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I. INTRODUCTION

ARIES-ACT2 is a design study for a fusion power plant with a DCLL blanket concept and conservative physics. Due to the early start of design drawings for an alternative DCLL concept, but still not defined parameters of the ACT2 power plant, first design proposals have been made using parameters of the ACT1 study.

ARIES-ACT2 power core is divided into 16 sectors (22.5°) and uses dual-cooled liquid metal blankets consisting of helium-cooled RAFS (F82H) steel structure and PbLi as breeder and coolant of the blanket. The helium inlet/outlet temperature is expected to be ~350/450°C and the PbLi inlet/outlet temperature ~460/700°C. The structural ring consists of a helium-cooled RAFS (F82H) structure with a helium inlet/outlet temperature of ~350/450°C. [1] Divertors, vacuum vessel and low temperature shield are assumed to be the same as ARIES-ACT1.

The design development of an DCLL alternative small module concept are shown as at state of June 28th 2013.

II. DESIGN DEVELOPMENT

A. *Preliminary design options for a DCLL blanket*

1) OB Sector

At the beginning no parameters for the ARIES-ACT2 power core were defined. So, a basic model of an OB module has been designed showing the principle idea of manufacturing and the helium/PbLi flow path using the major radius R=6.25m as the SCLL blankets in ARIES-ACT1. The major radius is expected to be >6.25.m. As a new design idea for a DCLL blanket the small module design coming from ARIRES-ACT1 has also been applied to the ARIES-ACT2 design. With the toroidal smaller module size the grid-like stabilisation plates forming several toroidal-poloidal smaller areas inside a blanket as used for the ARIES-CS studies [2] or the European DCLL concept [3] can be avoided, what results in a much easier fabrication. One OB1 segment has been divided into 4 smaller modules, which means 4 times bigger modules than in ACT1. Due to more modules than in a big module additional helium cooling pipes and manifolds are needed. The PbLi manifold is attached at the bottom of the module and can be designed in two options:

- The first option is an advanced concept. Using SiC_f/SiC as structural material, the material is self-cooled by the PbLi flow. The connection between the blanket module using a helium steel structure and the self-cooled SiC_f/SiC PbLi manifold is more difficult. Technologies of joining ceramics with metals are already available today. But the joining of SiC_f/SiC material with steel needs further research and has to be proven for fusion applications. An example for SiC-Ni-based alloy joining can be found in Ref. [4]
- The other option would be a double-walled and helium cooled steel structure, which is welded to the module. SiC inserts are needed to avoid currents between the structural material and the PbLi within the magnetic field and therefore pressure drops.

Both options provide challenges: The first one a leak- and pressure-tight joining of two different materials, and the second one a complicate steel structures with small helium channels and SiC inserts, which complicates assembling of the several parts and the connection of the helium channels within the different parts. It has to be decided, which concepts is more feasible.

First design drawings concentrated on the OB1 segment, where 4 modules has been applied per sector (see Figure 1, only one module is shown).

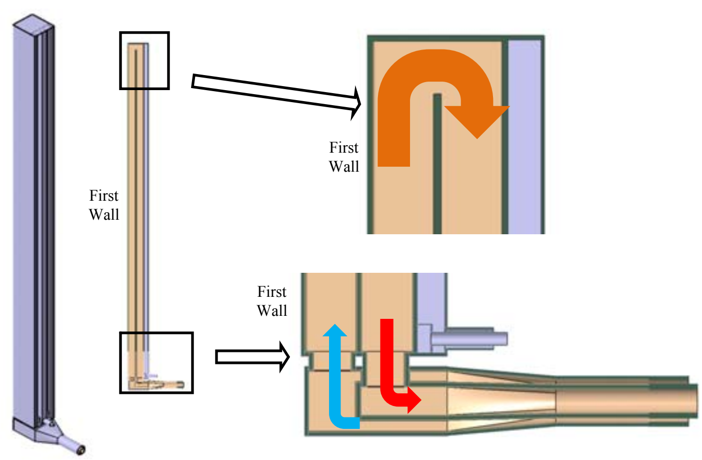


Fig. 1. First design of an OB DCLL blanket module, R=6.25m; PbLi flow path

The blanket consists of two big main channels, wherein the PbLi flow is guided in an upwards flow along the first wall and downwards flow in the rear channel. Along the back plate of the second channel, several manifolds in toroidal and poloidal directions are placed for a stepwise distribution of the helium coolant. At the bottom the module the PbLi manifold consisting of two interleaved boxes, which changes to two concentric pipes starting direct under the module. The cold inlet flow in the annular gap cools the hot outlet flow in the inner pipe.

The helium flow enters a toroidal manifold through a concentric pipe at the bottom of the module and divides into two similar streams. Each stream enters a poloidal manifold along the complete height of the module and flows into openings in the side walls (SW) for a counterflow along side and first walls (FW). After passing the first wall, each part flow cools one back (BP) or separation (SP) plate. The coolant enters the plates on one side, flows in toroidal direction, makes a U-turn and leaved the plate at the same side and level as the inlet. This concept requires a plate with two channels on top of each other, what requires further research about the fabricability. Afterwards the streams leave the side walls into another layer of poloidal manifolds. They are guided up and downwards to cool the top and bottom plate. The coolant leaves the top and bottom plate at the middle back into a central poloidal manifold before leaving the module through the concentric pipe at the bottom (see Figure 2).

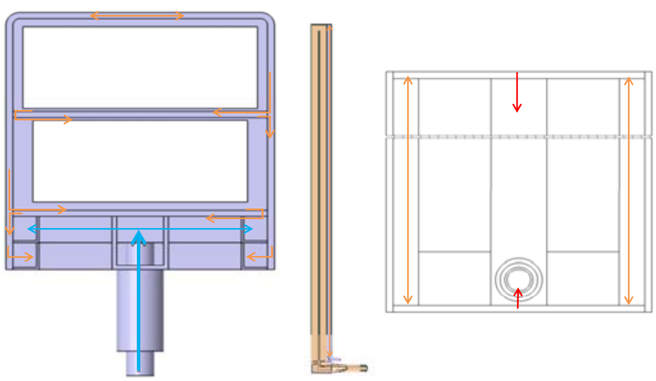
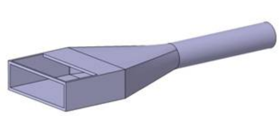


Fig. 2. First design for OB DCLL blanket module, R=6.25m; He flow path: Left: SW/FW flow, Middle and Right: Top/Bottom plate flow

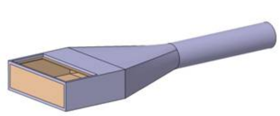
In case of a helium cooled PbLi manifold with SiC inserts, the fabrication sequence could look as can be seen in the following Table 1. Details for the helium flow path inside the PbLi manifold have not taken into account yet.

TABLE I. ASSEMBLY OF DCLL OB1 PBLI MANIFOLD

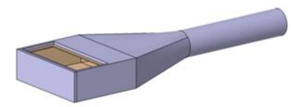
1. Bare outlet manifold



2. Paste inner SiC insert (move from open end of outlet manifold to direction of circular pipe)

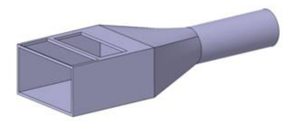


3. Welding of outlet manifold cap

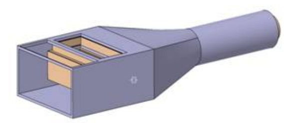


4. Paste SiC/outlet manifold structure into outer SiC insert
   Braze rectangular lid at the end

5. Bare inlet manifold

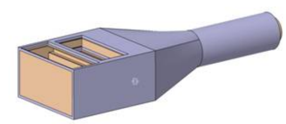


6. Paste inner SiC/outlet manifold structure into outer inlet manifold (move from open end of outlet manifold to direction of circular pipe)

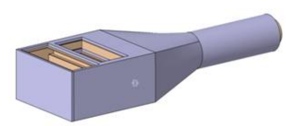


7. Paste inlet SiC insert into inlet manifold (move from circular end of outlet manifold to direction of rectangular side)

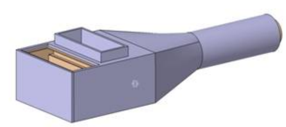
   Close insert SiC insert by brazing lid



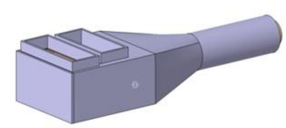
8. Welding of inlet manifold cap



9. Welding of outlet connector to blanket (two welds at inner outlet manifold and at outer inlet manifold)

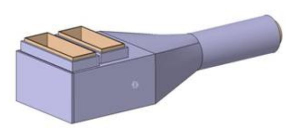


10. Welding of inlet connector to blanket (one weld at inlet manifold)



11. After welding of manifold onto blanket

    Insert of SiC blanket module inserts down to the manifolds



Details about the helium distribution and flow path inside the manifold walls as well as a leak tide connection between plates have not taken into account yet. In due time it will be necessary to revise this fabrication sequence.

A fabrication of the PbLi manifold with pure SiC is also possible and would simplify the manufacturing and assembling enormous. The open question of the connection between SiC and steel has still to be resolved then. But the complicate helium cooled steel structure and assembly steps would endorse to change to a more simple design.

2) IB Sector

Before the design of the IB Sector started, the major radius of the ARIES-ACT2 reactor has been adapted to 8.5m, but not yet finalized. Regarding this decision an IB sector with the new dimensions has been designed. The principle build-up of the module is similar to the OB segment, but the PbLi manifold at the bottom had to be redesigned, because of the side change of pipe access and FW (see Figure 3).

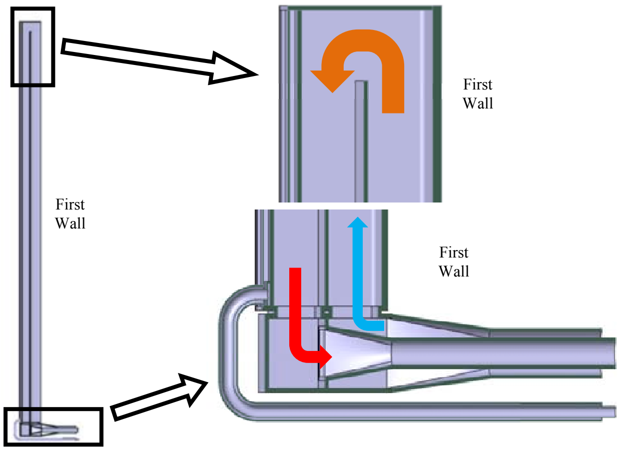


Fig. 3. First design for IB DCLL blanket module, R=8.5m; PbLi flow path

The PbLi flow of the IB module is consistent to the OB module. Only the PbLi manifold build-up had to be adapted.. The helium flow path is in principle the same as for OB path, but the helium feeding pipes had to be extended to the back, because of the limited space behind the PbLi manifold. If the pipes are integrated into the structural ring or if the radial back plate depth could be extended for a straight extension of the helium manifold down under the PbLi manifold without bending of the feeding pipes has still to be decided. The helium flow path can be seen in Figure 4.

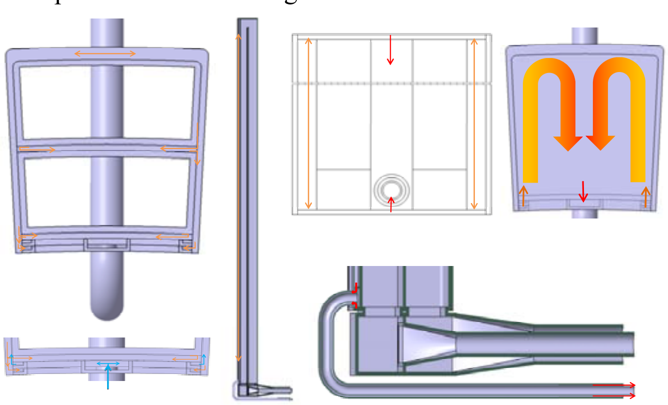


Fig. 4. First design for IB DCLL blanket module, R=8.5m; He flow path: Left: Inlet and SW/FW flow, Middle and Upper Right: Top/Bottom plate flow, Lower Right: Helium outlet flow

The main idea for this preliminary design option was to show an alternative design option to previous DCLL designs without a deep view into details. A combination of several smaller blanket modules as ACT1 to just one for ACT2 concept would remain the advantages of a simple manufacturing as in ACT1, but would result eventually in more steel and too less PbLi than a fabrication of just one big module with a stiffening grid inside, but this has still to be confirmed (both side walls of two neighboured modules have to contain cooling channels and cannot joined together without loosing the simple fabricability). There is also more steel necessary to feed each module with its own helium pipe. The helium coolant scheme/flow path has to be reviewed, if it is adequate for a sufficient heat removal and for cooling the first, separation and back wall in one (counter) flow path without intermediate mixing. Also the double walled back- and separation plate has to be reviewed for fabricability. Details of counter helium flow path and the distribution from the side wall into the separation plate and back into the side wall can be seen in Figure 5 (Model not to scale).

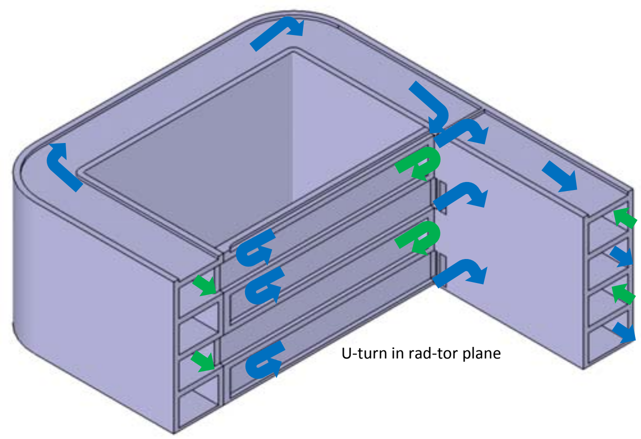


Fig. 5. Detail of helium flow path inside the modul walls

If such a double-channelled separation plate can not be manufactured the flow path has to be changed in a step by step flow like in the previous DCLL concepts [2,3] and a completely different flow path has to be determined to reach the intermediate plate. The present design of PbLi manifold should be possible to manufacture with SiC inserts similar as shown for OB1, but has not been demonstrated yet.

B. *Proximate design options for an IB DCLL blanket*

The previous design modules starts with PbLi manifolding and tapering direct under the module itself. If we look at that in more detail, than there is for the both OB sectors no other possibility for a later tapering of the big manifolds to smaller pipes to avoid an intolerable damage of the surrounding structural ring. But with the same design at the IB sector there is too much free space under the divertor due to the already smaller and circular pipes, which means not sufficient shielding, what is not tolerable (see rough sketch in Figure 6).

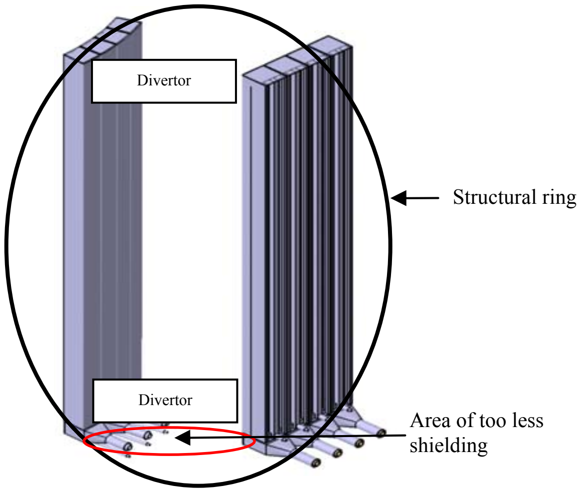


Fig. 6. Sketch of missing shielding under the divertor area

One proposal to avoid this free space was a different module design with one continuous C-shape similar to Aries-ACT1 for better shielding at the bottom and top. The PbLi channels should remain within the complete C-shape and manifolding should start at the end of the lower C part close to the lead-through of the structural ring. With the manifolding starting at the farthest end of the C, there are two layers of inlet and outlet channel on top of each other instead of already concentric pipes, which opens the question, how to bring the two channels (inlet+outlet) together to one concentric pipe in horizontal layer, without a complicate structure (including SiC inserts!) and with less space (see Figure 7). The divertor pumping duct is difficult to guide through a massive structure like that. Also the very long PbLi flow path with a one-way length of about L=~16m, and thereof ~12m height difference, is challenging, which could causes large pressure drops. In Figure 7 details of the helium flow path and the two layers of PbLi ducts can be seen.

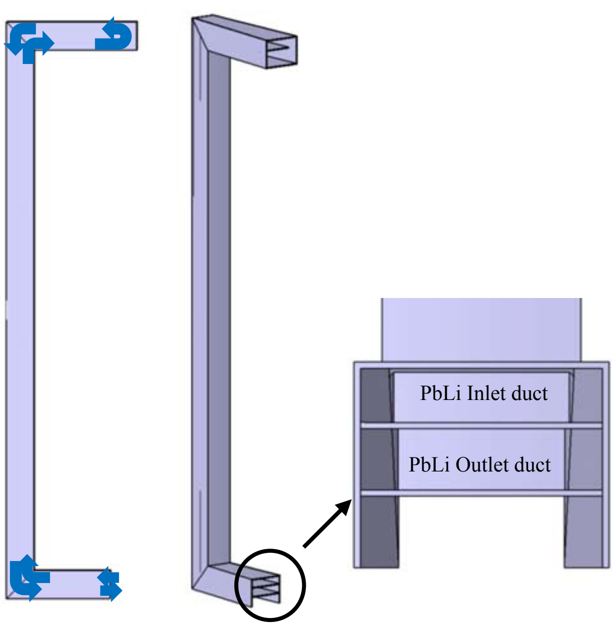


Fig. 7. Proposal of alternative C-shaped module, PbLi flow path, exemplarily for IB

Additional to the two layers of PbLi flow, also the helium flow path are taken into account. The main difference to Aries-ACT1 are the helium-cooled side-, first-, separation and back walls consisting of hot isostatic pressed (HIP) steel plates. It is very difficult to apply the design of ACT1 also to ACT2. As already explained several layers of manifolds are needed at the back of one module for a stepwise helium distribution. Due to the C-shape of the complete module also these manifolds at the backside need to have the C-shape, what opens the question, if such channels can be fabricated and leak-tight joined together. Also the connection of the separation plate with two layers of channels (see Figure 5) to the side walls seems to be very challenging in this C-shape. Figure 8 shows the helium flow path of such a design option with the counter flow at the first and side walls (left and middle), a cut through the gradually widening IB module (right top) as well as a rough sketch of the possible place for the helium manifolds at the back/bottom of one module (right bottom). Additional complicating to the fabrication question of all module parts at all is the gradually widening of the IB module and therefore the assembly and joining of all parts. Because of a straight module shape in the middle, the main idea for assemby of the separation-, back- and manifold plates into the SW/FW was a stepwise insertion of the intermediate plates from top or bottom. With the C-shape of all of these walls, it has to be thought over how and if an assembly and welding of all these plates especially with the SiC inserts is still leak tight possible.

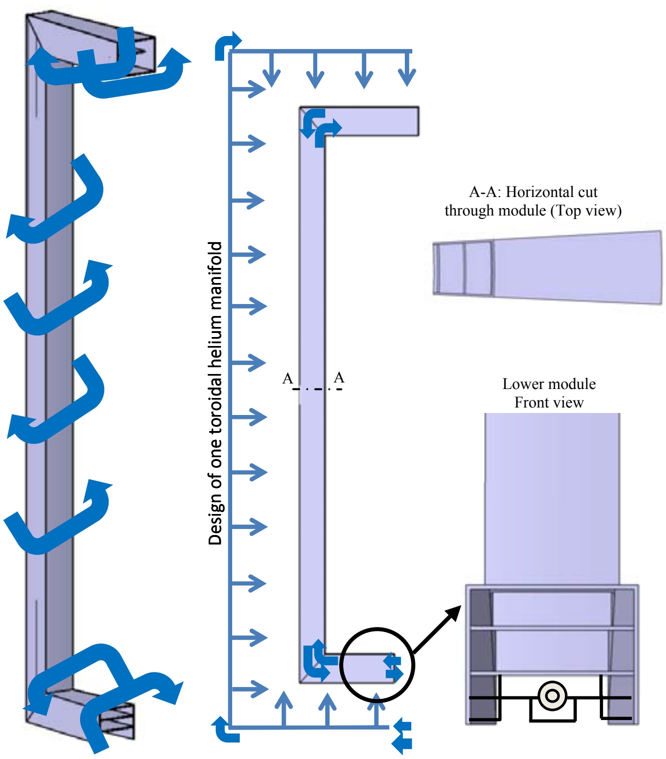


Fig. 8. Proposal of alternative C-shaped module, He flow path, exemplarily for IB

To avoid all these uncertainties the previous IB module concept has been renewed and revised. The new concept provides the same idea of two interleaving manifold boxes starting right under the vertical part of the module. They consists of a self-cooled SiC structure (not helium cooled), but starts with tapering to concentric circular pipes not before passing the divertor area. The connection point between manifold and blanket is still at the bottom of the module, but the helium cooled module walls do not have to be bended now (see Figure 9). The blanket structure is still cooled with Helium. The helium manifold in the following rough drafts are not yet designed, but can be extended at the back down under the PbLi manifold, where a concentric pipe feeds the manifold.

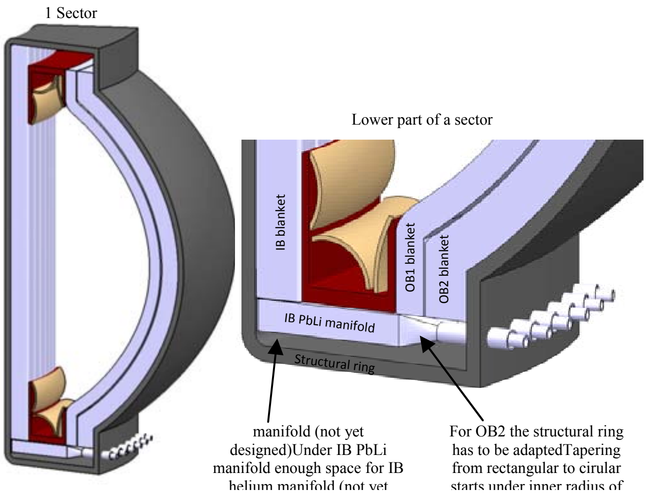


Fig. 9. Details of improved IB manifold design

As can be seen in Figure 10 the PbLi manifold has been designed again as two concentric rectangular channels over the complete length without the gradually widening with increasing reactor radius. Tapering happens close to the structural ring after passing the divertor. It is much easier to taper already concentric rectangular pipes than to join two layers of rectangular channels as in the previous design to one concentric circular pipe.

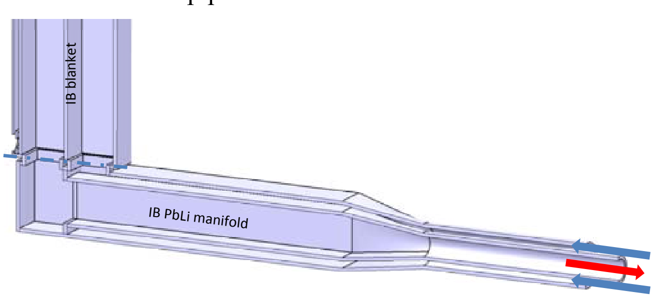


Fig. 10. Details of improved IB manifold design, Sectional view

With this straight manifold box there are increasing gaps between each manifold, which were first designed to ensure enough space for the divertor pumping ducts. On one side it is much easier to fabricate and assemble a straight box instead of an angled. Also unnecessary pressure drops due to changing cross-sections by gradually widening them first before tapering them to circular concentric pipes can be avoided. On the other hand it has to be clarified, if these gaps of about 131mm at the farest opened area are still tolerable, because shielding is no longer provided there. These gaps could be avoided, if pumping ducts are not foreseen in the reactor concept and only radial openings through the structural ring are used for pumping. It has to be proven if sufficient pumping is possible with only these gaps. If additional to that the concept of helium-cooled walls for the PbLi manifold will be chosen, it has to be clarified, how the coolant flow paths and how fabrication and assembly steps together with the SiC inserts will look like. Depending on the final PbLi outlet temperature of about 700°C right now, there are eventually high temperature steels available, which do not have to be cooled, what would simplifies the whole fabrication at all by omitting these SiC inserts. Figure 11 shows a top view of 6 IB modules with remaining gaps between the straight and not angeled manifolds and a bottom view with included divertor and OB blankets.

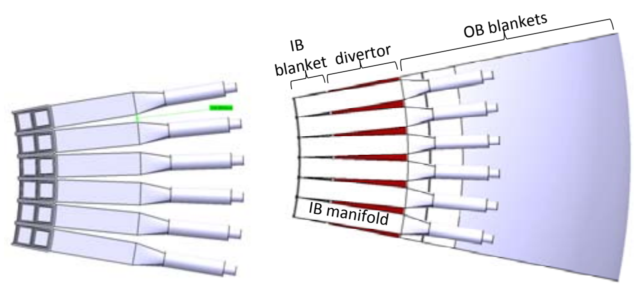


Fig. 11. Details of gaps between manifolds, view from top improved IB manifold design, Sectional view

C. *Proximate design options for an OB DCLL blanket*

With the improved design for the IB blanket also the OB blanket design has been adapted (see Figure 12). A preliminary stress calculation of the most stressed walls of one module (IB=FW, OB=SP) has shown, that with an increased FW wall thicknesses from 4 to 6mm at the inner module wall there are good results for 1.5 SM (see Chapter III). So, the number of modules per sector has been adapted to

- 6 IB modules
- 12 OB1 modules
- 12 OB2 modules

A rough design with the present IB module shows space limitations and fabrication challenges for OB1 and OB2. A similar manifold as shown in Figure 1 has been used.

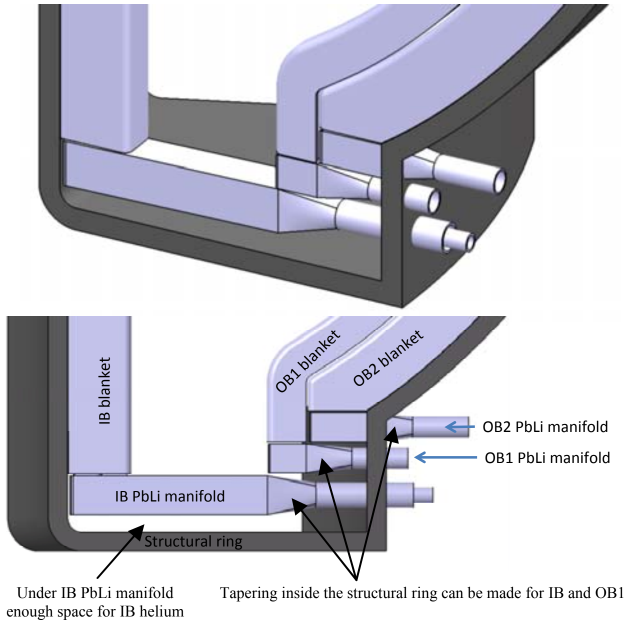


Fig. 12. Adaption of the OB blanket module

What can be seen in Figure 12, that the structural ring at the OB2 manifold region has to be adapted (thickened or just redirected). Tapering inside the structural ring is not possible, especially the tapering of OB2 manifold has no space. Also the helium feed pipes are still missing. All pipes together means probably too many penetrations for the structural ring. This has to be rechecked in a later phase of detailed designing.

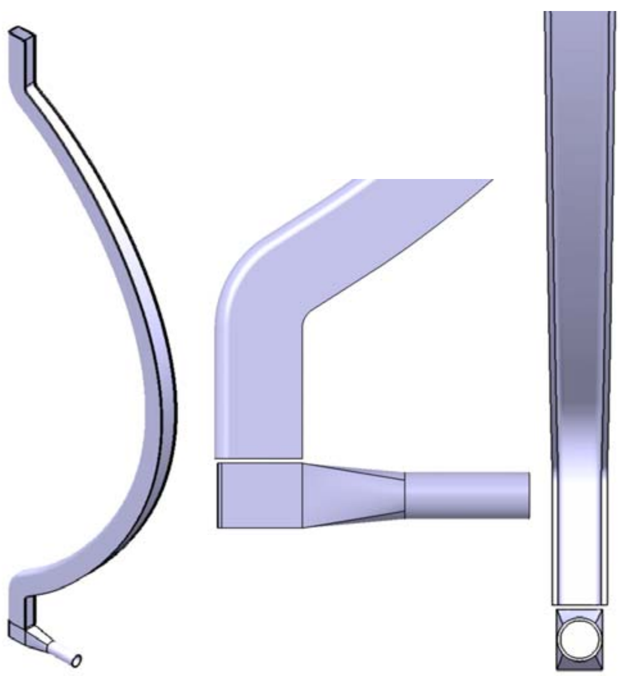


Fig. 13. OB1 module in iso (left), side (middle) and back (right) view

The main aspect of the adapted and more reactor like OB blanket design lies in fabrication and cooling. What can be seen in Figure 13 is the outer 3D shape of the complete blanket, which affects the FW, SW and BP walls changing its cross-section regarding to the different vertical levels. Due to the necessity of helium cooled walls, is has to be clarified, if a sufficient cooling channel system can be applied in the 3D structure. Also the fabrication of such huge structures is questionable. The SW/FW/SW/BP cooling scheme as shown in Figure 2 also applies here. Recent technology allows to fabricate these plates as two halves of straight plates, where channels has been milled out, then HIPed together and afterwards bended to a U-shape. A fabrication of a 3D structure with integrated helium channels means a bending of the so far straight U-shaped box in a second (poloidal) direction, what does not seems possible right now. Several smaller and straight modules in poloidal direction seem to be unavoidable. Welding at the FW should be avoided because of embrittlement of the welds. Another open question is how the SiC inserts can be assembled during build-up of the blanket.

D. Further ideas for an adapted design

Due to the many open questions regarding fabrication, it seems to be more reasonable to subdivide the banana shaped 3D design of the OB blankets into several smaller and straight modules in poloidal direction similar to ARIES-CS (see simple sketch in Figure 14). Additional to the so far designed blankets a OB3 and OB4 blanket has been included to fill the empty space behind the upper divertor. OB3 and OB 4 have the same design like the IB blanket with an PbLI manifold at the bottom. The OB3 manifold is connected to the OB1 manifold and OB4 manifold is connected to OB2 manifold.

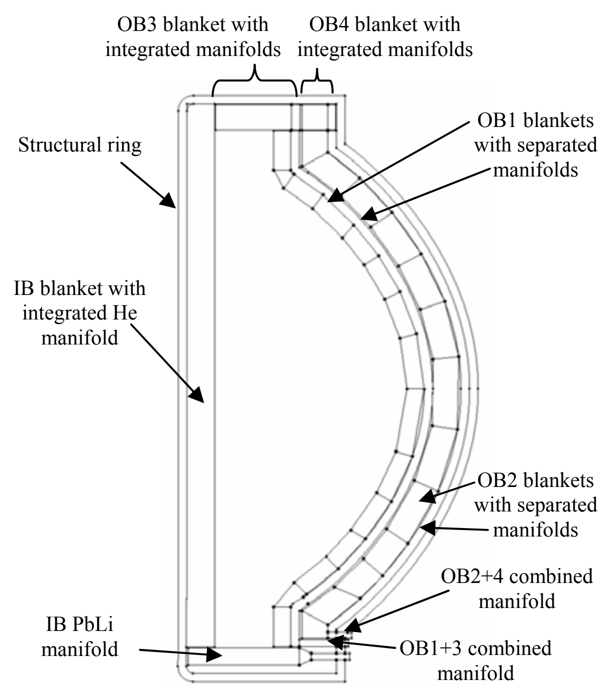


Fig. 14. Poloidal diveded OB modules

The number of modules in toroidal remains the same, what still avoid large MHD problems due to just a small transition from circular feeding pipe to full toroidal module size. In order that the upper modules of OB1 and OB2 as well as OB3 and OB4 can be fed with coolant, an additional manifolding layer for helium and PbLi right behind the OB1 and OB2 blankets are necessary similar to ARIES-CS. Each blanket module is fed by several short feeding pipes from the poloidal manifold behind them right into the blankets. With this solution, there is not much space for tapering the manifold feeding pipes from the probably smaller manifold feeding channel size up to the toroidal module size. But due to the small toroidal module size at all, it is unlikely that larger MHD problems will arise. Additional to that, there are more challenges expected due to the several radial layers of OB modules. Both of them needs its own manifold on the back, what increases the number of parts, which has to be joined together. The additional needed manifolds also probably makes the complete blanket sector heavier, what needs the bearing and connections between them has to be think through again. Additional mechanical attachment systems are probably needed instead of only welding. Also more radial space than an integrated "backplate" solution is needed, what increases the radial reactor dimension to the outside.

III. Design check

A. Stress resistance

For a decision and verification, if a small box design can withstand occurring stresses and loads comparable to a big box design stress calculations has been made. Concerning the small box design it was important for a sufficient box stability, that the toroidal width of the smaller boxes should not exceed the maximum length, where the FW/SW respectively the SP still could resist the operating loads like temperature, pressure and EM loads. Figure 15 shows the FEM model of the small IB blanket module used for the stress calculations in Ansys. All cooling channels inside the SW/FW/SP and BP are installed.

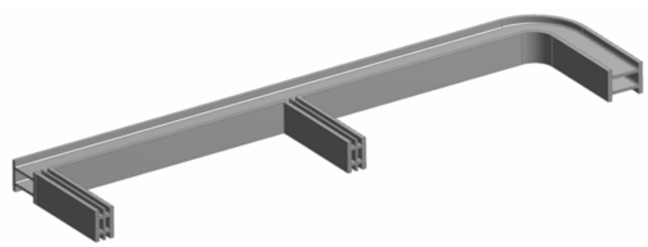


Fig. 15. FEM model: Half of a small IB DCLL box

The assumed loads has been applied:

1. Helium pressure in all cooling channels of the FW/SW, separation, grid and back plates, 8 MPa
2. Hydrostatic pressure of the Pb-17Li in the front breeding cell at the bottom, 2.0 MPa
3. Hydrostatic pressure of the Pb-17Li in the back breeding cell at the bottom, 1.8 MPa

The design limits for the used steel F82H FS can be seen in Table II. A maximum steel temperature of 450°C is assumed.

TABLE II. Design limits for F82H FS

	Sm MPa	1.5 Sm MPa
400 ˚C	156	234
450 ˚C	148	222
500 ˚C	139	209
550 ˚C	126	189

At first the number of small modules per sector had to be verified. Therefore, the FEM calculations has been made for 6 and for 8 Modules per sector with different toroidal widths. Additional to that it had to be differed between a side module at the outside of a sector and a inner module. The side walls of the inner modules are supported by the side walls of the neighboured modules. The side walls of the both outer modules are free to move sideways, what could cause higher stresses. First results show, that the inner modules have the Pb-Li hydrostatic pressure balance from both sides. The total stress of the inner module for the case of 8 modules per sector meets 1.5 Sm design limit. The 6 modules/sector exceeds the allowable stress (see Figure 16).

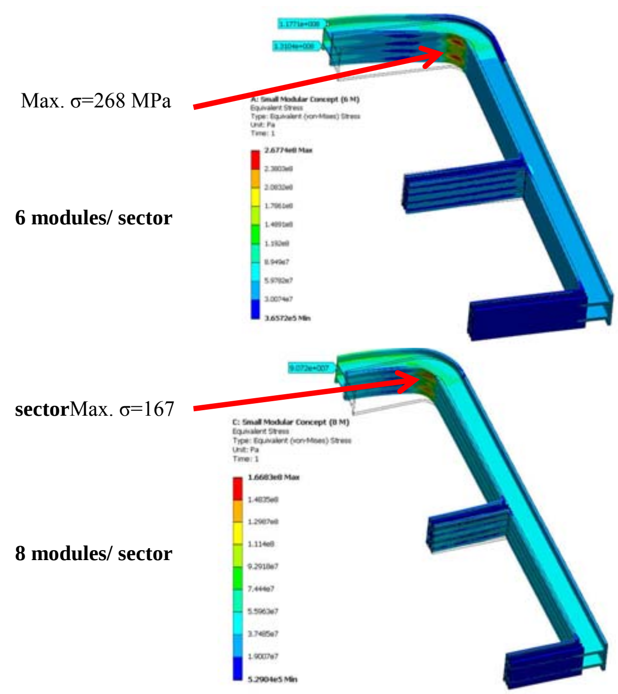


Fig. 16. Primary Membrane plus bending stress for the inner blanket module, 6 modules/sector (top), 8 modules/sector (bottom)

Figure 17 shows the result for the two possible outer modules of a sector. A free boundary is applied on the outer side wall. For the 6 modules/sector, the stress exceeds 1.5 Sm and for the 8 modules/sector, the stress meets 1.5 Sm.

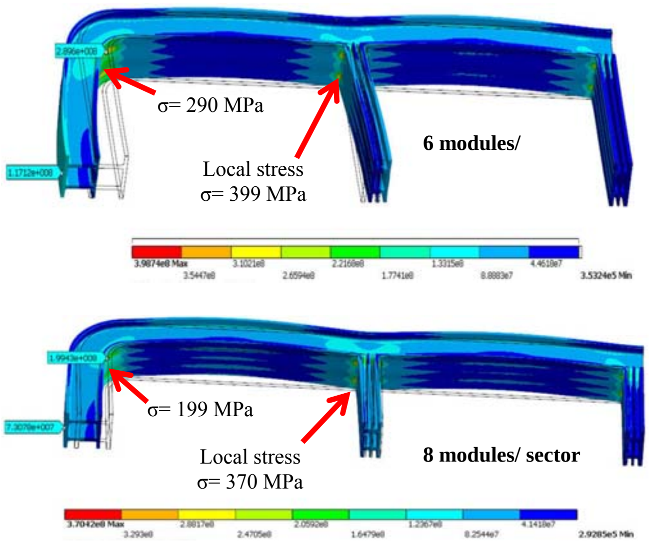


Fig. 17. Primary membrane plus bending stress for the outer blanket module, 6 modules/sector (top), 8 modules/sector (bottom)

The local stresses can be reduced by adding welding fillers at the corner between side wall and separation plate.To reduce the stresses in the corner of the side and first walls, the design must be modified. Fabrication and assembly of a blanket is easier, when it is not too small to have a better accessibility to the welds. So, it has been decided to try to modify the design of the bigger 6-module-per-sector concept. The first draft of this module as shown above had a FW and SW total thickness of 28mm with 4mm wall thickness on each side. The helium channels inside had a 20x20mm² cross section. This design has been modified stepwise to find a sufficient solution.

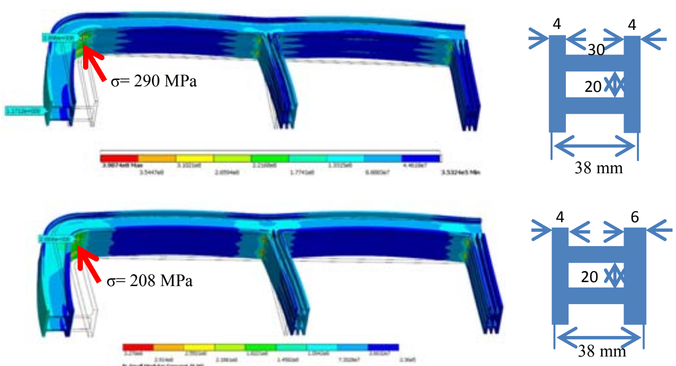


Fig. 18. Design solutions for an adapted 6 blanket modules/sector concept, Option 1 (top), Option 2: final solution (bottom)

Figure 18 shows exemplarily two solutions, whereof the second one meets the design limits. Increasing of the total and inner wall thicknesses in high stress areas (FW/SW) improved the results of the primary membrane plus bending stresses. A 6-module-per-sector concept can be realized with a total FW/SW thickness of 38mm with 4mm wall thickness on the outside and 6mm wall thickness on the inside of the module. The helium channels inside have a 20x28mm² cross section.

This design meets the design limits of the used steel. But with increasing the wall thickness to the inside of the module, also the material composition has to be check, if they still meet reasonable limits and requirements.

B. *Material composition*

A disadvantage of the small module design is the additional needed material for the intermediate module side walls instead of one big module with stiffening grid. It has to be verified, if such a concept still has sufficient breeding material and not too much additional steel per sector. So, a material calculation has been made to provide the percentage material composition for the different module sizes.

TABLE III. COMPARISON OF MATERIAL COMPOSITION OF THE DIFFERENT DESIGN OPTIONS

	ARIES-CS (2x2 m2 module)	**ACT2 DCLL (Sector)**	**ACT2 DCLL (6 Modules)**	**ACT2 DCLL (8 Modules)**
First Wall Panel 3.8 cm	8% ODS FS 27% F82H 65% He	33.7% F82H 66.3% He (4 mm 2nd wall)	39.3% F82H 60.7% He (6 mm 2nd wall)	35.5% F82H 64.5% He (4 mm 2nd wall)
Breeding Zone 58.2 cm	77% LiPb 7% F82H 3.7% SiC 12.3% He	79.2% LiPb 6.1% F82H 6.2% SiC 8.5 % He	72.3% LiPb 9.5% F82H 5.3% SiC 12.9 % He	65.5% LiPb 10.9% F82H 5.8% SiC 17.8 % He
Back Plate 3 cm	80% F82H 20% He	84.1% F82H 15.9% He	37.9% F82H 62.1% He	35.6% F82H 64.4% He
Max. Pr Load can take, MPa	(Hydrostatic pressure not considered)	**2.5**	**2.0**	**2.3**

It has to be clarified, if the material composition for the 6-modules concept still meets the breeding request (TBR>1).

IV. CONCLUSION

The previous chapters have shown the development steps of an alternative small DCLL blanket module, made within the Aries-ACT2 study and as at state of June 28th 2013. With a toroidal smaller blanket module design the advantages of less MHD problems as used for the SCLL blanket in Aries-ACT1 can be adopted. Detailed design parameter were not known during this time. So, former data as used in Aries-CS has been taken. The design development focused mainly on possible helium and PbLi flow paths and following from this possible design options, fabrication and assembling issues, and finally if these designs meet allowable stress limits. This paper should be seen as an idea for an alternative DCLL design and has to be reviewed as soon as further parameters are defined and a TBR>1 has been verified.

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