Oct. 1995

[8] G. H. Neilson et al., 23rd IAEA Fusion Energy Conference, Daejon, Korea (IAEA-F1-CN-180/FTP/P6-06), 2010

[9] L. V. Boccaccini, KIT, Personal communication, July 2012

[10] F. Cismondi, E. Magnani, and L. V. Boccaccini, Japan/US Workshop on Power Plant Studies and Adv. Technologies with EU and Korea participation, 22-24 Feb. 2011, NIFS, Toki, Japan

[11] D. Maisonnier, Fus. Eng. Design 83 (2008) 858-864