Studies of In-Vessel Component Integration for a Helium-cooled Fusion Reactor

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1. Introduction

In the European Power Plant Conceptual Study (PPCS) [1,2], three reactor models for the Fusion Power Plant (FPP) make use of the helium cooling technology for in vessel components, namely Model B with a solid breeder (the “Helium Cooled Pebble Bed”, HCPB) [3], Model AB with a stagnant PbLi liquid breeder (the “Helium Cooled Lithium Lead”, HCLL) [4] and Model C with the “Dual Coolant Lithium Lead” (DCLL) blanket [5]. For all the three models, the in-vessel configuration is completed by helium cooled divertors [6]. Hence, helium is used at high pressure – high temperature for the blanket (8-10 MPa, max. 500°C) and the divertor (10 MPa, max. 700-800°C) cooling systems. In the DCLL about 40% of the heat produced in the blanket is removed by Helium; the remaining 60% is transferred to the power generation system by a low pressure PbLi loop. These FPP concepts are under discussion for a Demo reactor and for a First Generation of Fusion Power Plant (FG-FPP). Table I shows the main design assumptions and lay-out parameters associates to these concepts.

The integration of these reactor models into the vacuum vessel (VV) (including a neutron shield and cooling manifolds) was the subject of a recent study performed at FZK. The aim of this study was to identify the critical issues related to the integration of systems that make use of the helium cooling technology. In fact for these reactor concepts the main integration issue is the accommodation of the large He pipes in the VV and the definition of a remote handling (RH) strategy for cutting/welding these pipes.

The “large module” system derived from the ITER “in vessel transporter” was selected as maintenance concept. According to this concept [7], the blanket in ITER is divided in modules that are attached directly on the VV. An in-vessel machine is used for attach/detach the mechanical connections of these modules and to cut/re-weld the pipes of the hydraulics connections. The coolant distribution system (manifold) is connected to the VV, as well; the relatively low differential thermal expansion (about 50K) makes this design possible. The water coolant pipes are routed through the upper ports outside the VV. This system is complemented by a “cassette” maintenance concept for the divertor based on a rail system supported from the lower ports.

This system has been developed for a low availability machine, in which scheduled replacement inside the VV are foreseen only for the divertor cassette. The investigation on the extrapolation limits of this system to reactor conditions was a second objective of this FZK study. Table II presents a list of the main differences between ITER and a FPP that are relevant for the design of the maintenance system. This list should be considered as preliminary and probably not complete, but it already gives a picture of the main different requirements. Some of these differences are related to the increase of the performances (fluences, coolant temperatures, etc.) or functions (heat extraction for electrical power production, tritium recovery, etc.); others are typical of any helium cooled system (as the presence of large tubes, the neutron transparency of helium, etc.).

Table I: major layout parameters of the PPCS Helium cooled concepts.

	Model B	**Model AB**	**Model C**
Blanket Type	HCPB (Solid Breeder)	HCLL (Stagnant liquid)	DCLL (Dual Coolant)
Structural material	EUROFER	EUROFER	EUROFER (ODS in FW)
BrederMaterial	Li4SiO4 – Li2TiO3	Pb/Li $_{\text{eutectic}}$	Pb/Li $_{\text{eutectic}}$
Multiplier	Beryllium	“	“
Coolant	Helium	Helium	Helium (40 %) Pb/Li $_{\text{eut.}}$ (60 %)
Divertor type	He-cooled	He-coooled	He-cooled
Coolant	Helium	Helium	Helium
Structural material	W-alloy / ODS steel	W-alloy / ODS steel	W-alloy / ODS steel
General parameters			
Electricity power	1.3 GW	1.5 GW	1.5 GW
Blanket Thermal Power	4.3 GW	4.5 GW	3.5 GW
Coolant temperatures	He: 300-500°C	He: 300-500°C	He: 300-480°C PbLi: 480-700°C
Dimensions (major rad.)	8.6 m	9.6 m	7.5 m
Coolant mass flow	He: 4.9 t/s	He: 5.1 t/s	He: 1.5 t/s PbLi: 46 t/s

2. General concept description

For the lay-out of the FPP, Model PPCS-B (at ~1500 MW electrical for a plasma major radius of 8.6 m) has been taken into account with a reactor segmentation into 18 equal sectors of 20°. As in ITER, three horizontal ports (upper, equatorial and lower port) per sector have been considered.

2.1 Radial build-up

Figure 1 describes schematically the radial build-up of the reactor in the blanket region; starting from the plasma chamber the first region is constituted by the blanket. This consists of the first wall (about 30 mm) followed by the breeding region (35-45 cm). The rear part is constituted by the supporting back plate including the helium manifold and part of the shielding (the Hot Temperature Shielding, HTS). Shielding material is steel and/or WC, integrated into the blanket. The blanket is cooled by Helium (300-500°C). A gap of few centimetres divides the high temperature region (HTR) from low temperature region (LTR). HTR and LTR are mechanically connected with an attachment system that must cope with thermal stresses due the temperature mismatch and withstand electromagnetic forces during disruptions.
The LTR consists essentially of the Low Temperature Shield (LTS) and the Helium Piping System (HPS) that transport the main coolant of the blanket. The structure of the LTS

operates at the same temperature of the VV so that can be connected rigidly to the supporting vessel; a water-cooled VV at 150°C has been assumed in the study. Pipes with Helium at 300-500°C are routed inside the LTS region.

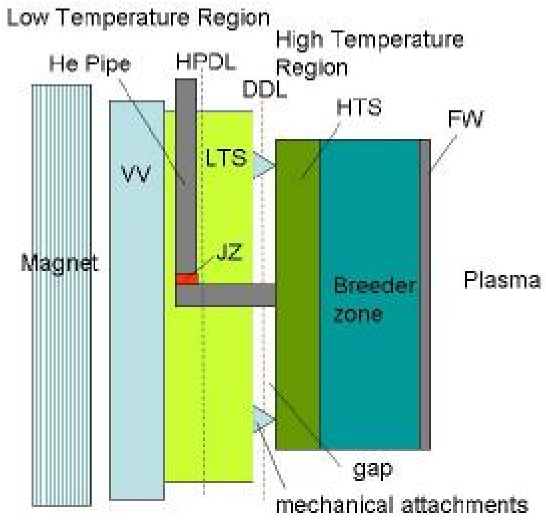


Fig .1 Radial built-up of in vessel components

In ITER, the dimensioning of the shielding thickness of the in-vessel components is mainly dictated by the protection of the VV (re-weldibility) and the magnets (material damage and heat deposition) from the neutron radiation. As the total fluence in the FPP is more than 2 orders of magnitude greater than in ITER, other requirements become important. In fact, the components inside the vacuum vessel are subjected to high energy neutron flux that limits their lifetime; in particular the He swelling of the structural material is considered the limiting factor in the blanket design. This is the main reason because martensitic steel has been selected as structural material for the blanket of the FG-FPP. A DDL (damage design limit) of 70 dpa is assumed for EUROFER (the reduce activation steel developed in EU for fusion application) in DEMO design, while for commercial FPP an improvement up to 140 dpa is anticipated. This means that an in-vessel component is considered permanent (i.e. it doesn't require scheduled replacement) if the cumulated damage for the entire life is lower than the DDL. The LTS and HPS are designed in this integration concept as permanent components; at the contrary the blanket shall be replaced every 3-6 years.

Table II: comparison among major requirements from ITER and first generation reactor.

	ITER	**Fusion Power Plant**
Dimensions:	Major plasma radius 6.2 m	7.5 – 9.6 m (for ~1500 MWel)
Power densities:	0.78 MW/m2 as neutron wall load 0.25-0.5 MW/m2 as surface heating	2.5 MW/m2 0.50 MW/m2
Fluences	max 0.5 MWa/m2 at the FW	~100 MWa/m2 (for 40 FPY at FW)
Pulse length:	400s (1000-3000 in advanced scenarios) and long dwell: ~1200s	steady state or long pulses (e.g. 10000 s and short dwell)
Blanket	No tritium production. (*) Low coolant temperatures (no electricity production) Water cooling.	Tritium production and extraction Higher temperatures for electricity production He cooling High shielding capability
Divertor	"Cold divertor"	Divertor integrated in the power generation system (divertor heat ~17% of the reactor thermal power).
Availability:	10%	>70-75%

(*) the installation of a breeding blanket in the second operation phase is not excluded in the ITER design.

Another important design limit is the re-weldability of the structure and in particular of the hydraulic connections. This is important if pipes necessitate to be re-welded several time e.g. for replacement of the breeder blanket modules. Usually this design limit (He production design limit, HPDL) is assumed 1 appm. This limit is in general more restrictive of the DDL so that more shield thickness is necessary to assure this requirement.
Another requirement can be derived by energy deposition consideration; it is favourable for the overall efficiency of the fusion reactor (transformation of the fusion power to electrical power) that the major part of the heat generated be removed by the high temperature coolant and hence used for the electrical power generation at high efficiency. Heat removed by low temperature loops (like in the VV and in the LTS) is practically discharged for electrical production. An optimisation of the reactor performances calls for high heat deposition (>95%) in the HTR. Limiting factor for the lifetime of the divertor is the erosion of the target plates with an envisaged lifetime of 2 years for the FG-FPP.

2.2 General Design Description and assumptions

The adaptation of the "in-vessel transporter system of ITER" to a FPP configuration considers the following segmentation (see Figure 3) for the removable components (blanket and divertors):
a) The "Cassette Divertor System" (with a segmentation of 3 cassettes per sector) is adopted for the design of the divertor at the lower part of the VV. Cassette are mounted on a rail systems and are replaced trough the lower ports (4 ports on 18 are dedicated to the Remote

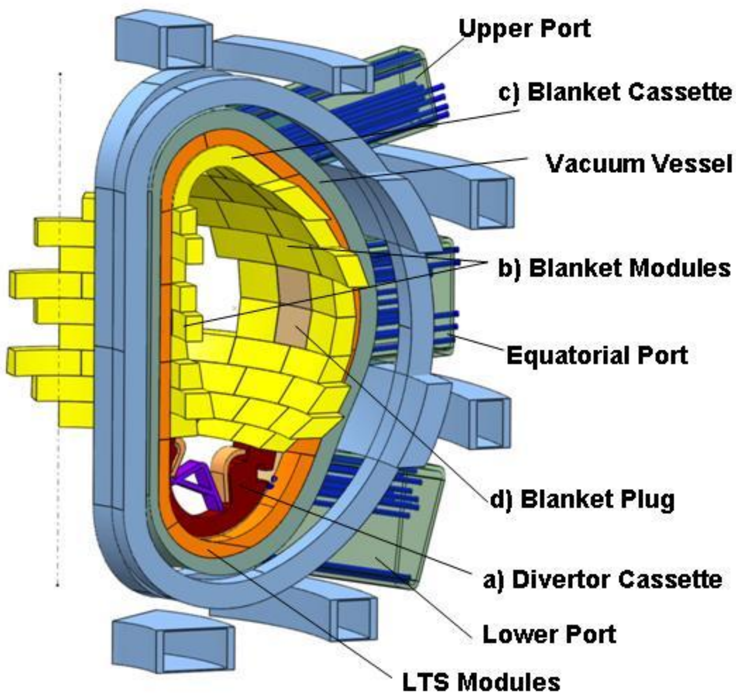


Figure 2: Reference configuration for blanket/divertor segmentation.

Handling, RH).
b) "Blanket Modules" are foreseen for the equatorial region of the inboard and outboard. They are connected to the lying behind LTR and are replaced with the help of an in-vessel machine trough 4 RH equatorial ports.

c) The blanket at the upper part of the VV is integrated into “Blanket Cassette” rather than modules. This choice is justified by the wish to avoid a difficult geometrical integration of modules in a part of the reactor at high curvature. The cassettes are replaced through the 4 dedicated RH upper ports; the helium coolant pipes are distributed to the 18 lower ports. Some cassettes have only shielding functions as they are dedicated to diagnostic or windows for plasma heating systems that necessitate an allocation in the upper ports.
d) Additional blanket modules (“Plug Blankets”) are foreseen on the 18 Port Plugs that close the equatorial ports. These modules will be extracted with the Port Plug and the cooling helium pipes will be routed inside the ports themselves. Also here, some blankets will be used as windows for diagnostic and heater systems allocated in the equatorial port plugs.
The maximum weigh of 10 t has been chose for the blanket modules. This assumption has a strong impact on the total number of modules present in the reactor and, hence, on the complexity and time of the RH operation. This choose was the consequence of the decision to limit the internal diameter (ID) of the helium pipes to 150-200 mm and to keep the Helium velocity in the range 50-75 m/s. Furthermore, only 2 coolant pipes for each module have been considered; as the pipe welding connection is the most time consuming operation in the blanket replacement, larger modules with more than 2 pipes are not so advantageous in comparison to smaller ones. Consequently, 10 t has been used as requirement for the RH machine used for the blanket manipulation.
Behind the blanket modules/cassettes and divertors a low temperature shielding/manifold region will be arranged as permanent components. The concept foreseen LTS modules attached to the VV. The LTS modules cover the whole VV internal surface (except port opening) providing the attachment for the blankets and divertors. The LTS can be cooled by water (this is the favourite concept) or Helium (if water should be avoided). The piping system connected to these components has not addressed in details at the moment. Water piping can eventually come directly from penetrations in the VV avoiding additional tubes inside the VV. This could be possible because the temperature requirements are the same, but several concerns have to be addressed for the safety assessment. The maximum weight of the LTS Modules should be compatible with the tools system used for the RH of the blanket system to allow the initial assembly and possible repairs. The pipes of the HMS are integrated in these modules.

3. Issues related to the maintenance system

The main issues discussed in this section are related to the scheduled replacement of the blanket modules that constitutes abut the 75% of the blanket coverage. The lifetime of this component is considered for the FG-FPP of about 3 years. The number of these components (312) and the complexity of the interface with the surrounding reactor make this operation the most demanding. Replacement of the divertors (2 years lifetime) and blanket cassette, or plug blanket systems have not been yet analysed in detail.

3.1 Module/reactor interface

As far as the definition of the module/reactor interface is concerned, the experience of the ITER design shows that several systems should be provided at the rear side of the module; mechanic attachments, hydraulics connection (main coolant and tritium recovery pipes) and the electric grounding system. The mechanical connections between the HTR and LTR have to cope to the EM loading and compensate the thermal mismatching. In this study a system of ITER derivation is adopted [8], namely shear keys and flexibles for the equatorial blankets and rail system for the cassettes.

The hydraulic connection of the main pipes will be discussed in Section 3.3; in addition in a FPP the recovery of the tritium bred in the blanket becomes a major functional requirement. For this operation the HCPB concept and in similar way the HCLL require an additional piping system to contain the He purge gas or the PbLi, respectively. For both systems this means that 2 additional pipes (of about 7cm-ID each) shall be connected to each module. The lay-out of this system and the RH connection/detachment procedures have not be addressed in this study, but their impact in the overall complexity and time requirement is not negligible. For the DCLL the tritium extraction function is performed by the main PbLi lines.

3.2 In-vessel machine

The replacement of the equatorial blanket modules requires the use of a manipulator able to operate inside the VV. This manipulator should grip the modules and transport them through one of the dedicated RH equatorial port to the transport cask. At the same time this machine should be able to lock/unlock the mechanical attachment of the module. Operations related to the welding of pipes are not foreseen for this machine, however, connection of electrical connector should be considered.
The system assumed in this assessment has a capacity of 10t and is described by Nagy [9]; this system (see Figure 3) will be mounted/dismounted automatically using only the access of

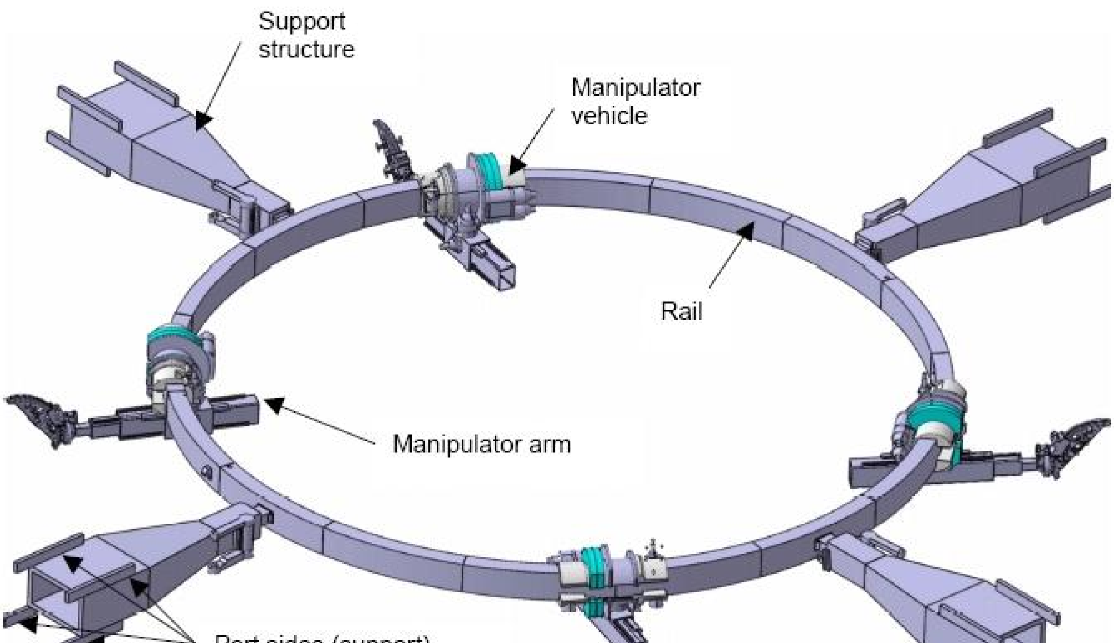
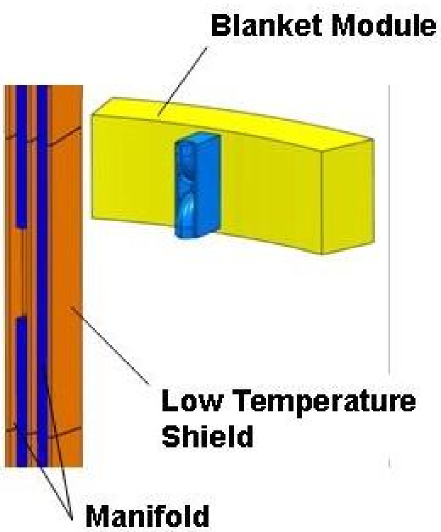


Figure 3: the in-vessel machine [9]

the 4 equatorial RH Ports. An increase of load capacity can be realised with an alternative concept, i.e. a “pillar system” that uses the rails of the divertor and blanket cassette system.
Blanket and divertor cassettes are moved toroidally in the rail system and extracted by manipulators allocated in casks docked on the RH upper/lower ports.

3.3 RH connection of Helium Pipes

According to this maintenance concept, the helium pipes necessitate to be welded and cut with RH tools inside the vacuum vessel. In addition the location of the junction zone (JZ) should be protected by neutron damage to assure the re-weldibility of the junction during all the life of the reactor (see section 2.1). Three technologies have been considered for this operation: front tools, orbital tools and in-bore tools. Front tools are the ITER solution for the shielding blanket. A special hydraulic connector has been developed [8] at the interface manifolds-module. The welding/cutting tools are operated by the in-vessel machine; they penetrate in holes (only 3cm diameter to reduce neutron streaming) realised in the front of the blanket and reach the joint position. The tools have a periscope head able to penetrate the small frontal holes and then, after a rotation of 90°, to weld and cut from the inner side the connector (about 6 cm ID). The operation is complicated by the necessity to seal the 3cm frontal holes with weld from the vacuum chamber side. A similar operational mode seams extremely complicated for the assumed Helium pipes. The dimension of the tubes (150-200 mm ID) will require periscope tools able to enter in small holes (3cm) and then cut and weld about diameters 5-7 times the enter dimensions. Furthermore, the presence of the large Helium pipes that should go straightforward in radial direction up to the JZ (that is located deeply in the LTS), will make very difficult to fulfil the HPDL. Orbital tools can be alternatively adopted; they are operated by the RH machine, as well. The most critical issue is the accessibility of the junction that is placed deep inside the LTS. The operation is judged feasible, but extremely complicated by the necessity to free the JZ by the protecting shielding. The resulting RH procedure will require additional shielding plugs (how they can be cooled?) and the access with a serial procedure of replacement, i.e. key modules or piece of shield should be removed to give accessibility to the JZ.



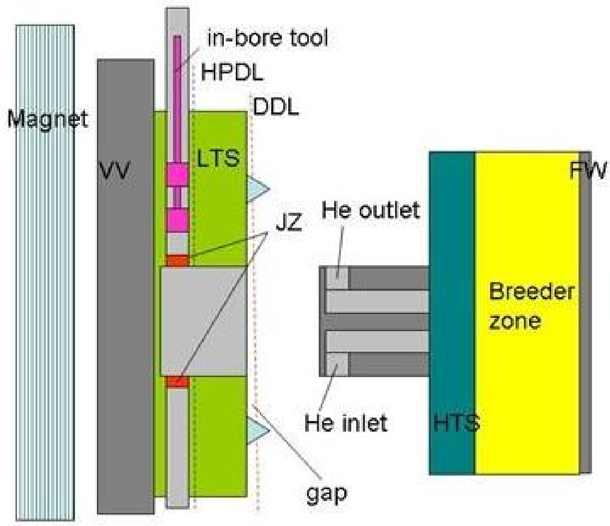


Figure 4: Hydraulic connection based on in-bore tools

A third possibility has been considered, namely in-bore tools; the rational is to try to use the presence of a permanent system of large pipes to guide tools from the VV outside to the junction. The second consideration is to use a system independent from the internal operation of the in-vessel machine, suitable for a large degree of "parallelisation". As the welding is the most time consuming operation, the increase of the number of "trains" simultaneously

operating during the RH, will reduce about proportionally the time of the whole operation. To allow this kind of operation, every blanket module is connected with an independent pair of pipes of the manifold system to an out-of-vessel collector. Figure 4 shows an example of the proposed connection. The JZ is located in a protected position inside the LTS and can be reached by in-bore tools that move inside the connecting pipes; a "foot" attached to the module have the function to support the pipes and acts as vertical shear keys in the mechanical attachment.
Several requirements should be considered in the lay-out of the pipe systems, as the necessity of place for the cutting/welding/testing head, minimum bending radius for the tubes, tolerance of the junction for the re-welding operation, etc. A more complete discussion of the technological aspects related to this proposal can be found in the paper of Rey [10].

3.4 Manifold Systems

Figure 5 shows the resulting lay-out of the piping system for a 20°-sector. Place availability in the strongest requirement; in fact all the three ports of the sector are necessary to host the piping system. In each port the pipes (with the exception of the pipes related to the cassette and the plugs) are routed near the wall leaving place for the necessary systems in the port (heating, systems, diagnostic, RH access ports, etc.).

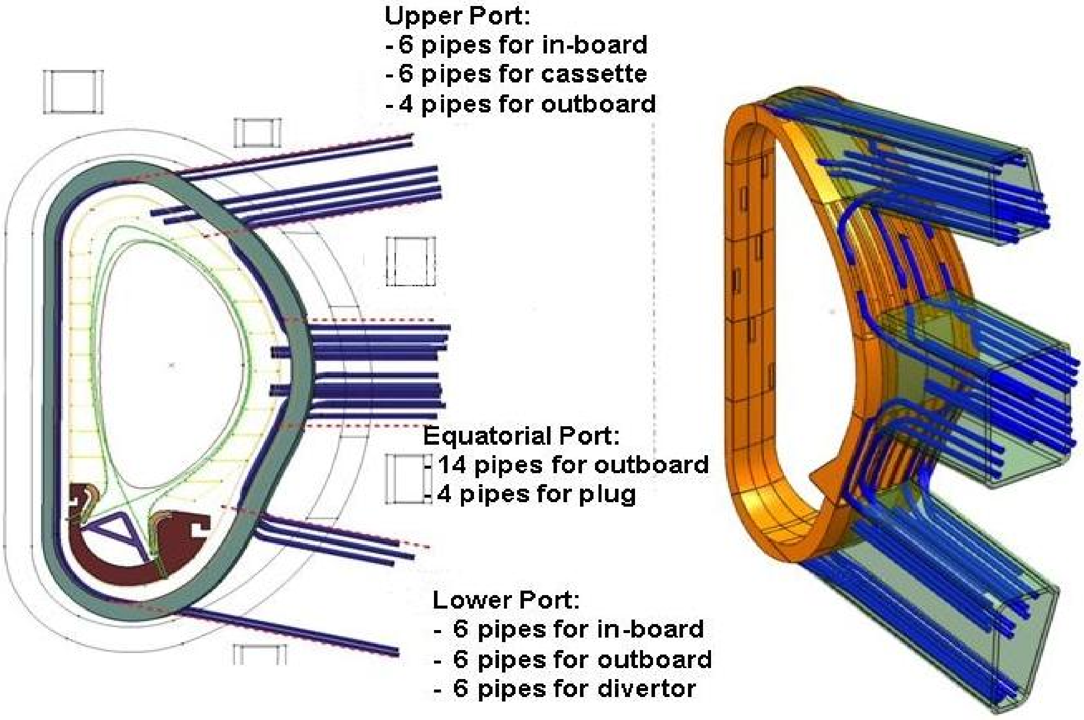


Figure 5: Piping lay-out for the investigated integration concept.

A second important requirement is the necessity of a thermal compensation. The HPS, which has been designed as permanent component, has to be fixed to the LTS-VV systems. The temperature difference between the two systems is in operation 150K for the "cold leg" pipes and 350K for the "hot leg" pipes. The mechanical connection between this two systems require fix points at least at the entrance of the module and at the entrance in the VV (in a port). Additional connections in between will be required to avoid vibration of the system and to facilitate assembly procedures. The concept used in this assessment foresees that each pipe is mechanical connected to the LTS module that is crossing. Hence, a compensation system should be foreseen in between two adjacent LTSs to reduce the thermal stresses. Again the paper of Rey can be considered for more information on the technology available for this task [10]. Figure 6 shows a possible design of an in-board pipe based on a technological extrapolation of this compensation system as discussed by Rey.

3.5 Neutron Streaming

The considered replacement concept requires that the large pipes of the HPS should be routed under a thick shield in order to keep the neutron damages below the DDL during the lifetime of the reactor. Furthermore, the junction should remain re-weldable. For this reason the pipes are routed behind the LTS with the exception of the module "feet" where the tube should enter the modules. This location is a weak position for the shielding capability; in fact two large holes are opened in the shielding and helium is transparent for neutron. The LTS concept has been proposed because assures excellent shielding features with a compact design (low thickness). This good feature risks to be jeopardised by the helium connectors, obliging to increase locally (but only locally is possible?) the shielding thickness. This point should be analysed carefully for any maintenance scheme with Helium coolant where pipes are routed through a shielding system.

Figure 6: Example of thermal compensation for an inboard pipes.

4. Conclusions and future work

The application of the ITER maintenance principle on a FG-FPP based on Helium cooling has been analysed in this paper. Several issues have been identified and possible solutions have been proposed. In particular, critical points for the integration design are the large number of modules, the thermal compensation of the large pipes, neutron streaming at the hydraulic connection, space availability. The study will be used by the FZK Demo Integration Group for the next step of the work, in which improvements of the presented scheme but also alternative maintenance proposals (like a Multi-Module System based on vertical ports) will be investigated in detail.

The study as been done with reference to the HCPB reactor, however many results of the study can be extrapolated in simply way to the HCLL; additional considerations are necessary for the DCLL, in which the large pipes should be shared among the two main coolants loops.

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