Design and integration studies of a diagnostics slim cassette concept for DEMO

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Abstract. The Diagnostics Slim Cassette (DSC) is a concept currently proposed for DEMO to host the microwave reflectometry diagnostic in a dedicated poloidal section, for the feedback control of plasma position and shape, providing also the radial edge density profile at several poloidal angles. This DSC, which is expected to house up to 100 antennas and waveguides, is to be integrated with the Breeding Blanket (BB) segments. Moreover, it is being designed with Remote Handling compatibility in mind to facilitate a "fast" exchange by Remote Maintenance (RM) when needed, fulfilling one of the aims of the Work Package Diagnostic and Control. In this approach the pre-assembled (banana-shaped) DSC modules are inserted/removed from the Upper Port (UP) of the Vacuum Vessel (VV) at least when the BB segments are replaced. Here the main constraints related to the integration of the DSC with the BB, the UP and the Equatorial Port are identified and discussed in detail, with a strong focus on the required RM operations inside the VV (in-vessel), providing solutions that can be adapted to present and future blanket and UP designs.

Keywords: Diagnostics Slim Cassette (DSC); Remote Maintenance (RM); Breeding Blanket (BB); Water-Cooled Lithium Lead (WCLL); microwave (MW) reflectometry; Failure Modes Effects and Criticality Analysis (FMECA); Diagnostic and Control (DC)

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1. Introduction

Since in DEMO the plan is to implement only diagnostics that are needed for control of the tokamak plasma, it must be possible to repair or replace them if needed [1]. Therefore, one of the aims of Work Package Diagnostics and Control (WPDC) is that all diagnostics and, in particular, their in-vessel components are designed with remote handling (RH) compatibility in mind. To achieve this the adopted strategy has been that all in-vessel diagnostic components should be hosted either in a port plug—as is the case for several spectroscopy diagnostics or the neutron/gamma cameras—, or in a diagnostics slim cassette (DSC)—as envisaged for microwave (MW) reflectometry—, to facilitate a expedite exchange by remote maintenance (RM).

Microwave (MW) reflectometry is a diagnostic foreseen for DEMO as the main backup solution for the magnetics diagnostic, the latter being one of the main tools for plasma behavior real-time monitoring. And given that the MW (horn) antennas and the in-vessel waveguides (WGs) of the MW diagnostic—as well as the magnetic diagnostics—will experience loads 10 to 50 times larger than on ITER, failure of both magnetics and MW diagnostics would put equilibrium control of the DEMO plasma at risk. Therefore, it is important to design these systems in such a way that they may be replaced in case of failure. The DSC aims to address this problem.

In the DSC approach a pre-assembled ("banana-shaped") diagnostic module—a dedicated poloidal structure with a (toroidal) thickness of 20 cm to 25 cm—containing the MW antennas and its WG is inserted in between two Breeding Blanket (BB) segments (or laterally integrated into a BB sector) from the Upper Port (UP) openings in the Vacuum Vessel (VV), and the only additional RM action for mounting or dismounting would be the fixation of its WGs near the port plate. The objective is that when the BB segments are "routinely" replaced through the UP, the DSCs will be taken out also through the UP, after disconnecting their wares/lines, and new cassettes re-installed in the same way. Therefore, the UP geometry as well as the other components that will share its space play an important role in the design and integration of the DSC in DEMO. There are variants of this concept: the DSC could be i) handled independently of the BB, ii) attached to the BB segment, iii) inserted into a BB segment, in which case it would share the first wall and the cooling water manifold with the BB.

The objective of this work is to continue the design and integration studies of the DSC [2], focusing on the in-vessel RM operations required for the DSC and its WGs—the ex-vessel RM procedures are outside the scope of this work. The aim is to provide design solutions that can be adapted to existing as well as future BB and UP designs. Therefore, it is important to present and address the main constraints that will shape the design and integration of the DSC in DEMO, namely: 1) the BB segmentation i.e., the way in which the BB is divided into elemental segments (5 BB segments per UP/sector); 2) the "chimneys" protruding from the back of each BB segment in the UP opening (through which the pipes carrying the BB cooling and breeding fluids are connected to the BB segments; the "chimneys" are also the interface used to remove/install the BB segments themselves); 3) the space available in the UPs; 4) the BB pipe modules (grouping, in the UP, the BB pipework that transport the breeding and cooling fluids between each BB segment and the ex-vessel); 5) the UP neutron shield plug and 6) the Upper Limiters (ULs) or the diagnostics systems for Diagnostics and Control (DC) housed in the UPs; and, somewhat counter-intuitively, as it is not in the way of the DSC extraction, 7) the geometry of the Equatorial Ports (EPs), which are envisioned to accommodate the Outboard Midplane Limiter (OML), the Electron Cyclotron (EC) launcher for the Heating and Current Drive (HCD) system, as well as port-based diagnostics for DC.

As the design of the DSC depends heavily on the configurations of the above components, the concepts herein presented are subject to many uncertainties arising from their different design stages. Among them, the Computer Aided Design (CAD) models for the "chimneys" and for the BB pipe modules in the case of the Water-Cooled Lithium Lead (WCLL) blankets have the largest impact on the assumptions made throughout. Nevertheless, the approach has been to propose and analyse concepts that can be adapted to different blanket and UP configurations.

This paper is organised as follows: section 2 introduces the DEMO VV and its maintenance ports, the blanket segmentation and architecture, the WCLL blanket concept, the pipework for breeding and cooling fluids, the limiters (in the UP and EP), and the UP neutron shield plug, as these components will provide the boundary conditions that will shape the design and integration of the DSC. The Reflectometry Diagnostic for DEMO is presented in section 3, together with the integration approaches and challenges, as well as the impact of the DSCs on the Tritium Breeding Ratio. The DSC design developed in the frame of WPDC and the main constraints related to the integration of the DSC within the BB segmentation, as well as with the UP, the WCLL blankets, and the RM requirements are covered in section 4, including a brief introduction on how the DSC aims to address the needs of reflectometry for DEMO (and how it can be suited to the integration of magnetics sensors as well). An effort was made to analyse the design choices for each component and to evaluate how they might apply to the DSC design. Finally, conclusions are reported in section 5.

2. The DEMO tokamak

2.1. Vacuum vessel and blankets

The toroidal shaped VV of the DEMO tokamak (see figure 1) will be lined with an inner wall made up of the BB, the divertor, and the port plug based Plasma-Facing Components (PFCs), namely the limiters and the port based diagnostics. Therefore, the VV must provide support to the In-Vessel Components (IVCs) and the equipment inside the VV ports, in particular the attachment for the BB, the port plugs and the pipework. The BB plays a double role: (i) breed the Tritium (T) necessary to fuel the fusion process and achieve T self-sufficiency; and (ii) remove heat from inside the tokamak with active cooling loops, transferring it through heat exchangers to a power conversion system for electricity generation. Additionally, the BB will contribute, together with the VV, to shield components of the facility (particularly the superconducting magnets) from nuclear radiation.

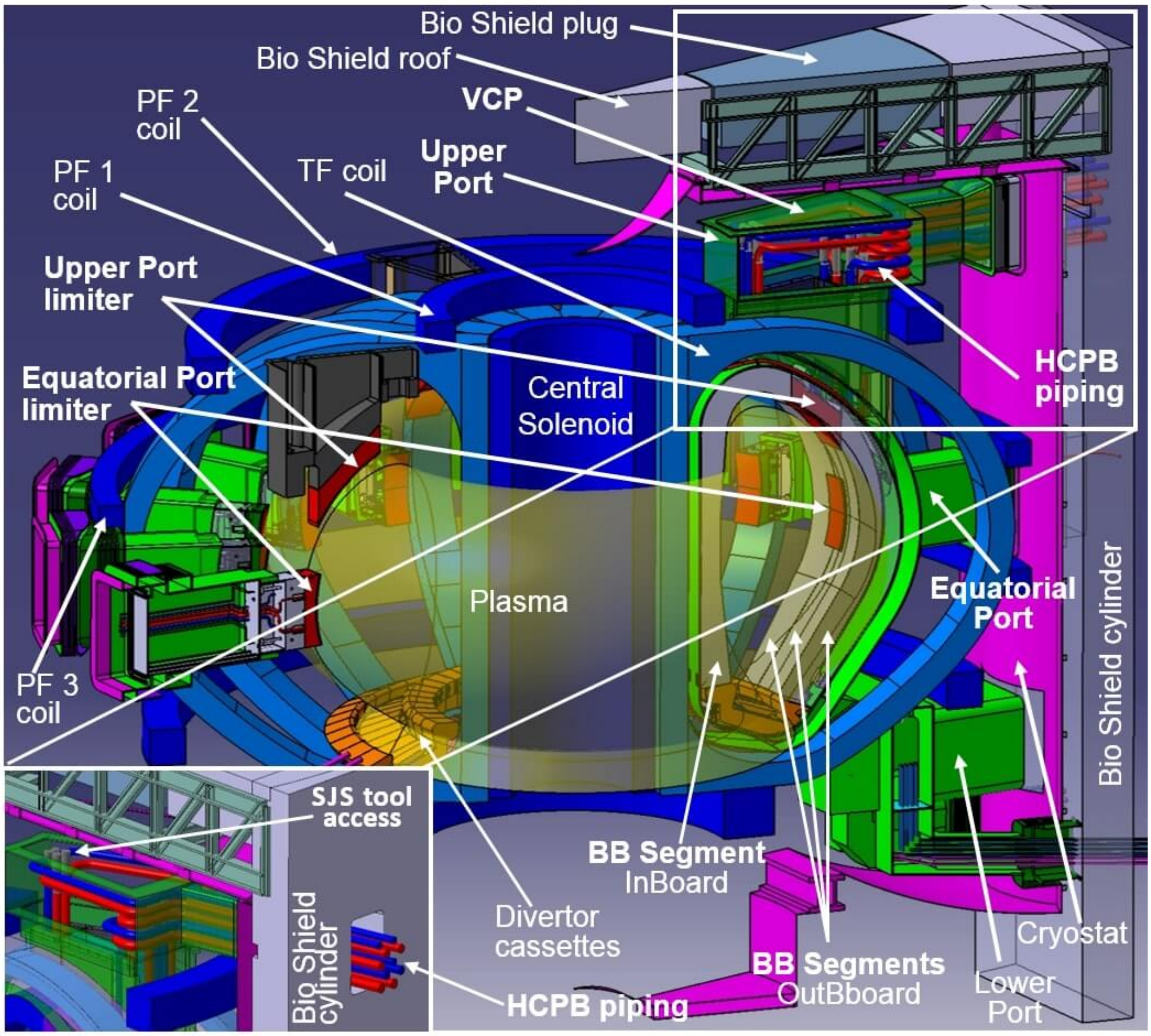

Figure 1. The DEMO tokamak (PMU 2017 version) illustrated with the HCPB piping. The inset depicts a different perspective of the UP region (CAD models taken from [3], inset and bioshield from [4]).

2.1.1. VV ports In DEMO the entire BB must be replaced at least once during the lifetime of the reactor. To enable this operation, which must be achieved via RM, the BB is divided into **segments** that are removed and replaced individually through the VV ports, in which most diagnostics, heating and current drive systems and the feeding pipes for IVCs and auxiliary systems like vacuum pumps are also integrated.

There are three different types of ports through which access to the inside of the DEMO VV is provided, as depicted in figure 1 and figure 2: 1) the UP, which allows entry from the upper part of the tokamak; 2) the LP, which offers access from below, in particular to the divertor; and 3) the EP, which provides radial access. Each type of port has its own specificities, with the UPs being mainly required for the maintenance of the BB segments, besides enabling the connection of pipes that carry cooling and breeding fluids to the BB—indicated as “Helium Cooled Pebble Bed (HCPB) piping” in figure 1 and figure 2, as used for the HCPB blanket concept—, while the EPs are expected to accommodate the OMLs as port plug components, besides the EC launcher for the HCD system, as well as port-based diagnostics for DC.

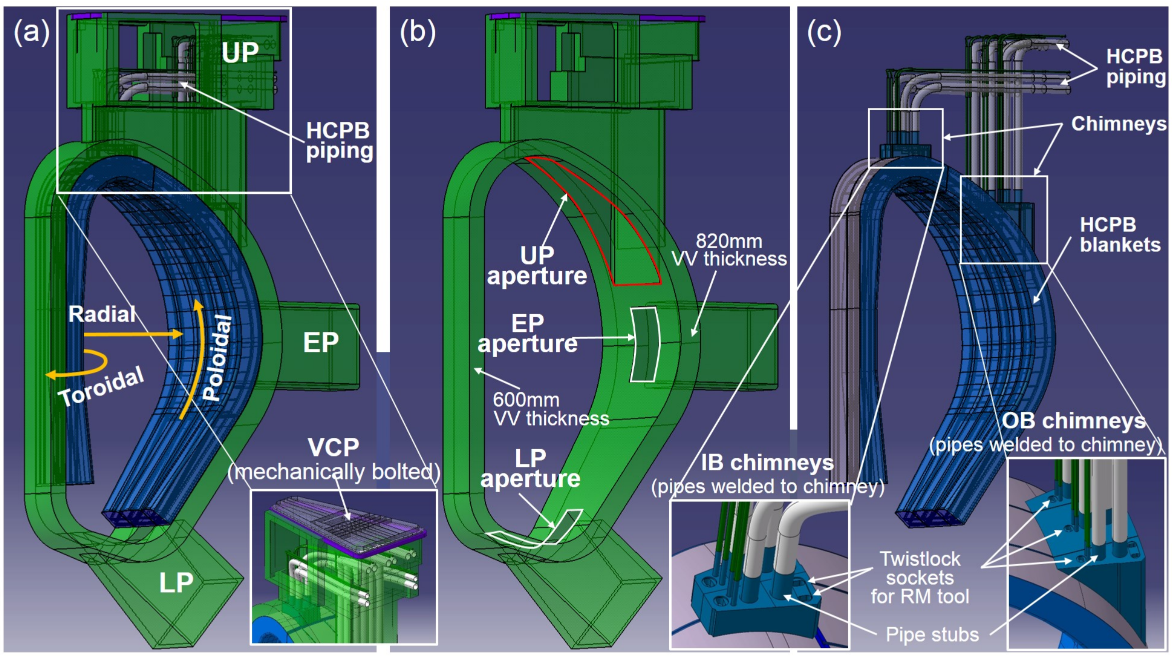

Figure 2. One sector of DEMO illustrated with the HCPB blanket concept. The insets offer different perspectives of the UP (a), and of the “chimneys” with the twistlock sockets for the RM tool (c) (CAD model from [5]).

The UP will be the main port involved in the present work, although the location of the EP has an impact on the design and integration of the DSC (see section 4). Note that access to the VV through the UP requires opening/closing the Vacuum Closure Plate (VCP), a 75 mm to 100 mm thick plate with 300 mm stiffening ribs, having a mass of 20 t to 25 t, which is mechanically bolted to the VV (see figure 2)—after removing the UP Bioshield (concrete) plug (see figure 1)—involving tasks that will all require a RM deployment system. Yet, these and other activities that have to be carried both inside and outside the bioshield, but are outside the VV, are beyond the scope of the present work.

2.1.2. Blanket segmentation: LIBS, RIBS, LOBS, COBS, ROBS The current DEMO tokamak design used as the basis of the present work incorporates 16 Toroidal Field (TF) coils, being, thus, divided into 16 sectors (22.5°) in the toroidal direction around the

VV, as shown in figure 1. It has 5 BB segments per sector, as depicted in figure 3, two inboard (IB) and three outboard (OB): a left inboard segment (LIBS), a right inboard segment (RIBS), a left outboard segment (LOBS), a centre outboard segment (COBS), and a right outboard segment (ROBS). Each BB segment has a surface which faces the plasma, the so called First Wall (FW), and two lateral sides (which originally extended radially), dubbed Side Walls (SWs), besides a Back Plate (BP), which closes the rear of the segments, and the bottom and top caps. This design corresponds to the DEMO 2017 baseline configuration.

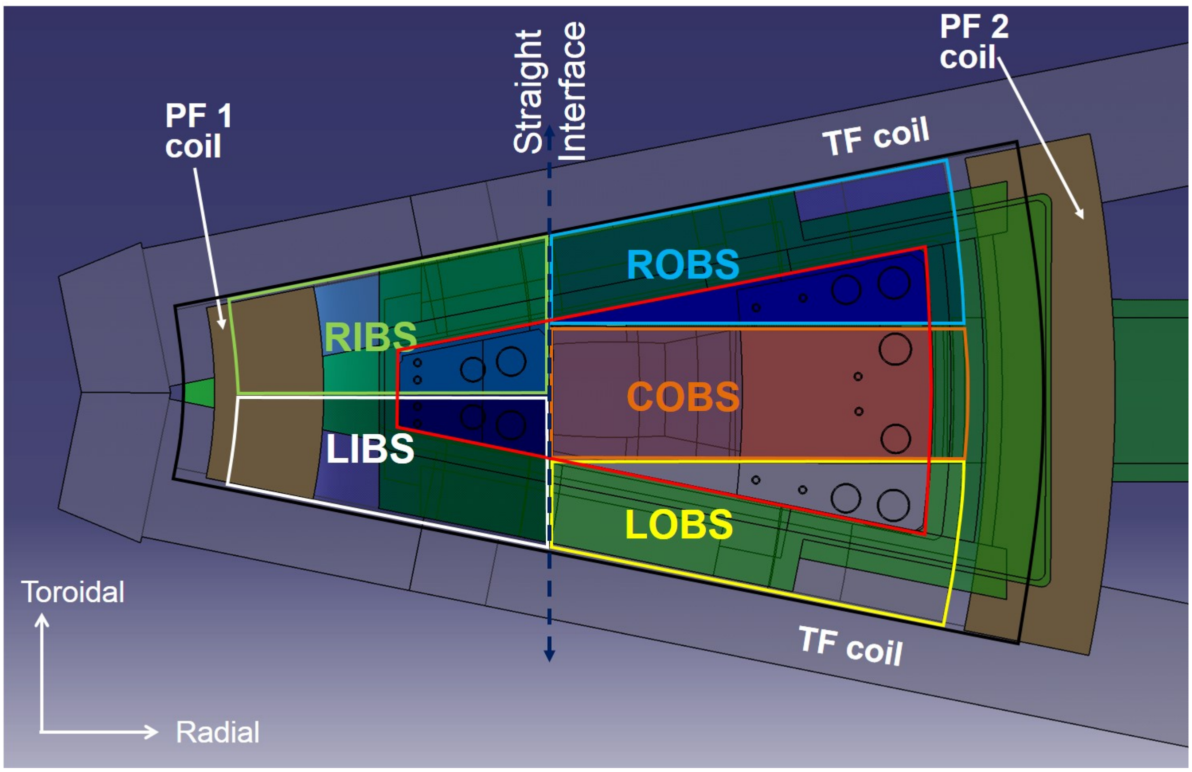

Figure 3. BB segments in DEMO, with the RIBS, LIBS, ROBS, COBS, LOBS and the UP opening on the VV delimited with, respectively, green, white, light blue, orange, yellow, and red lines; the black line delimits the outer walls of the VV (top view) (CAD model taken from [6]).

Note that the UP and, most notably, the opening through which the BB maintenance will be carried out, is constrained not only by the number and the (toroidal) width of the TF coils, but also by the two upper Poloidal Field (PF) coils, PF1 and PF2, which limit its radial extent. In combination they restrain the UP opening into a narrow, somewhat trapezoidal, shape that is seen through the (green) VV in figure 3, where it is delimited with a red line (see also figure 2 (b)).

2.2. Parallelization of the COBS side walls and straight interface between the IB and OB blankets

The BB segmentation used in this work assumes, as shown also in figure 3: (1) the parallelization of the COBS SWs — i.e., its lateral walls (and the corresponding adjacent lateral wall of the LOBS and ROBS) are in parallel planes instead of in radial planes — to avoid clashes between the OB BB segments; and (2) a straight Interface between the IB and OB BB segments across each port (as opposed to a toroidal cut), indicated by the dark blue vertical dashed line in figure 3, given that linear translations maximize the use of the port, whereas toroidal movement does not [7].

2.2.1. Piping for BB cooling and breeding. Pipe "chimneys" In DEMO the cooling and breeding fluids are connected to the BB segments through the so-called "chimneys" (see insets of figure 2 (c)), being piped from the ex-vessel area into the UP—linked on the other end to the Primary Heat Transfer System (PHTS) and the lithium lead (PbLi) system—and routed through the port annex to the BBs, bypassing both the bioshield plug in the UP and the corresponding VCP (see figure 1)‡. Due to the levels of neutron bombardment within the inner area of the port it is assumed that it will not be possible to use mechanical flanges there, welding being the joining method chosen, as it provides the required performance in that harsh environment.

In the case of the BB pipework, the connection of these pipes to the pipe stubs in the BB "chimneys" is expected to be cut and welded using the Service Joining System (SJS) in-bore laser cutting/welding tools [8]. These tools are deployed through access points along the axis of the pipes (see inset of figure 1) [9, 10, 11] to conduct all the cutting/joining operations inside the pipe. The minimum pipe diameter for internal welding with this tool is DN80 ($\sim$75 mm internal diameter)§ [12], whereas the minimum bend radius of the pipes in which it can be deployed is 1.5 m [8, 13].

It must be pointed out that these pipe "chimneys" serve, additionally, RM purposes as they contain the interface to remove/install the BB segments themselves with recourse to a set of 3 twistlock pins—rotating connectors as used in shipping containers—in the RM tool (the Hybrid Kinematic Mechanism, aka the Tricept [14, 15]) and the corresponding twistlock sockets in the "chimneys" (see insets of figure 2 (c)), into which the twistlock pins are inserted and rotated to secure the connection. In addition, it is worth noting that space in these "chimneys" is very limited.

2.2.2. Pipe modules and mechanical pipe connectors In DEMO the cooling and breeding pipework for the BB will be grouped into pipe modules, one module per BB segment. The most likely structure for the pipe modules is a space-frame arrangement

‡ On a recent proposal for the WCLL BB concept, the breeding fluid (PbLi) is fed via the lower port and extracted through the UP (see figure 7 and figure 9).

§ DN stands for "Diamètre Nominal" and refers to the internal diameter of a pipe, whereas the dimensionless whole number that follows it corresponds to the approximate internal diameter of the pipe in millimetres.

(with a rigid structure body) [9], as illustrated in figure 4. These pipe modules will be removed and replaced through the UP whenever BB maintenance is carried out—prior to the BB removal—, with recourse to the same RM tool (Tricept) used to manipulate the BB. Therefore, the pipe modules are provided on the top with an interface similar to that in the BB "chimneys", with the same 3 sockets for the RM tool's 3 twistlock pins and the access points for deploying the SJS cutting/welding tool, to separate the pipes in the pipe modules from the BB.

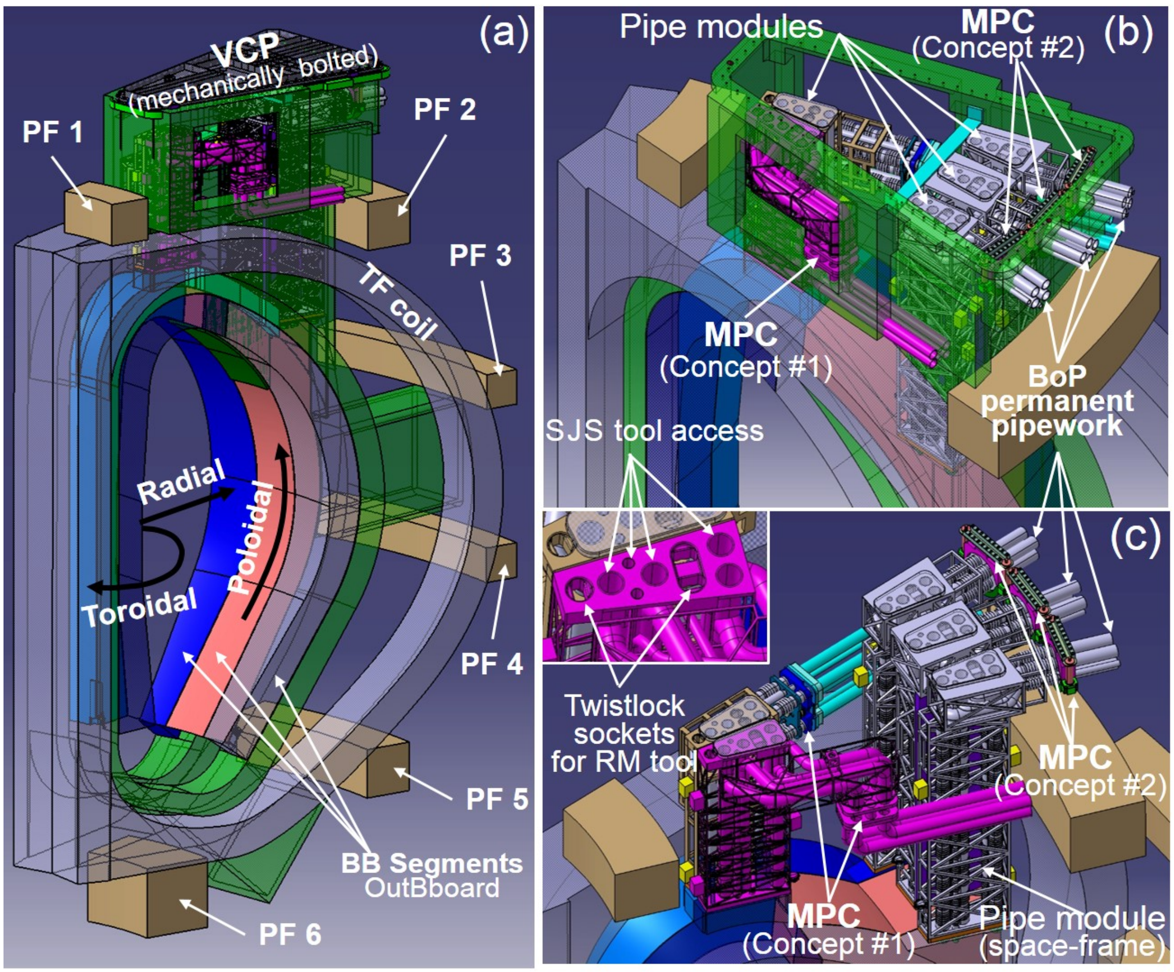

Figure 4. One sector of DEMO with a pipe module concept (space-frame configuration), revealing two multi-pipe MPC concepts and the RM interface on top of the pipe modules (inset of (c)) (CAD model from [16]).

For the connection of these pipes to the interface with the Balance of Plant (BoP) — permanent — pipework, which will require a reasonable number of connect/disconnect cycles within the lifetime of the plant, a Mechanical Pipe Connector (MPC) is the preferred solution. Various MPC concepts have been developed which, naturally, require tooling designs to operate the MPC [17, 18]. Two multi-pipe MPC concepts (#1 and #2) are illustrated in figure 4 [17].

2.3. Limiters

Although the blanket FW in DEMO is to be actively cooled and protected by a plasma-facing tungsten armour (2 mm to 3 mm thick), it is anticipated that plasma transient events may bring extreme energy and power densities far exceeding the blanket FW heat flux limit. The protection of the BB FW from these events involves the installation in certain regions of the machine of dedicated discrete limiters with appropriate design and cooling such that they can withstand the transient heat loads while providing protection to the BB FW [19, 20, 21, 22].

Given that the thermal loads can be so large that their plasma facing tungsten armour can be damaged, a key feature of these limiters is that they will be sacrificial components, requiring replacement more frequently than the BBs—or the neutron shield—themselves. So as to reduce the time required for their remote replacement, the limiters (except for the IB limiters) will be installed in dedicated ports, integrated as port plug components, such that their removal does not require prior removal of other IVCs. A consequence of such an integration in DEMO is that they will have an impact on the integration of the DSC as well.

In the current concept it is envisaged to install limiters in or through the UP and the EP: 8 ULs and 4 OMLs, as illustrated in figure 5, besides 4 Outboard Lower Limiters (OLLs), and 4 Inboard Midplane Limiters (IMLs) [19, 20, 22].

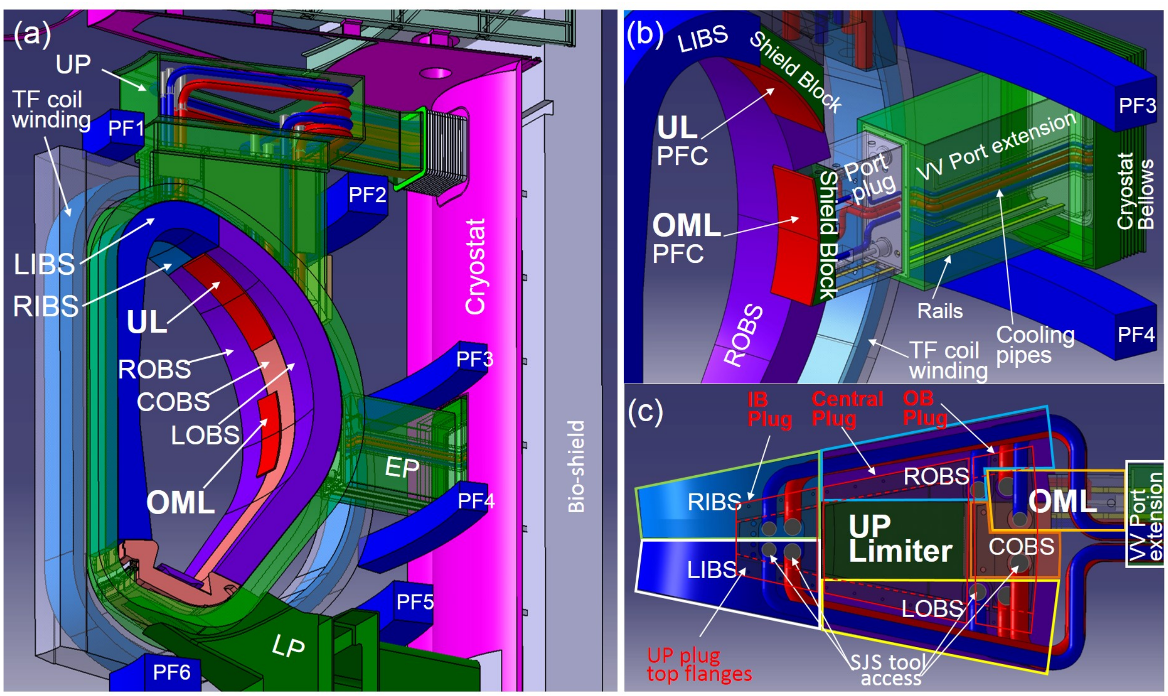

Figure 5. Limiters proposed for the UP and the EP illustrated with the HCPB piping. Figure (c) depicts an upper view of the sector (CAD model from [4]).

2.3.1. Upper limiters The ULs will be installed in every other UP, i.e. at 8 out of 16 UPs—whereas the DSC for MW reflectometry is to be implemented in only two sectors, eventually four if the number of antennas is not enough (if the DSC is also chosen to host the magnetics sensors, as discussed in section 3.2, four additional DSCs will be required). Each UL, with an overall surface area of $1.5\,\mathrm{m} \times 3.4\,\mathrm{m}$ (W x H), will replace the top section of the COBS.

To ease the UL replacement it has been proposed to divide the UP shield plug assembly into three sections (using a box-type design, as seen through the VV in figure 5 (a)): the Inboard Plug, the Central Plug, and the Outboard Plug [23], which are attached to the port shoulder, delimited with a red (solid and dashed) line in figure 5 (c). The UL is to be integrated into, or be part of, the UP Central Plug, and the limiter—as well as the shielding block—is provided with active cooling [19, 24]. In this case, to replace the UL the Central Plug is removed without the need to remove any other component or pipework except its own supports and supply lines, being an RM preference that the UL be removed vertically, so that its removal kinematics does not interfere or clash with other hardware in the port [9].

It is reasonable to presume that there will not be an UL in a port with a DSC, given the space restrictions prevailing in the UP (particularly for routing pipes and WGs out of the port). Conversely, it is expected that where an UL is present, there will not be a DSC [9].

2.3.2. Outboard midplane limiters It is foreseen that the 4 OMLs will be placed periodically 90° apart [19]. The corresponding limiter, with an overall surface area of $1.1\,\mathrm{m} \times 2.8\,\mathrm{m}$, is attached to a port plug and integrated (toroidally offset) into an EP, which is, itself, toroidally offset from the sector centreline—with the cooling pipes running aside at the port—making the configuration not fully radial, as depicted in figure 5. This port plug reaches all the way through the blanket to the plasma and so the port itself must be toroidally offset from the sector centreline in order to avoid splitting the blanket segments vertically. This offsetting requires cut-outs in adjacent BB segments of only $\sim$0.6 m (approximately 1/3 of their nominal toroidal width), so as to maintain their vertical integrity/stability [21]—but having an impact on the the integration of the DSC.

2.3.3. Outboard lower limiters; inboard mid-plane limiters; EC HCD; port-based diagnostics The OLLs are envisioned to be located further down from the OMLs, present in only 3 to 4 sectors, and serviced through the offset EP [19, 21], whereas the 4 IMLs are expected to be attached directly to the VV wall between two BB segments and have a front maintenance scheme from the EP [19].

In addition to the OML and OLL, it is foreseen that the EC launcher for the HCD system will use an offset EP [25] and that port-based diagnostics for DC will be integrated into EPs as well. Still, various decisions are yet to be made whose outcome may vary the allocation of the EPs in the future [25]‖.

2.4. UP neutron shield plug

In DEMO the UP neutron shield plug is a component of the UP that resulted from the division of the COBS into a reduced size COBS segment and a small plug (at its upper end) [7]. A consequence of this division is that the UP plug needs its own active cooling (most likely by water), coolant pipes (possibly grouped into its own pipe module), and pipe connections. Moreover, in order to provide shielding to components in the UP region, notably the magnetic field coils, that are left under-protected from neutron streaming through the UP openings in the VV [27], this UP plug must include also the UP neutron shield on its back. An illustration of the UP plug in a previous version of DEMO is portrayed for illustrative purposes in figure 6 (in figure 5 of [28] it is shown in yet another old version of DEMO). The main advantages advocated for this division of the COBS were: being handled vertically by the vertical transporter (possibly a simple crane system) together with its neutron shield and pipe module, thus exempting cutting and welding operations on this plug; eliminating the risk of clash between the resulting reduced-size COBS and the inboard pipes; allowing to rapidly open a window that could be used for inspection and deployment of other RH equipment.

It should be pointed out that the UP neutron shield plug has, in addition, a "keystone" role, given that it holds the five BB segments in position during operation, and must be provided with a fixation system to the VV, into which it will react the loads faced during operation (e.g. from the BBs as they expand under the operational conditions, and from disruptions). It will be approximately the thickness of the VV (not less than 0.7 m thick) to achieve its shielding functions—major toroidal dimension 2.5 m; minor toroidal dimension 1.5 m; for an expected mass of around 4 t to 8 t (drained), assuming a construction similar to the divertor [9].

The introduction of both the UP neutron shield plug and the UL has an impact on the design of the DSC, as they require that the OB section of the DSC be split poloidally in a similar manner, i.e., into two sections (see below section 4.3). In addition, if all of the EPs will have a port plug reaching all the way through the blanket to the plasma and offset from the sector centreline, as envisaged for those sectors with EP plugs—such as for DC, or with limiters (OML and OLL), or with an EC system—, it will have an impact on the design of the DSC as well, given that it will reduce the possible options for integration.

2.5. WCLL blanket concept

Various BB concepts have been proposed and studied for DEMO over the years [30, 31]. The concept being considered in this work is the WCLL [32], which uses reduced activation ferritic-martensitic steel, EUROFER97, as structural material, relying on

‖ The Neutral Beam (NB) and the Ion Cycloton (IC) HCD systems are being foreseen to be integrated in the EP as well [26] but these systems are not DEMO baseline systems at present.

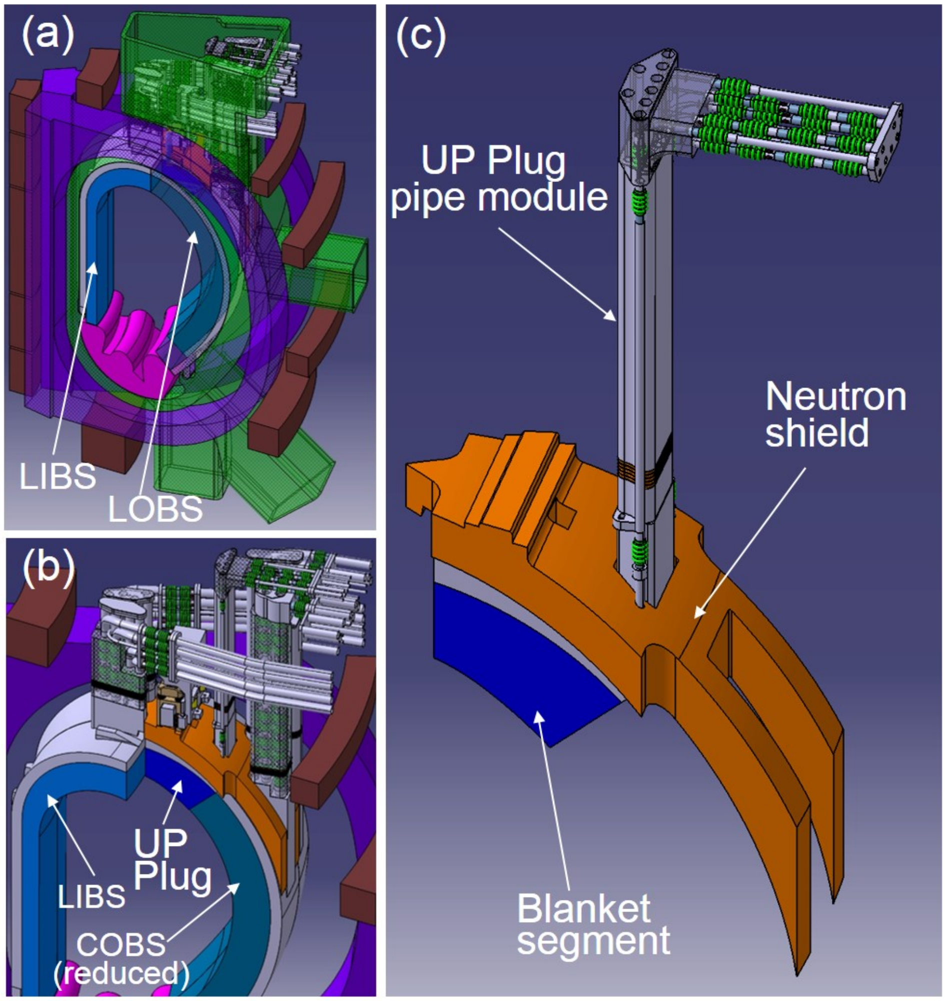

Figure 6. The upper port plug or "keystone" concept, with the neutron shield and corresponding pipe module attached in (c) (CAD model from [29]).

a Lithium Lead eutectic alloy (PbLi) as T breeder (via its Li component), neutron-multiplier (through the Pb component) and T carrier, using 6 loops to circulate the PbLi through the blankets [33], besides water as coolant in two dedicated and independent water loops [28, 34, 35].

2.5.1. DEMO WCLL SMS blanket architecture It should be remarked that the Single Module Segment (SMS) BB architecture is now the reference in DEMO, as depicted in figure 7. In this approach each segment is composed by the FW, the SW, the bottom and top caps, and the BP, being supported by a Back Supporting Structure (BSS), which attaches the BB to the VV (using keys in the BSS and corresponding housings in the VV). In the SMS the profile of the FW follows the last closed magnetic surface without sharp edges and discontinuities. According to [36] the OBS maximum mass shall be 80 t, whereas for the inboard segment (IBS) it should be 60 t; the poloidal length of the IBS is ∼13 m, while for the OBS it is ∼14 m; the toroidal length of the

FW for the IBS is ∼1.12 m, for the COBS it is ∼1.48 m, whilst for the LOBS and ROBS it is ∼1.24 m. The radial thickness of the IBS is in the range from 770 mm to 1200 mm, and that for the OBS is 1000 mm [35].

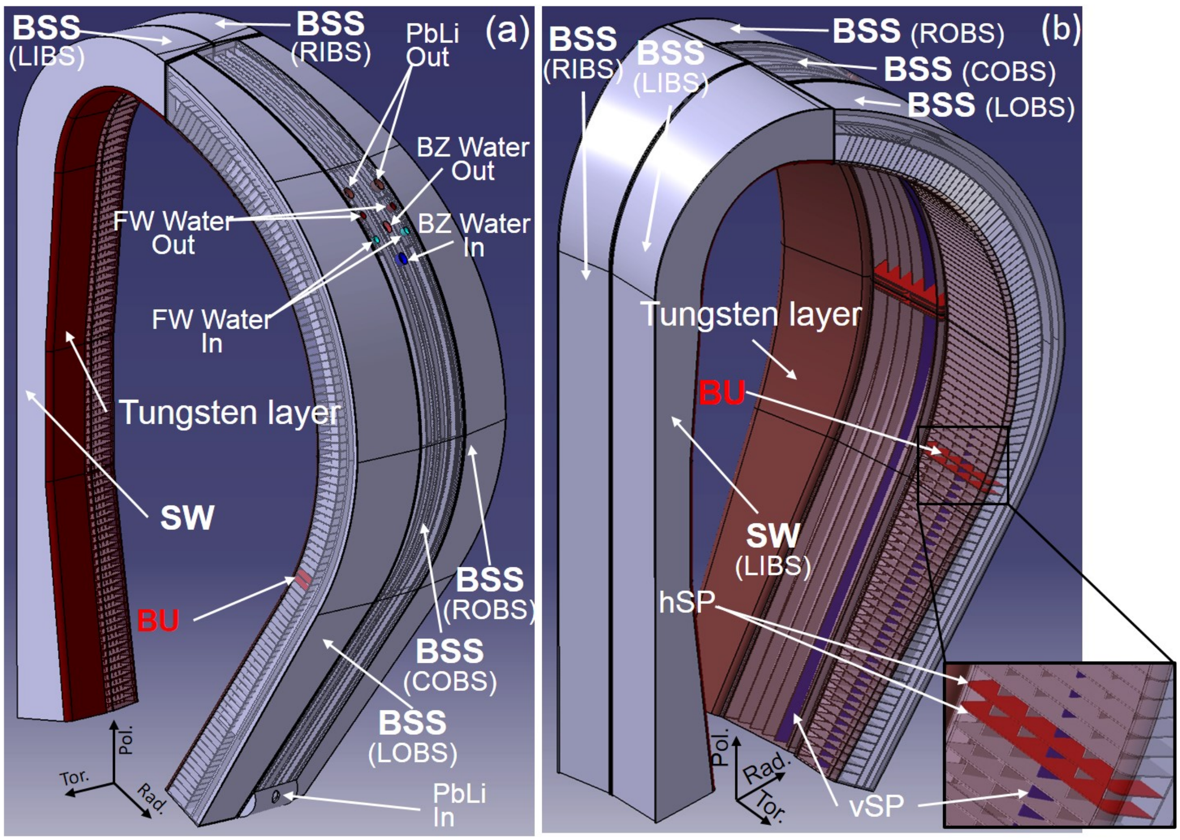

Figure 7. The WCLL blanket design with the SMS architecture showing the inner structure of the BZ, with its stiffening plates (hSP, vSP), the internal arrangement of the PbLi and the water manifolds. A (270 mm high) equatorial slice of the BU is highlighted in red (see figure 8) (CAD model taken from [37]).

2.5.2. The breeding units: FW-SW, BZ, PbLi and water manifolds, BSS Each of the BB segments in the WCLL design consists of a stack of about 100 toroidal-radial Breeding Units (BUs), each comprising the FW-SW, the Breeding Zone (BZ), the corresponding part of the PbLi and water manifolds, and the BSS. A BU is highlighted in red on the LOBS of figure 7, whereas a (270 mm high) equatorial slice of the COBS, highlighted in red on the same figure, is detailed in figure 8 — representing, in fact, a stack of 2 BU.

The FW-SW is a U-shaped plate 25 mm thick cooled by water—circulating in channels created inside this plate—which is delivered and collected via the corresponding water manifold. The BZ is reinforced by various Stiffening Plates (SPs) (vSP, hSP) and baffle plates, whereas other plates (BP1, BP2) separate the BZ from the PbLi and the water manifolds. The BZ is filled with the breeding material through the PbLi manifold,

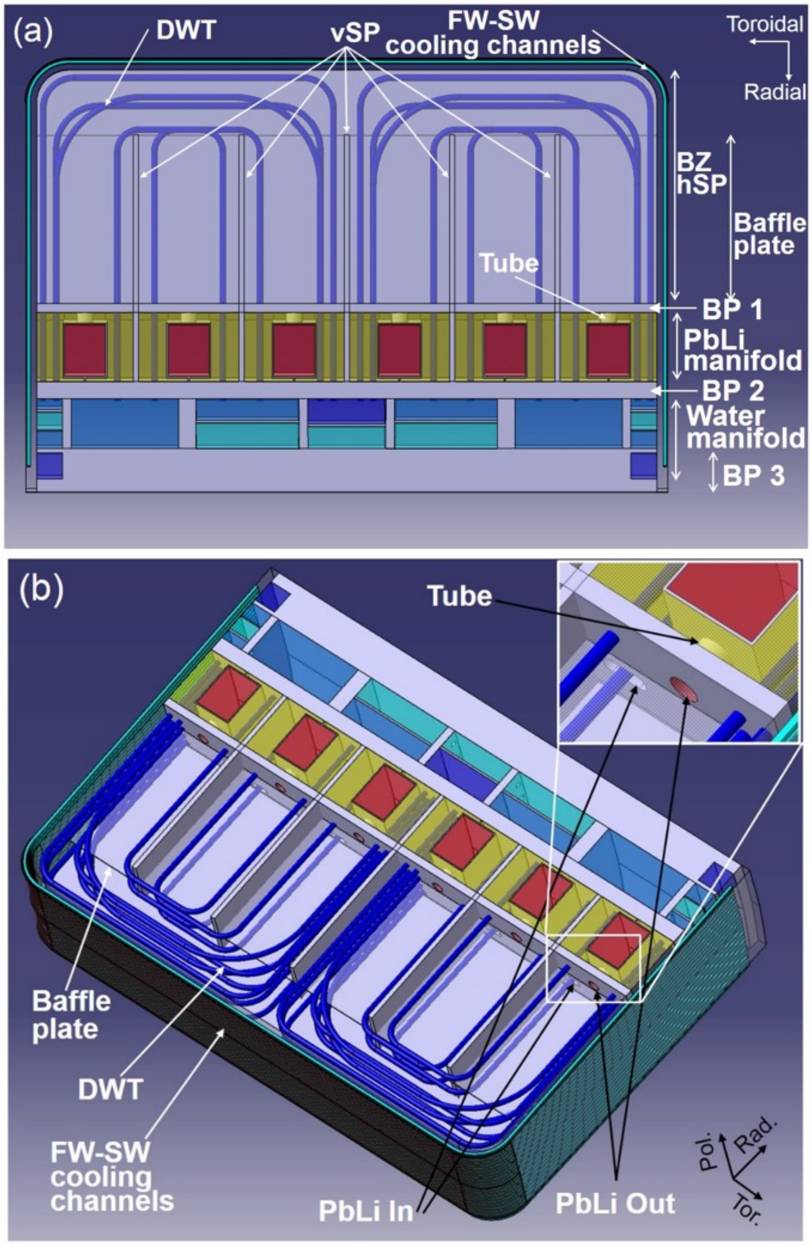

Figure 8. A breeding unit of the COBS (equatorial slice 270 mm high, highlighted in red in figure 7 (a)): (a) cross sectional (top) view; (b) perspective (CAD model taken from [37]).

a coaxial square structure shown in figure 8, and cooled by water flowing inside Double-Walled Tubes (DWT), delivered and collected via the corresponding water manifold (see figure 8).

Each blanket is sustained by a continuous steel plate running along the back of the BB segments (see figure 7 and figure 8), with a maximum radial thickness of 100 mm, which closes the rear of the BB segments: the BP3, also often called BSS. This is the backbone of the BB segments, as it provides four distinct and key functions: 1) supporting structural loads of the BZ and providing stiffness to the whole structure; 2) housing the FW water coolant manifolds, as well as water and PbLi spinal collectors (BZ water cooling being independent from FW water cooling); 3) shielding the VV and the TF coils from radiation coming from the plasma; 4) housing the attachment system to the VV.

2.5.3. The WCLL pipes In the WCLL concept the UP has 10 pipes arranged in 5 rows of 2 pipes, as depicted in figure 9, each pair carrying the same type of fluid: in each pair the larger-diameter pipes are connected to the 3 OB BB segments (DN200 for FW water cooling; DN350 for BZ water cooling and for PbLi), whereas the smaller-diameter pipes are connected to the 2 InboardBB segments (DN100 for FW water cooling; DN200 for BZ water cooling and for PbLi). The lower port has 5 input pipes of PbLi, grouped in two rows: one row with 3 input pipes for the three OB BB, and one row with 2 input pipes for the two IB BB. Note that the model in figure 9 uses the "chimneys" of the HCPB blanket concept, for illustrative purposes only, the aim being to delimit that region, since the WCLL "chimneys" are not yet designed. Note, moreover, that the PbLi inlet pipes for the LOBS and ROBS in the lower port are not yet included in this model.

3. Diagnostics slim cassette

3.1. The reflectometry diagnostic in DEMO

The MW reflectometry diagnostic for DEMO [2] has a twofold objective [38]: i) to provide data for the feedback control for plasma position and shape, and ii) to provide the radial edge density profile at several poloidal angles. As a matter of fact, with its reduced access needs, front-end robustness, space coverage and spatial resolution, MW reflectometry is a strong candidate to fulfil those objectives.

For the MW reflectometry diagnostic to achieve this, several antennas should be distributed at several poloidal locations, looking directly to the plasma. Indeed, in DEMO the MW reflectometry measurements are foreseen for 16 different locations surrounding the poloidal plane, using a cluster of antennas in each location (gap), given that this can improve the ability to receive the signal reflected by the plasma. In fact, ray-tracing simulations have shown that at the equatorial level the "single pair" approach (i.e. using one emitting and one receiving antenna), will be able to provide good spatial resolution, whereas near the LPs and UPs the curvature of the plasma will cause significant problems for the operation and accuracy of MW reflectometry measurements [39]. At the latter locations, a cluster of 4 to 6 antennas (i.e. 3 to 5 receiving antennas per 1 emitting antenna) may be required to ensure that the reflected beam is captured, even under conditions of larger plasma-wall distance. Thus, in order to fulfil the MW reflectometry requirements for DEMO, up to 100 antennas may be required, duplicated in a second sector to provide redundancy. Still, the number of

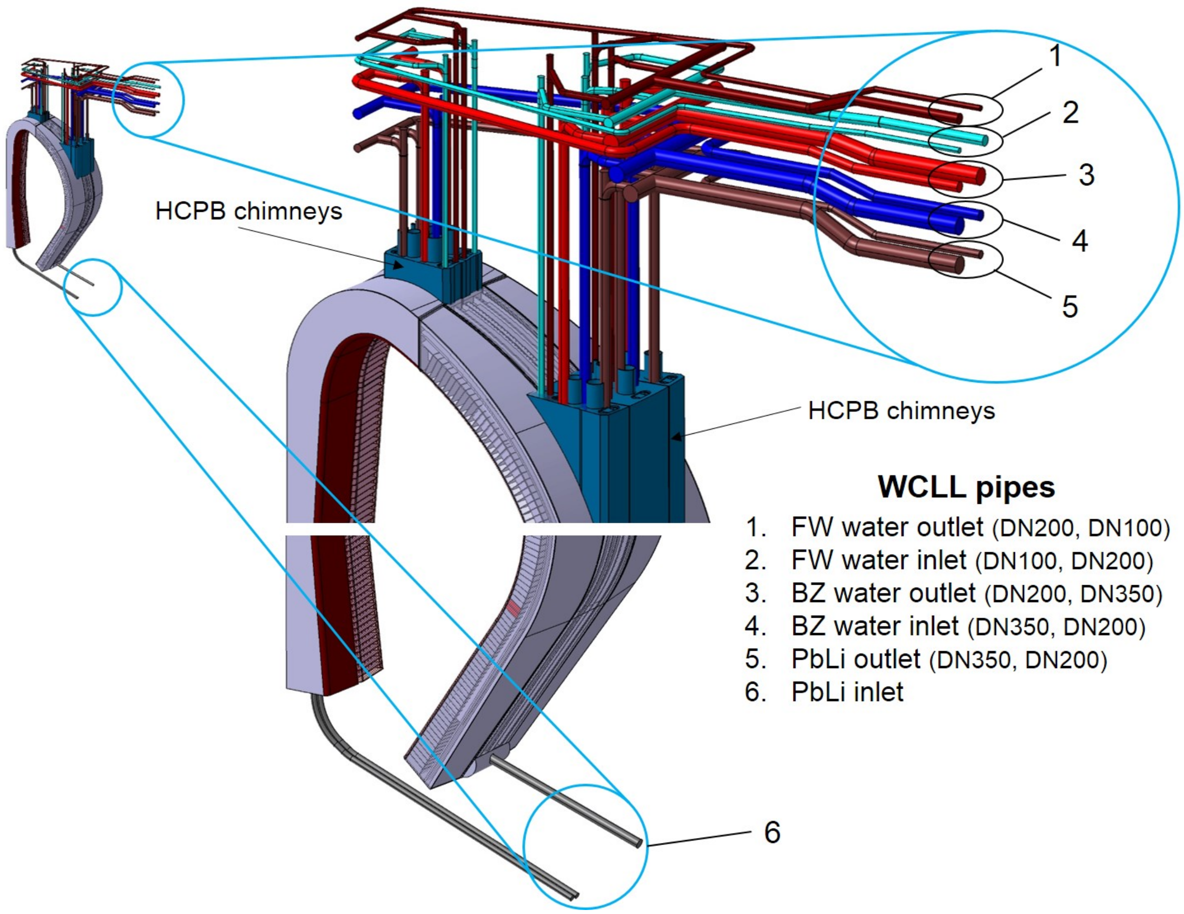

Figure 9. Feeding pipes for the WCLL model of figure 7 using, for illustrative purposes, the "chimneys" of the HCPB concept (the lower port PbLi inlet pipes for the LOBS and ROBS are not yet included in this model)(CAD models: WCLL blankets and piping [37]; HCPB "chimneys" [5]).

sectors may increase to 4 if less antennas and WGs can be fitted in each sector.

The integration of these antennas and the respective WGs with the BB segments imposes challenges: on the one hand, they shall withstand the harsh radiation environment foreseen for DEMO during the extended periods of operation between BB replacement; on the other, they shall be compatible with the BB RH operations. In fact, the implementation of the MW reflectometry diagnostic requires that its antennas be placed in front of the plasma; therefore, they are foreseen to be made of EUROFER, with the possible addition of tungsten coating—taken from the experience of the BB project for the use of materials for in-vessel components¶. The WGs, made of EUROFER and eventually copper-coated for increased electrical conductivity, must be routed from the plasma-facing antennas up to the diagnostic hall, crossing two vacuum boundaries: one

¶ It has been recommended that the antennas should be made of tungsten, be retracted from the BB surface by about 100 mm, to keep erosion below 10 μm year^{-1}, and be replaced together with the BBs—erosion implies a greater surface roughness, which leads to a higher reflection coefficient, Voltage Standing Wave Ratio (VSWR) and losses, thus reducing the antenna efficiency [39].

at the VV level (primary vacuum boundary), the other at the cryostat level (cryostat vacuum), before entering the building through the bioshield barrier.

3.2. Magnetics sensors in DEMO

In DEMO the magnetics diagnostic will be one of the main tools for plasma behavior real-time monitoring, allowing to determine the plasma shape and distance to the FW—and optionally to detect Magnetohydrodynamic (MHD) instabilities—by measuring the local distribution of the magnetic fields at certain distances from the plasma. In order to provide high-accuracy measurements, its front-end components must be located as close as possible to the plasma, between the BB segments and the VV, where they are subjected to high radiation and thermal loads. Therefore, it is crucial to allow for replacement of its front-end components if the performance of the diagnostic is compromised by failure of sensors or cables [40]. The need for eventual replacement of the magnetics sensors in case of failure makes the DSC also a possible solution for the integration of magnetics in DEMO. In that case, the DSC design could be adapted to host the magnetics sensors, attached to the BSS.

The in-vessel sensors of the magnetics diagnostic are planned to be distributed in 4 toroidal segments, each with 60 sensors distributed poloidally around the plasma. An overall assessment of the number of Hall sensors required for DEMO is 240 units in-vessel and 552 units ex-vessel [40], with similar numbers for mirnov/saddle coil type sensors.

3.3. The diagnostics slim cassette concept

The primary integration approach for the MW reflectometry diagnostic in DEMO has been based on the construction of an independent slim cassette structure (with an independent FW), now called DSC, to be integrated with the BB segments [2]. This structure is a poloidal section with a thickness of 20 cm to 25 cm in the toroidal direction, containing all the antennas and the corresponding rectangular WGs—attached to the antennas and routed to the UPs—required for MW reflectometry, as illustrated in figure 10. The antennas will be distributed in clusters at 16 locations (gaps: G1 – G16), arranged vertically in each gap, with the clusters of antennas distributed in different planes in the toroidal direction (as shown in figure 10 (right)), to avoid clashing between WGs (each with 19 mm × 9.5 mm of inner cross-section). For replacement of the DSCs, the WGs would be disconnected near the UPs and the poloidal segments would be replaced using a similar procedure to that of the BB segment exchange. Then, the new DSCs segments would be inserted, and the WGs would be re-connected to the extensions via the UPs. When the BBs are (routinely) exchanged, then the DSCs will also be taken out after disconnecting the lines, and new cassettes re-installed in the same way.

One of the original objectives of the concept was to ensure that the segmentation between the DSC modules is the same as in the BB segments [2], thus helping to maintain a similar mechanical behaviour and to preserve the compatibility with RH operations when installing or removing the BB segments. This same overall approach is being pursued here, now applied to the WCLL blanket concept and for an "updated" version of DEMO (2017)+.

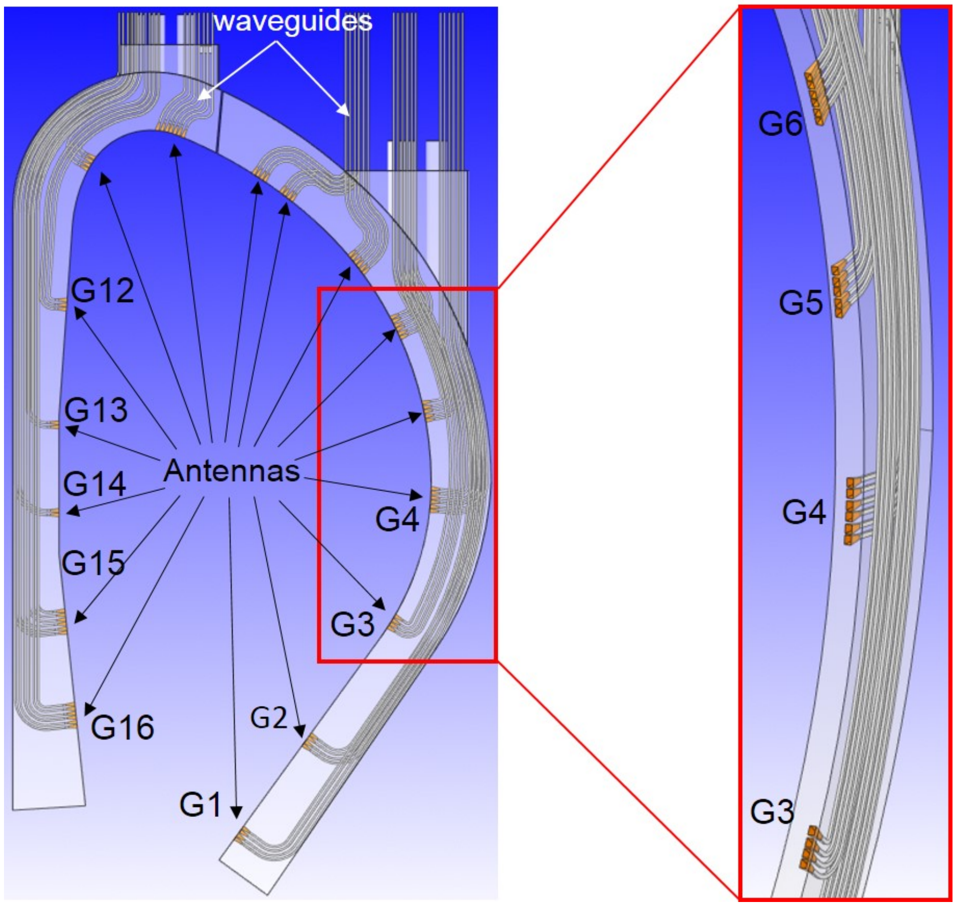

Figure 10. The DSC concept, including the routing of WGs to/from the antennas in 16 different clusters (gaps G1 to G16), where the right picture shows a different perspective of the DSC.

Although the DSC concept introduced in this section allows this paper to be read as a standalone document, it does not provide all the details that shaped the DSC design during the past 5 years. In particular, nuclear and thermal analyses have been recently performed for a DSC segment at the IB, which included a proposal for a cooling system design that aims to keep the operation temperatures within the limits foreseen for DEMO. These analyses, which still apply to the current DSC design, can be found in [41].

+ At the time of [2] the DSC was being developed for the HCLL blanket concept, in which He is used as coolant for the BB, and would be used as coolant also for the DSC, shared via the BSS.

3.4. Impact of the DSCs on the tritium breeding ratio

An issue that needs to be addressed regards the number of DSCs—to fulfil the requirements for MW reflectometry and, eventually, to host the magnetics sensors—and its expected impact on the Tritium Breeding Ratio (TBR)*, given that they reduce the amount of volume available for breeding Tritium.

A first conservative estimation was made based on the results presented in [42].In that reference, the effect on the TBR resulting from the introduction of several IVCs was evaluated for the HCPB blanket configuration. The IVCs introduced in [42] were the following: 4 IMLs, 4 OMLs, 8 ULs, 4 OLLs, 3 NBIs systems, and 9 EC antennas (representing also diagnostic port plugs for which no design was available). These IVCs occupy a total FW area of $120.1\,\mathrm{m}^2$. Although it was not possible—and it was deemed not essential—to evaluate the impact of these IVCs on the absolute value of the TBR, a relative TBR reduction of 10.9% was calculated in that study, when compared to the configuration without any IVCs.

Extrapolating from these results, considering that two DSCs would be required for MW reflectometry and four for magnetics—at different toroidal locations—, it is concluded that the integration of 6 DSCs with 20 cm of toroidal thickness would reduce the TBR further by 2.9%. However, when considering a WCLL blanket configuration instead of HCPB, a lower reduction is expected as the HCPB blanket configuration is expected to yield a higher TBR when compared to the WCLL configuration. For 6 DSCs with 25 cm of toroidal thickness, the reduction would be ∼3.7% for HCPB and ∼2.8% for WCLL.

Yet, as a first estimation, this extrapolation is deemed conservative, given that a large percentage of the $120.1\,\mathrm{m}^2$ of IVC surface considered in reference [42] is located at the EP (namely: the 4 OMLs, the 9 EC and 3 NBI systems), where the neutron fluxes (and thus the contribution to the TBR) are higher. The DSC, on the other hand, will cover a full poloidal section.

A simpler and perhaps more accurate estimation is to divide the area that the DSCs occupy by the total FW area of DEMO ($1473\,\mathrm{m}^2$). The results obtained with that approach for the FW area and the expected TBR reduction are presented in table 1. As this table shows, in the worst case (6 DSCs 25 cm thick), the relative TBR reduction would be 2.7%, while in any other case (lower number of DSCs or lower DSC thickness) the reduction would be below 2.2%. Taking into account that WPDC is expected to claim up to 4% of TBR reduction, this would leave an additional 1.3% for other diagnostics in the worst case.

4. Diagnostics slim cassette integration

* The ratio of the rate of tritium production in the system to the rate of tritium burned in plasma.

Table 1. Estimated effect of the DSCs on the TBR.

DSC (number × thickness)	Total FW area [m^2]	TBR Reduction [%]
4 × 20 cm	21.4	1.5
4 × 25 cm	26.92	1.8
6 × 20 cm	32.1	2.2
6 × 25 cm	40.38	2.7

4.1. CAD model and interfaces to ex-vessel

To study the integration of the DSC with the UP, it is convenient, as a starting point, to divide the DSC into two sections, as illustrated in figure 11: the IB High Field-Side (HFS) and the OB (Low Field-Side (LFS). Due to the possible presence of the UP shield plug (the "keystone", see section 2.4) and UL above the OB section (see section 2.3.1), this division will be revised at a later stage, to include a third section (see section 4.3 below).

As the space in the UP is very limited, an assumption is made that the WGs coming out of the DSC (up to 100) have to be routed through the blanket pipe "chimneys". Given that they are already crowded with water and PbLi pipes for the BB, and space is also required to attach the RM tools, the integration of the WGs in the UP is, therefore, strongly dependent on the design and location of the "chimneys" above the blankets.

4.2. Diagnostics slim cassette locations

Two approaches were followed for the integration of the DSC with the DEMO BBs: (a) with the IB and OB sections of the DSC aligned in the same radial plane; (b) with a non-co-planar splitting of the IB and OB sections of the DSC—the IB section inserted (in a radial plane) to the left/right wall of the RIBS/LIBS and the OB section aligned parallel to the lateral parallel walls of the ROBS/COBS/LOBS.

The main locations that can be considered for the DSC integration were divided in six groups and are shown in figure 12 (although some of the combinations in some groups were omitted):

(1) inserted symmetrically in the middle of each sector;

(2) inserted symmetrically between two consecutive sectors (i.e., half of the DSC in each sector);

(3) inserted to the left/right wall of the RIBS/LIBS (non-symmetrically);

(4) inserted on the side of the BB, to the left wall of the LIBS and LOBS (non-symmetrically);

(5) IB section inserted to the left/right wall of the RIBS/LIBS and OB section inserted to the left/right wall of the ROBS/LOBS;

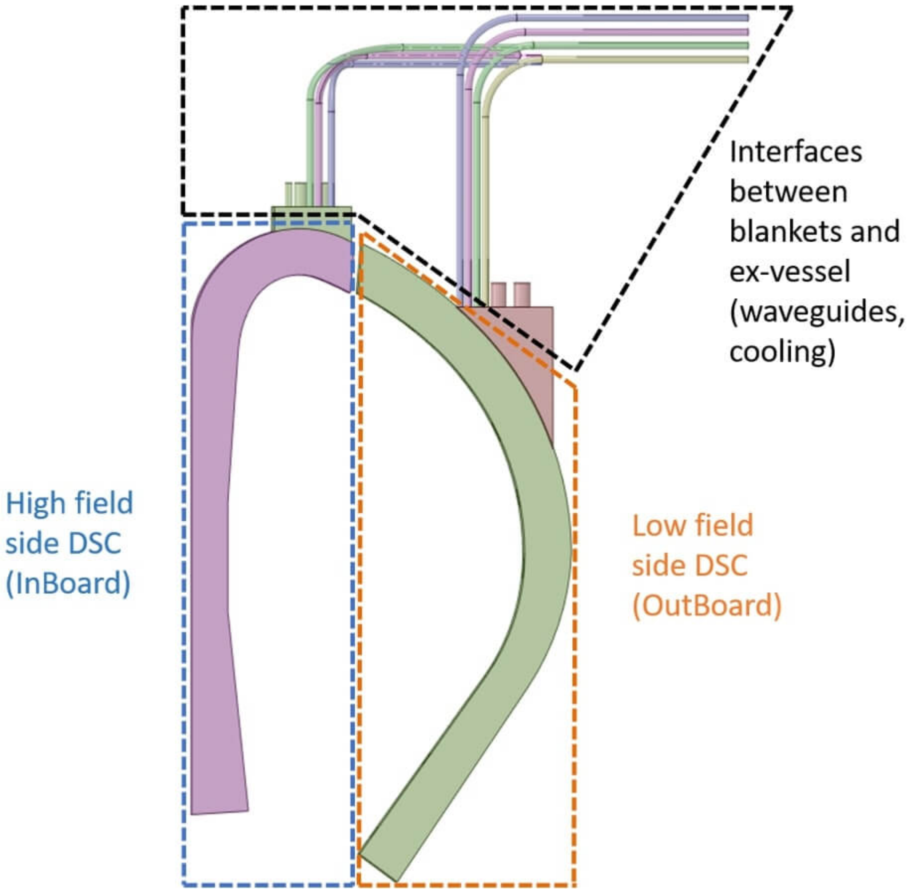

Figure 11. IB and OB sections of the DSC and interfaces to ex-vessel.

(6) IB section inserted to the left/right wall of the RIBS/LIBS and OB section inserted to the left/right wall of the COBS.

In figure 12 the (200 mm wide) DSC is represented in purple and, for illustrative purposes, use is made of the blankets and “chimneys” from HCPB (shown semi-transparent), while the EP plug (with an OML), offset from the sector centreline, is delimited with a yellow line and the UP aperture on the VV is delimited with a red line. Note that with the parallelization of the COBS side walls, as well as the adoption of the straight interface between the IB and OB BBs (section 2.2), the LIBS/RIBS can be extracted with the ROBS/LOBS in place, respectively. Note, also, that each of the locations presented in figure 12 requires that the two sections (IB and OB) of the DSC be specifically designed for that position, given that this straight interface breaks the rotational symmetry around the major axis of the tokamak. On the other hand, it should be remarked that if the DSC is to be handled independently from the BB, it must be separated from the BB on its two lateral sides by a 20 mm gap [36], as this is a requirement for RM. When compared to a DSC attached to the BB this represents an extra 20 mm gap, if the attachment system does not add to the toroidal width of the components. Moreover, dissimilar thermal behaviour between the DSC and the BB, due to different construction and internal configuration, could complicate RM operations.

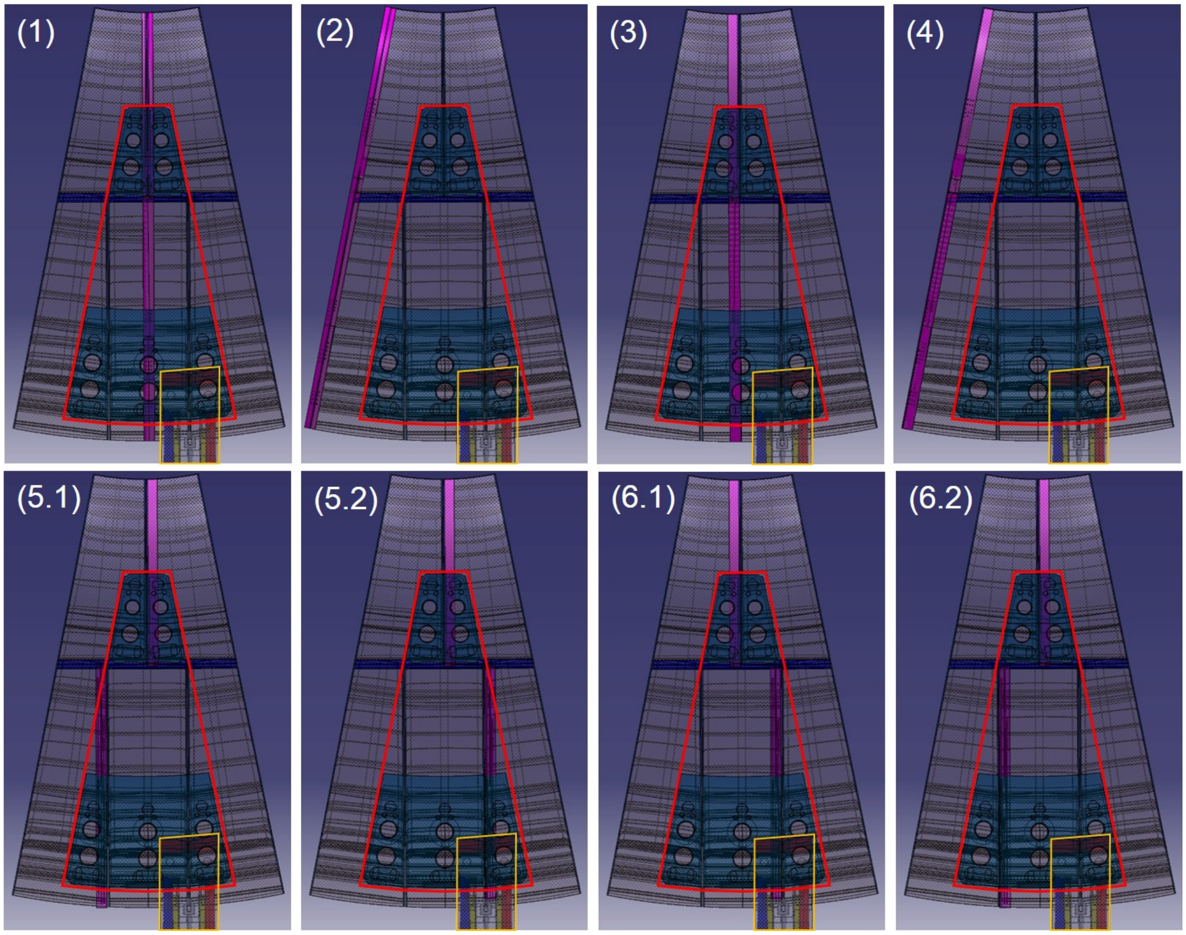

Figure 12. DSC integration alternatives illustrated using the BB and "chimneys" from HCPB, the EP offset from the sector centreline (delimited with a yellow line), the DSC (in purple), and where the red line delimits the UP aperture on the VV (top view) (CAD models: BB and "chimneys" from [5]; EP limiter from [4]).

4.2.1. Impact of a non-co-planar splitting of the DSC on the performance It should be pointed out that the splitting of the DSC into two subsections that are not in the same poloidal plane, as in figure 12 (locations (5) and (6)), will have no significant impact on the performance and measurements capabilities of the MW reflectometry system. This results from the fact that the probing signal from each antenna cluster location will travel to the plasma being reflected on a specific plasma layer and returning to one of the receiving antennas of the same cluster. There is no need that the probing signal crosses the plasma between IB and OB (interferometry). In fact, it is even imperative that this doesn't happen to minimize cross-talk between opposite channels. Therefore, the installation of the two subsections in different poloidal planes will contribute to minimizing the risk of cross-talk. Still, the resulting toroidal shift of the two subsections should be taken into account when performing correlation studies between HFS and LFS plasma.

For magnetics, the toroidal misalignment of the two subsections should also not be a problem, as confirmed by the magnetics diagnostic development teams. The only caveat is that the same shift should be applied at each toroidal location, to maintain each measurement location toroidally equispaced. This is ensured in both configurations of figure 12 in which the DSC is split into two subsections that are not in the same poloidal plane (locations (5) and (6)).

4.2.2. Location (1) **Location (1)**, in which the DSC is integrated symmetrically in the middle of the BB sector, would be the perfect choice if the DSC could be handled (extracted/inserted) independently of the BB. In this case, the WGs, as well as the water-cooling pipes of the DSC would be rooted vertically through the UP which, *per se*, would pose no problem. Indeed, in this case it could be envisioned that the DSC would be replaced without having to extract any of the sector's blankets: the OB segment of the DSC would be extracted first and then, if need be, the IB segment extracted through the space left open by the removal of the DSC OB segment (and the reverse for installation). This is, probably, the main selling point for the proposal of an independent DSC that would house the MW reflectometry diagnostic: to allow maintenance of the DSC independent from that of the blankets, thus reducing both the maintenance/replacement duration and costs of the operation.

However, such a solution would probably require the development of a dedicated end-tool to manipulate the 200 mm wide DSC, and the corresponding independent pipe modules that would have to house the WGs, as well as the necessary cooling pipes of the DSC.

Still, from the BB point of view, and given that the DSC for MW reflectometry is to be implemented in only two of DEMO's 16 sectors/ports, this location would have the strongest impact on the segmentation of the BB. In fact, it would lead to two different designs for the LIBS, the RIBS, and the COBS.

For the IB this solution implies that the LIBS and RIBS would have to be reduced in the toroidal direction, but would retain symmetry across this direction. This would be somewhat beneficiary for their RH strategy: it would be a mirror of one-another, even if necessarily different from that for the full LIBS and RIBS, which would have to be used in ports without a DSC. Moreover, this would be beneficiary from the RM point of view, since the resulting slimmer LIBS and RIBS would have a reduced mass.

For the OB this solution cuts the COBS in two halves which, in the end, leads to two very slim central segments ("mini-COBS"). From the outset, this also doubles the number of (PbLi and water) pipes and, consequently, pipe modules that would populate the COBS (where there is actually more real-estate), besides requiring the extraction of the two resulting "mini-COBS" (and corresponding pipe modules) in two independent operations, before the removal of any of the remaining BB segments (ROBS, LOBS, RIBS, LIBS), which would be more time-consuming than the removal of the full single COBS. Nevertheless, the handling procedure for these two "mini-COBS" would be a mirror of one-another, even if necessarily different from that for the full COBS, which would still have to be used in ports without a DSC.

Yet, it should be pointed out that if the DSC would be handled attached to the BB, the removal of the IB section through the UP could raise problems due to the increased toroidal size of the combination of the BB and DSC IB sections.

However, if all of the EPs will have a port plug reaching all the way from the port through the blanket to the plasma and offset from the sector centreline (as envisaged for DC, OML, OLL, or an EC system), the right "mini-COBS" described above would be cut by the EP plug in such a way that the material left over (at the EP region) would not be sufficient to assure the mechanical integrity of the resulting "mini-COBS" (the cuts taking over much more than 1/3 of their nominal toroidal width). Therefore, this solution would be highly unsuited.

4.2.3. Location (2) **Location (2)**, in which the DSC is inserted symmetrically between two consecutive BB sectors — i.e. toroidally half in one sector and half in the contiguous sector —, would lead to two different designs for the LIBS and LOBS of the sector shown in figure 12, as well as to two different designs for the RIBS and ROBS of the sector to its left.

From the RM point of view, even if the DSC could be handled/manipulated independently from the BB, this location would require the removal of the COBS and LOBS before accessing the OB section of the DSC and, in addition, the removal of the LIBS before accessing the IB section of the DSC. Moreover, the DSC sections could not be handled directly with the Tricept BB manipulator (see section 4.5.2), at least from the top, and would require the development of an appropriate end-tool for the Tricept to attach to the lateral surfaces of the DSC and include corresponding attachment features on the side of the DSC. Alternatively, it could be envisaged the recourse to other concepts such as wall-mounted rails deployment attached to the inside wall of the VV UP, which allow robot arms to vertically translate down discrete radial/toroidal positions [9]. However, the length needed for the robot arm to reach the DSC from the rail position and, above all, the weight of the DSC itself that it would have to manipulate, would make this solution impractical.

If the DSC would be attached to the corresponding BB segments and manipulated as a single unit, the removal of the IB as well as of the OB sections through the UP could raise problems, too, due to the increased toroidal size of the resulting combination of the BB and DSC sections.

Note, moreover, that for the DSC pipes to be routed from the top of the (200 mm wide) DSC through the aperture of the UP (delimited by the red line in figure 12), which is ∼600 mm away toroidally, requires upfront some toroidal bending. Compounded with the small gap between the back of the BB/DSC and the VV in this region, which is reasonable to assume that should not be used for routing WGs—150 mm to 200 mm has been removed from the VV internal wall at its highest points to avoid BB clashes during initial vertical lifts [43]—this location would make it virtually impossible to route the DSC pipes through the UP. Note, in addition, that strong bends in WGs degrade heavily the RF signals.

On the other hand, for location (2) the presence of an EP offset from the sector centreline and reaching all the way through the blanket to the plasma would not pose a problem.

4.2.4. Location (3) **Locations (3)**, with the DSC inserted to the left/right wall of the RIBS/LIBS (another option is possible but was not shown in figure 12, nor added to the discussion, because it would have more drawbacks than the option discussed), would be somewhat more appropriate than location (1), since it would only involve two different designs for the RIBS/LIBS. Nevertheless, it still requires the splitting of the COBS, into two very slim and, in this case, non-symmetrical COBS sub-sections. This would entail different RH approaches for the two slimmer COBS sub-sections. Moreover, it would require the extraction of the two resulting "mini-COBS" in two independent operations, which would be more time-consuming than the handling of a single segment. In addition, given that the two resulting "mini-COBS" are not symmetrical, their handling strategy would not be a mirror of one-another. Yet, as in location (1), if handled independently of the BB, the DSC would be replaced without having to extract any of the sector's blankets. Moreover, if the DSC would be handled attached to the BB, the manipulation of the IB section would not pose the problem discussed for location (1), given that the toroidal width of the combined component would be the same as the original BB. Note that locations (3), like (1), allow for the DSC piping to be extracted vertically through the UP.

Still, if all of the EP will have a port plug reaching through the blanket to the plasma and offset from the sector centreline, the right "mini-COBS" would be excised by the EP plug to such an extent that the mechanical integrity of the resulting component could not be assured. And this would be even more dramatic for the alternative implementation of location (3) not shown in figure 12, in which the OB section of the DSC would sit even closer to the EP.

4.2.5. Location (4) **Location (4)**, in which the DSC is inserted on the side of the BB (non-symmetrically) i.e., attached to the left side of the LIBS and LOBS, would be better than location (2), as it leads to two different designs only for the LIBS and LOBS, thus reducing the number of different BB designs. Still, all the other issues discussed in association with location (2) are not improved, except if the DSC segments would be attached to the corresponding BB modules and manipulated as a single unit, in which case the toroidal width of the combined component would be the same as the original BB, and thus would not be a problem. However, similarly to location (2), this location would make the routing of the DSC pipes—most notably the WGs—through the UP virtually impossible.

Note that, for location (4), just like for (2), the presence of an EP offset from the sector centreline and reaching through the blanket to the plasma would not pose a problem.

4.2.6. Location (5) **Locations (5)**, with the IB and OB sections of the DSC in different vertical planes—the IB section of the DSC attached to the left/right wall of the RIBS/LIBS and the OB section of the DSC attached to the left/right wall of the ROBS/LOBS—leads to two different designs for only two segments: the RIBS and the LOBS for (5.1); the RIBS and ROBS for (5.2). Note that other options were possible but were not shown in figure 12 nor added to the discussion, because they would have more drawbacks than the ones discussed.

If the DSC would be manipulated independently of the BB, this configuration could allow the removal of the OB as well as the IB section of the DSC after removing just the COBS — thus, with the LIBS, LOBS, RIBS, and ROBS still in place. However, if the DSC would be attached to the BB, the removal of both sections of the DSCs would involve removing: the 3 OB segments for (5.1), i.e. the COBS, LOBS, and ROBS; just 2 OB segments for (5.2), the COBS and ROBS. If, however, the objective would be to remove just the IB section of the DSC then: (5.1) and (5.2) require the removal of only the COBS and ROBS. Note that locations (5), unlike locations (2) and (4), allow for the DSC piping to be extracted vertically through the UP.

If all of the EPs will have a port plug reaching all the way through the blanket to the plasma and offset from the sector centreline, then option (5.1) would have no compatibility issues whatsoever. Quite on the contrary, option (5.2), in which the OB section of the DSC falls straight into the region occupied by the EP plug, would face serious problems: having to do without an important part of the OB section of the DSC, on the one hand, and having the OB section of the DSC split into two (non-contiguous) subsections and the RH issues that it would entail, besides the problem of routing the WGs from the lower sub-section of the resulting DSC up into the UP.

4.2.7. Location (6) **Locations (6)**, with the IB and OB sections of the DSC in different vertical planes, as the previous case, but with the IB section of the DSC attached to the left/right wall of the RIBS/LIBS and the OB section of the DSC attached to either the left or the right wall of the COBS, leads, like for locations (5), to two different designs for only two segments, here the RIBS/LIBS and COBS. Note that other options were possible but were not shown in figure 12 nor added to the discussion, because they would have more drawbacks than the ones discussed.

Yet, if the DSC would be manipulated independently of the BB, this configuration could allow the removal of the OB section of the DSC with all the 5 BB segments in place, which would be an important advantage, and could allow the removal of the IB section after removing just the COBS—thus, with the LIBS, LOBS, RIBS, and ROBS still in place. If, however, the DSC would be attached to the BB this configuration could still allow the removal of the OB section of the DSC in the first removal operation, that of the COBS, and allow the removal of both sections of the DSC after the removal of just 2 OB segments: removing the COBS and LOBS for (6.1), thus with the ROBS and RIBS still in place; removing the COBS and ROBS for (6.4), thus with LOBS and LIBS still in place. In addition, these locations (6) allow for the DSC piping to be extracted vertically through the UP, like locations (5), as well as (1) and (3).

If all of the EPs will have a port plug reaching all the way through the blanket to the plasma and offset from the sector centreline, then option (6.1), in which the OB section of the DSC falls straight into the region occupied by the EP plug, would face the same problems discussed above for locations (5). Note, moreover, that if the DSC would be handled independently of the BB, the reduced width (at the EP) of the COBS resulting from the EP opening in (6.2) might be insufficient for their mechanical stability. However, if the DSC would be attached to the corresponding BB, the stability of the COBS should be retained for (6.2).

4.2.8. Discussion It is clear that, from the BB perspective, for locations (1) and (3) the division of the COBS in two slimmer halves that they entail is reason enough for their outright rejection. Locations (2) and (4), if for no reason other than not allowing for the DSC piping, most notably the WGs, to be routed through the UP, makes these solutions clearly unsuited. Therefore, the preferred solutions from the BB perspective would be the non-co-planar splitting of the IB and OB sections of the DSC, namely locations (5) and (6), which lead to a reduced number of different BB segment designs: only two segments for each. Furthermore, they allow for the DSC piping to be routed vertically through the UP with no toroidal bending. However, the best overall solution would be location (6), given that it allows for the OB section of the DSC to be handled in the first removal operation, whether it would be as an independent segment or attached to the BBs. Moreover, if the DSC is to be attached to the BBs it allows for the removal of the IB segment after removing just two of the OB segments.

Still, the presence of the EPs having a port plug reaching all the way through the blanket to the plasma and toroidally offset from the sector centreline tips the scale clearly towards just two of the options in location (6) and, in addition, for the attachment of the DSC to the corresponding BB so as to guarantee the mechanical stability of the COBS.

Given these constraints, the more appropriate solution would be location (6.2) and for the DSC to be handled attached to the corresponding BB instead of independently.

Yet, the integration of the DSC proposed in location (6.2) still faces various challenges. Indeed, the joint handling of the DSC and the BB requires the development of an appropriate attachment between the two components. On the other hand, the UP "chimneys" (illustrated in figure 12 for the HCPB concept) are somewhat crowded with the BB piping and the twistlock sockets for the Tricept, making the space left for routing the DSC pipes (for WGs and cooling) scarce. This is more prominent in the RIBS (besides the LIBS, LOBS and ROBS), although not so much the case in the COBS. But this issue can be even more striking for the WCLL pipework, displayed in figure 13—where use is made of the HCPB "chimneys" for illustrative purposes—, particularly for the COBS. In addition, the DSC pipework ought to be attached (or integrated) in the corresponding BB pipe module, and be handled as a single unit. Still, attention must be paid to two topics: one is the eventual differences in thermal expansion

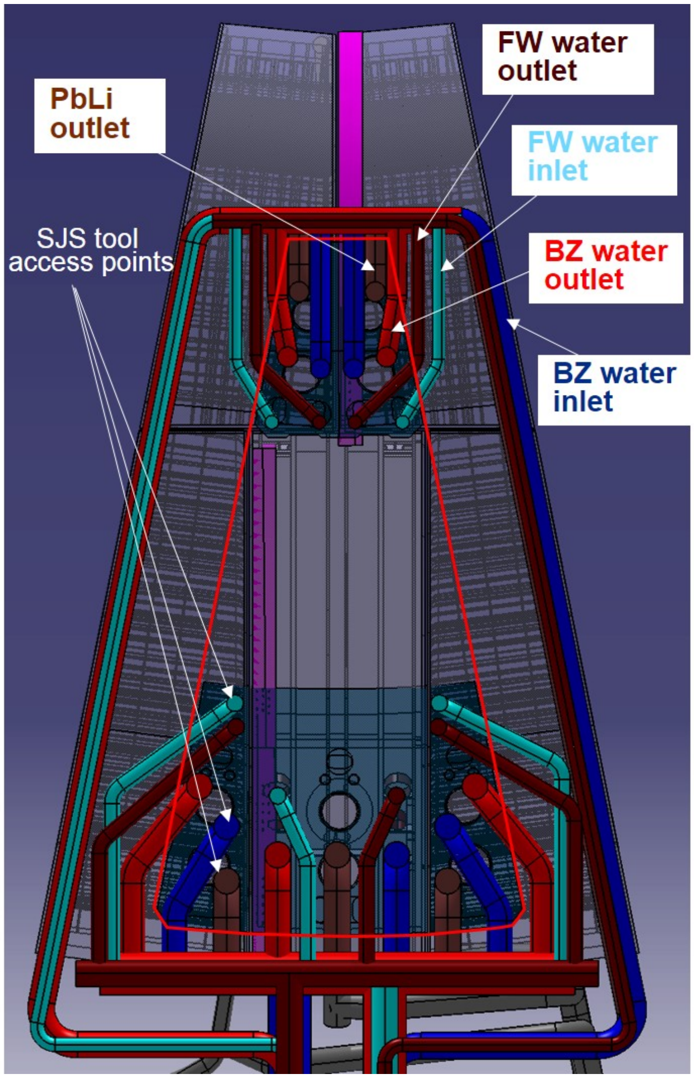

Figure 13. The selected DSC configuration (purple) illustrated with WCLL blankets and piping, where the HCPB "chimneys" are used for illustrative purposes (CAD models: WCLL blankets and piping [37]; HCPB "chimneys" [5]).

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between the BB and the DSC pipework, which would need some form of compensation; the other is the alignment requirements and strategies, most notably for the DSC WGs which, at the frequencies involved in this diagnostic, could be more stringent than those for the breeding and cooling fluids.

Therefore, it is clear that a successful integration of the DSC in DEMO calls for a redesign of the WCLL BBs having in mind, from the outset, also the needs of the DSC in terms of space, as well as the restrictions posed by the WGs — e.g. the radius of curvature for a single rectangular WG shall be >1200 mm [38] —, in a location where space is a premium, in a process that should develop in close proximity with the owners of the appropriate work packages: WPRM, and WPBB (which own the BB pipe modules).

4.3. Integration with the UP

From the discussions above, the DSC can be categorized by the position into three sections: the IB, the OB, and the "keystone", as pictured in figure 14. This figure shows also a preliminary sketch of a concept for the interface of the DSC rectangular WGs with the ex-vessel, in which the WGs are grouped inside pipes, with an appropriate number of such pipes for each of these three sections.

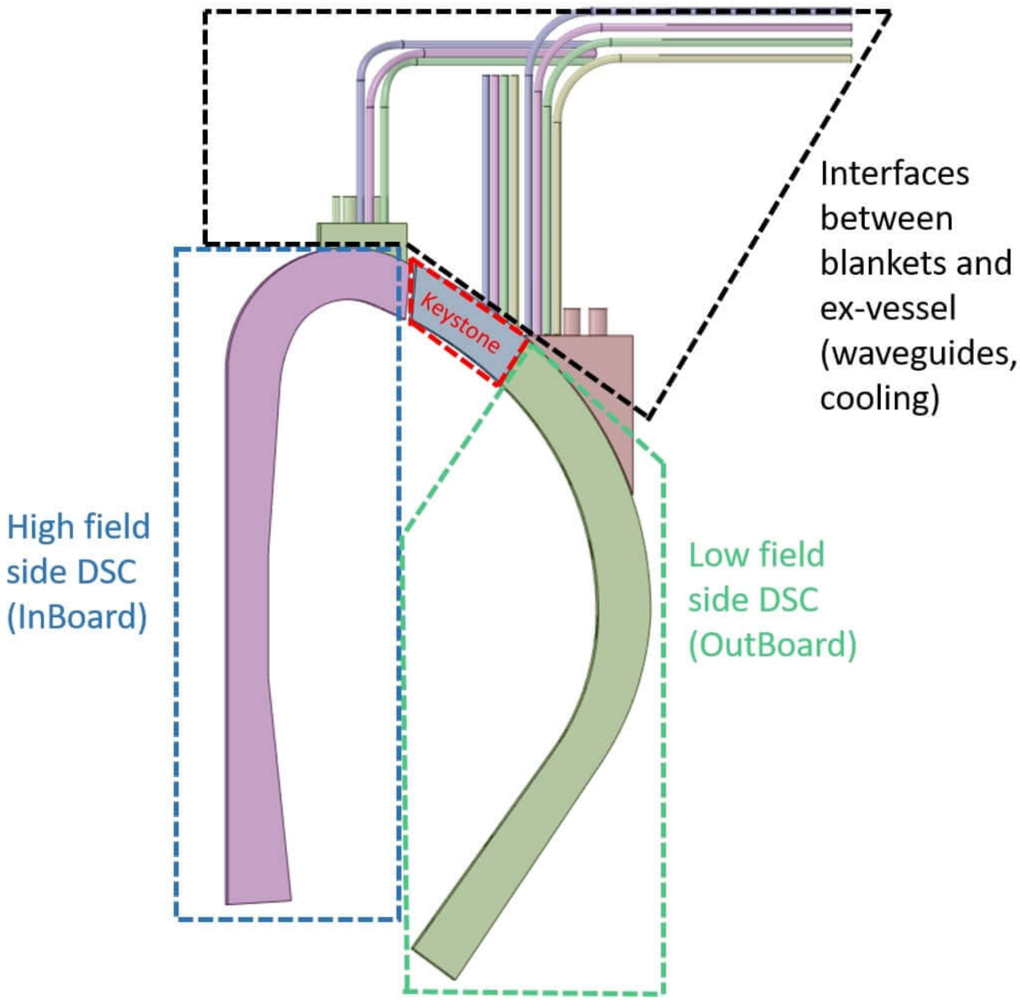

Figure 14. The three-section DSC: the IB, the OB, and the "keystone", as well as the corresponding WG "interfaces" with the ex-vessel.

An early concept for a WG male-female socket that would connect these WG pipes to the "chimneys" in the UP is depicted in figure 15. In this concept the WGs are ordered in a rectangular grid with a male/female ridge/groove around each WG to more effectively reduce the crosstalk between the WGs. Use is made of passive alignment features such as a (partially tapered) pin/hole arrangement and an annular groove/ridge arrangement close to the pipe rim, which would have to be tailored to the requirements of the WGs — given the frequencies involved in this diagnostic these requirements could be more stringent than those for the (breeding and cooling) pipes. This socket would

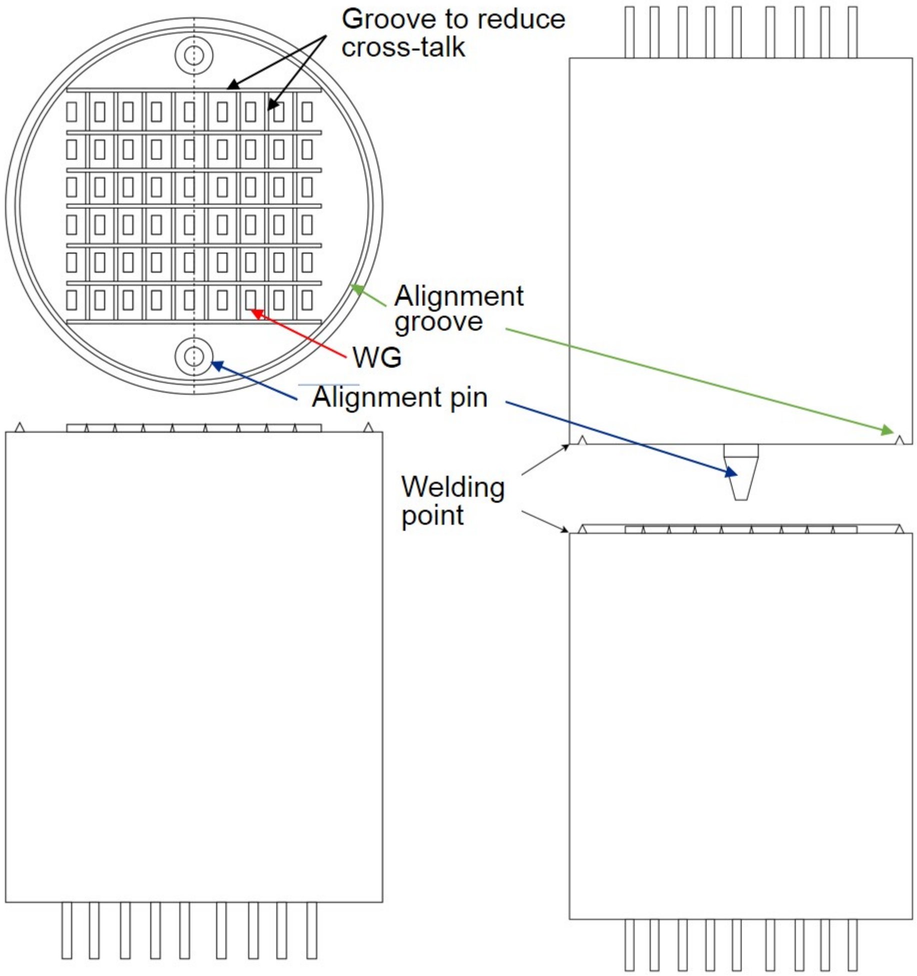

Figure 15. Concept of a WG male/female socket arrangement with alignment features.

be welded around the rim by welding/cutting tools that operate externally to the pipes (section 4.5.3).

The WG interface concept is presented in more detail in figure 16, where it is illustrated with the HCPB "chimney" in the IB section of the DSC. Remember that the WGs have 19 mm × 9.5 mm of inner cross-section, whereas the DSC is 200 mm wide. The sockets for the WG pipes shown in figure 16 are based on the concept of figure 15, in which the annular groove/ridge arrangement was substituted by a male-female arrangement fully on the outside rim and, given the space constraints of the "chimneys", have a diameter 154 mm which can accommodate fewer WGs.

A preliminary concept for the WG modules is presented in figure 17 for the IB and the OB section of the DSC, including also the WG pipes for the "keystone" section of the DSC, illustrated with the HCPB pipe and "chimney" concept of figure 2. It should be underlined that these supporting modules containing the WGs are expected to be integrated with the pipe modules of the BB, which, if designed with space for the WGs in mind, will allow for a much simpler design of the WG module structures, especially

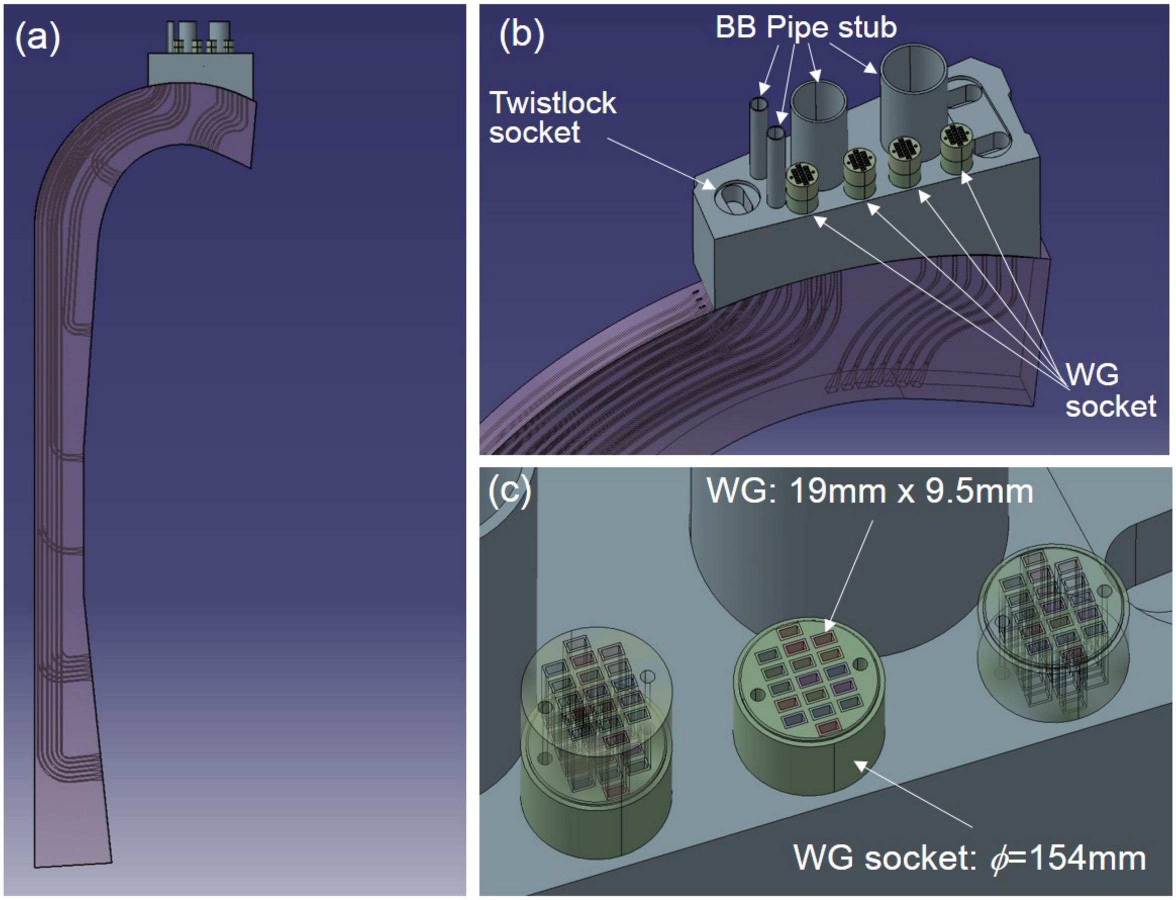

Figure 16. DSC with the WG Interface on an HCPB RIBS "chimney" in which the DSC rectangular WGs are grouped inside pipes.

at the IB. It should also be highlighted that the design of the WG extensions at the IB module must be carefully considered, to avoid as much as possible any curvatures in the toroidal direction, which may affect the wave propagation inside the WGs.

4.4. Integration with the WCLL blanket

Two approaches are being considered for integrating the DSC with the WCLL blankets and are presented, for illustrative purposes only, in figure 18:

a) The DSC is attached in front of the BSS (common BSS);
b) The DSC is attached to the side of BB.

As discussed above (section 2.5.2), the WCLL blankets have two independent water cooling circuits: one for the FW-SW, the other for the BZ, as highlighted in figure 18 in different shades of blue. It should be pointed out that whereas in previous versions of the DSC [2], developed for the HCLL blankets, He was used for cooling the BBs as well as the DSC, the DSC is now being developed for the WCLL BBs, with water used as coolant for both the BBs and the DSC. The new DSC has two cooling systems, one

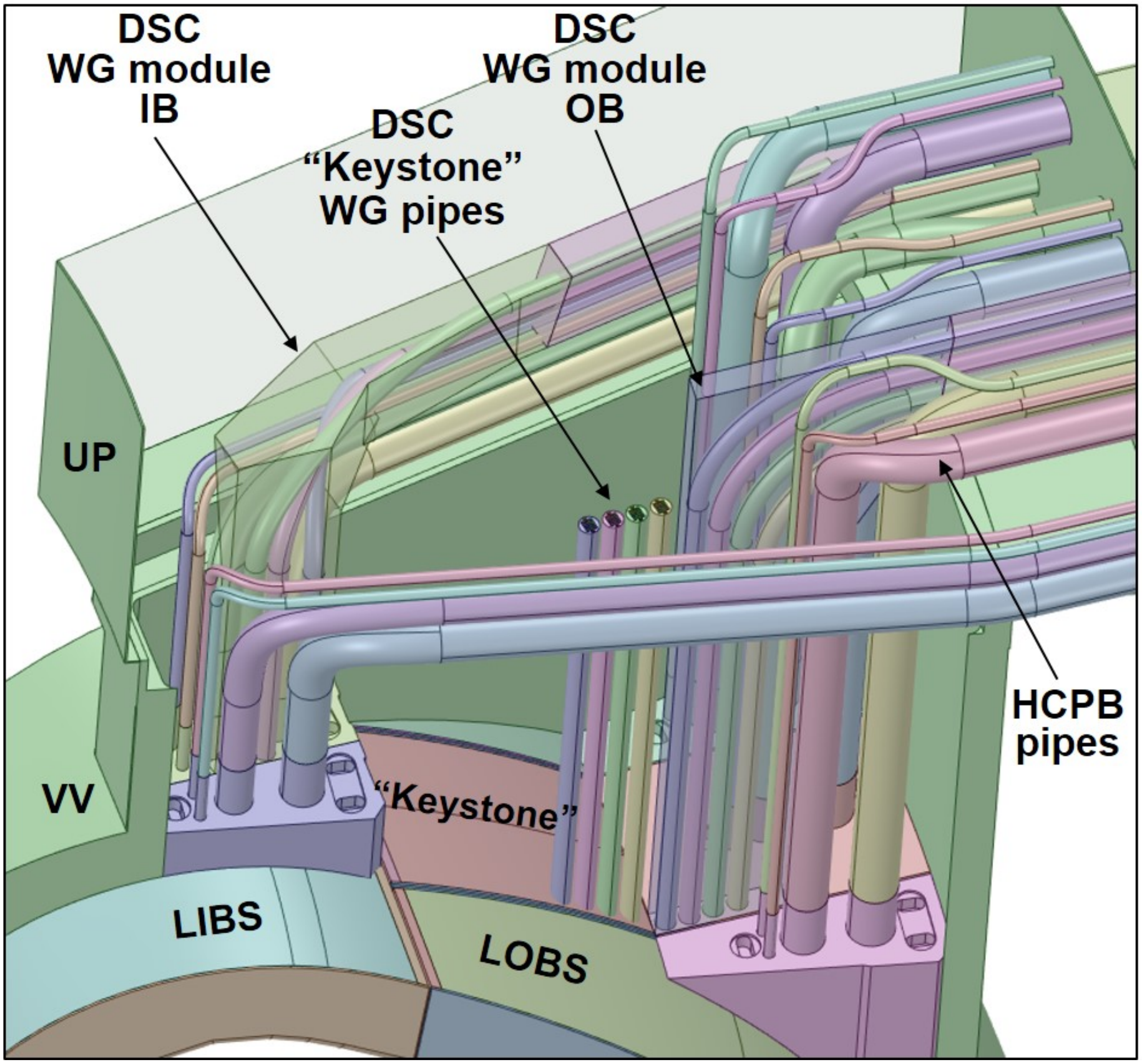

Figure 17. The supporting modules concept for the IB and the OB WG extension of the DSC, including the "keystone" WG pipes, using the HCPB "chimneys" and piping.

for the FW-SW, the other for the shielding blocks inside the DSC, where concentric cylinders are used and in which water circulates from the outer cylinder to the inner one [38].

In approach a) the WGs in the DSC will have to sit closer (radially) to the plasma, under somewhat higher radiation fluxes. In this case the water cooling for the DSC could be supplied via a manifold in the BSS that supplies inlet/outlet channels to the BB cooling circuit. Moreover, the DSC and the BB could have a circuit for cooling their own FW-SW. Here, sharing of the FW with the BB could be envisaged and be more easily achievable than for the second case. This would make the DSC fully attached to the BB.

In approach b) the BSS must be reduced in the toroidal direction, which implies a

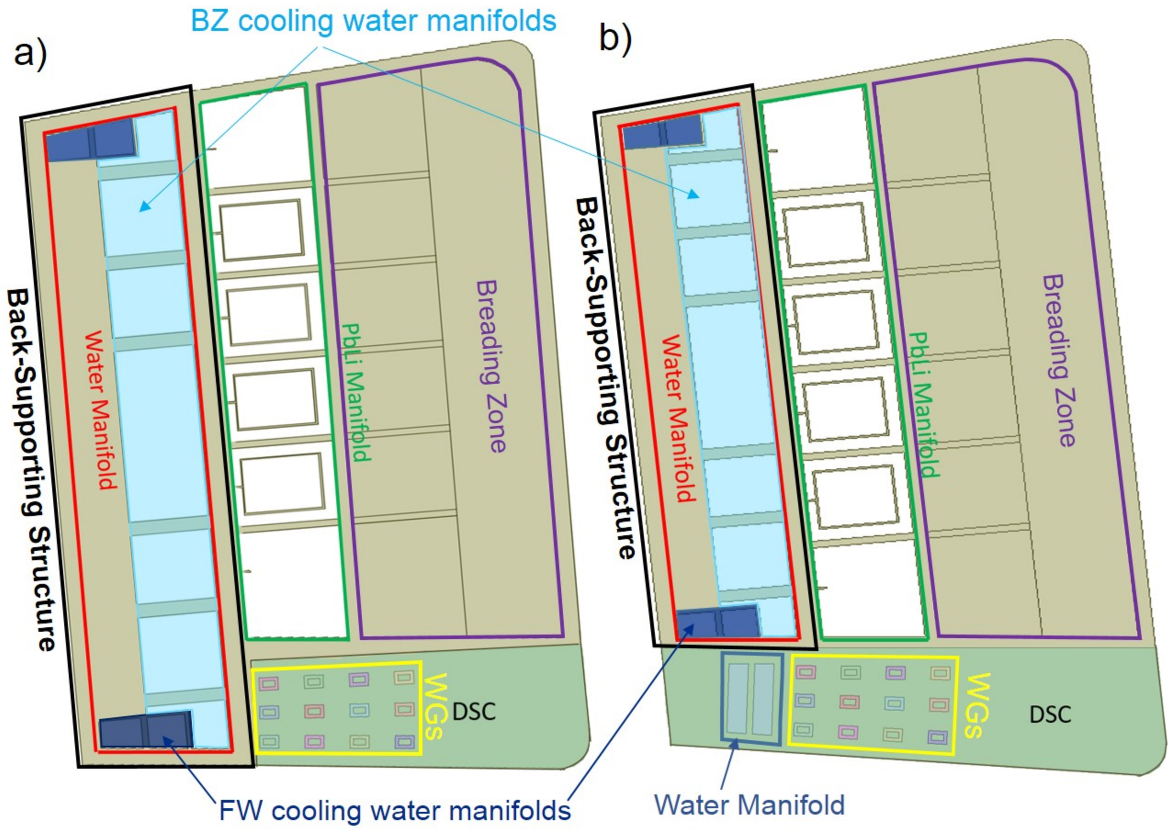

Figure 18. Two types of attachment between a WCLL blanket (light brown) and a DSC (light green), illustrated with an IB segment (cross section view): a) common BSS; b) DSC attached to the side of BB.

reduction of the BSS water manifold channels as well. In this case the WGs are placed further back (radially) than in the previous approach. Here, cooling of the DSC can be ensured by direct connection to the inlet/outlet channels of the BSS water manifold. In this case access of the DSC to the water channels might be easier. If water for cooling the FW and the shielding blocks of the DSC could be supplied via the BSS, this could free real-estate for the WGs to be more easily routed out of the "chimneys" of the UP.

Irrespective of the solution, the integration of the DSC will imply a re-design of at least part of the BSS water manifold, in addition to the design of the attachment between the BB and the DSC, to ensure that the two components are inserted and removed as one single component compatible with RH operations for installing or removing the BB segment. As stated above, a successful integration of the DSC in DEMO calls for a redesign of the WCLL BBs having in mind, from the outset, also the needs of the DSC in terms of cooling, in a process that should develop in close proximity with the owners of the various work packages involved. The subject of the DSC integration with the BBs will have to be studied in more detail in the future.

4.5. Integration with RH

The DSC is a maintainable component of the reactor, i.e., it is expected to be removed/exchanged during the lifetime of DEMO. Given that MW reflectometry is currently envisaged as the main backup solution for plasma control in case of failure of the magnetics diagnostic, failure of both systems would compromise equilibrium control. As such, even though redundancy is contemplated for both diagnostics, it shall be possible to replace the DSCs in case of failure. The DSCs are also expected to be exchanged during routine BB replacement, when the closest BB are removed or during an opportunistic maintenance operation on other BBs. Therefore, the integration of the DSC has RH needs—and may share the same procedures and tools already planned and designed for operations with the BBs [44]—namely the following, which are addressed in the next sections:

- Identification of the in-vessel RH needs, section 4.5.1;
- Identification of the RH tools available (Tricept) and the required interfaces, section 4.5.2;
- Pipe cutting/welding tools, section 4.5.3;
- Structural analysis of the DSC (a first estimate of the stability and deformation of the DSC), section 4.5.4;
- Sequence of procedures for DSC extraction and installation, section 4.5.5;
- Required space to perform the extraction and installation of the DSC, section 4.5.6; and
- Failure Mode, Effects and Criticality Analysis (FMECA) and risk assessment of RH operations with the DSC to identify, analyse and provide the means to mitigate risks, section 4.5.7.

As stated above, in order to fulfil RM requirements, the BB segments have to be separated by a 20 mm gap [36]. Yet, it should be pointed out that, according to [45], these 20 mm gaps are less than the expected deflections and manufacturing tolerances for such large components. Nevertheless, any RM tool that will handle the DSC shall be compliant with this gap between BB segments.

4.5.1. In-vessel remote handling needs of the DSC The maintenance operations of the DSC in-vessel, i.e., the operations of extraction and installation, have the following needs:

- Cutting and welding pipes (with WGs, cooling pipes, etc.);
- Removal and installation of the IB and OB segments of the DSC; and
- Lifting and ex-vessel transportation (both not in the scope of this work).

The removal and installation operations include the manoeuvring of components and the alignment and plug-in of the inboard and outboard DSC segments and "keystone". The operations of cutting/welding, removal and installation require RH tools, which are already designed for the maintenance of the BB. In-vessel operations of inspection, cleaning and calibration are not foreseen and, hence, no additional RH needs are required.

4.5.2. Transporter concepts Different concepts of blanket transporter systems were compared based on an evaluation criteria in references [36, 14]. It was found there that the two best approaches are the Hybrid Kinematic Mechanism (HKM) and the 6 Degree of Freedom (DoF) telescopic arm. Still, the HKM concept (a.k.a. Tricept) was selected in those studies for further development [15], given that the telescopic arm concept proved to be unworkable when subjected to a basic structural analysis.

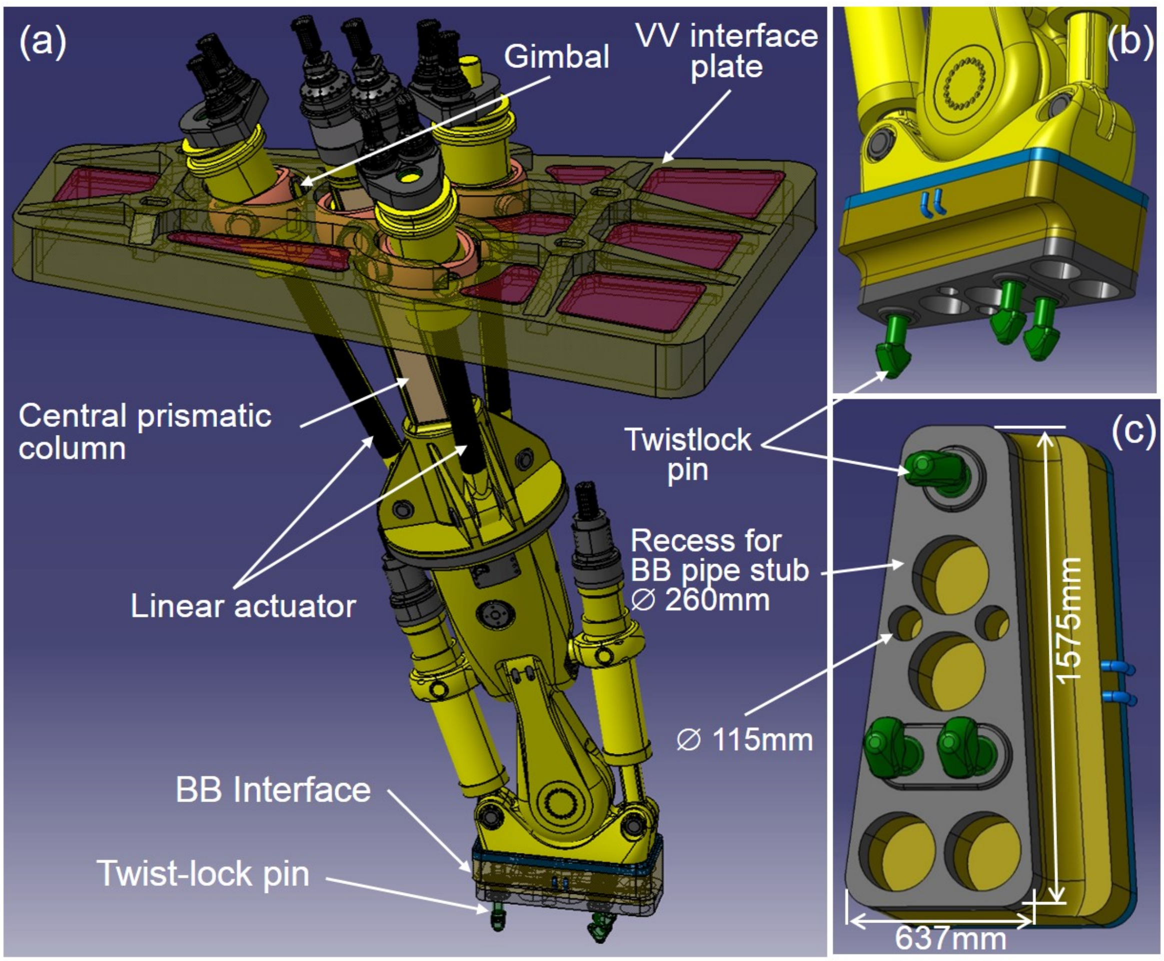

Figure 19. The HKM BB transporter concept (tricept) (CAD model from [46]).

As shown in figure 19 the HKM comprises 3 linear actuators attached around a central prismatic column. In the base of each of these actuators there is a gimbal arrangement built into the UP VV interface plate that enables free x-y rotation, but prevents rotation about z, whereas the central column provides support against any torque resulting from any load away from the axis of the column. The UP VV interface plate is a rigid frame that matches the shape of the UP itself and docks on to the UP flange. It can transmit the reaction loads from BB manoeuvres directly to the port and serves also as interface with the VTS, a crane-like system.

The design of the Tricept BB interface is based on using twistlock rotating connectors, widely used for a range of lifting interfaces, as in shipping containers. With the relatively small space available on the BB "chimneys" for the transporter interface, and having to share this space with the BB pipework, it is still possible to fit 3 twistlocks spaced as shown in figure 19.

This Tricept manipulator has been designed to handle the large and heavier in-vessel components, mainly the BB and pipe modules, as illustrated in figure 20, where it is shown docked to the UP while manipulating the ROBS using a 2014 DEMO baseline. The tricept has a height of ~10 m, and a total mass of ~70 t. Thus, considering BBs with a mass of ~80 t, the VTS—which deploys the tricept—must be capable of operating with a ~150 t payload.

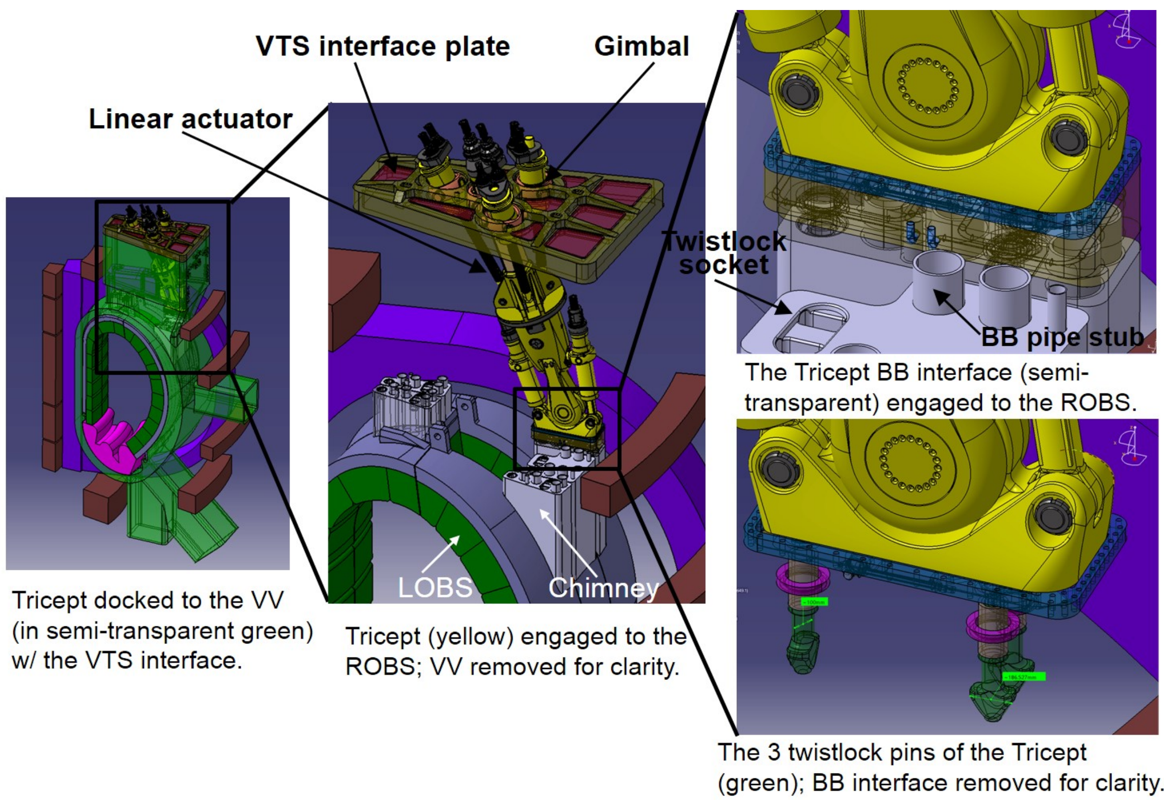

Figure 20. The HKM BB transporter concept (tricept) docked to the UP while manipulating the ROBS (2014 DEMO baseline) (CAD model from [46]).

Additional RH tools were developed for the UP RM deployment system. One of them is based on the telescopic mast concept that provides a deployment point for remote maintenance equipment, which has at least some degree of lateral stiffness [9]. The depth of the port implies that, if the mast is to extend sufficiently, it will most likely have to consist of at least 3 telescoping sections. This is so that, once retracted sufficiently to allow the longest hardware (the pipe modules) to be extracted over the bioshield floor, the overall height of the mast and load is not taller than an OB blanket segment with its transporter (some 18 m), as this is anticipated to be the tallest single lift and hence drive the height of the tokamak building roof. A large supporting structure with toroidal motion capability (but fixed into a datum toroidal position before deploying the mast, without moving while the mast is in use) and the ability to translate the mast radially is required in the confinement cell.

Another RH tool concept which was developed is based on a robot arm dexterous manipulator, and uses wall-mounted rails attached to the UP walls to allow the RM equipment to vertically translate down discrete radial/toroidal positions [9]. It could enable tasks to be performed simultaneously in different areas of the port, reducing maintenance time. However, the RH operations with these two tools (telescopic mast and robot arm on wall-mounted rails) are not addressed here.

4.5.3. Pipe cutting/welding tools The pipes that group the WGs (section 4.3) will have to be cut from the DSC. Yet, the SJS in-bore laser cutting/welding tools developed for the breeding and cooling pipework (section 2.2.1) cannot be used here, given that the cutting/welding task must be performed by tools that operate externally to the WG pipes.

Such a system has been developed specifically for cutting/welding the DN200 (water) cooling pipes of the Neutral Beam systems in ITER [47, 48]. It comprises a set of three tools: a cut tool with a lathe based mechanical cutting; a weld tool, based on Tungsten Inert Gas (TIG) arc welding; and an alignment tool, which is used also to support and position the weld tool. This welding tool has a space requirement of 3× the diameter of the DN200 pipe, with an additional (external) access zone of 600 mm, requiring 4 m^2 for four DN200 pipes. In contrast, the DEMO SJS in-bore laser cutting/welding tool needs 0.4× the diameter of the same DN200 pipes—and no external access zone—, requiring just 0.6 m^2 for four DN200 pipes [10].

Cutting/welding tools that operate externally to the pipes have also been considered in a review for the pipework in the Vertical Pipe Chutes for DEMO Ex-Vessel RM Systems [49] (Appendix D). In this study a keep-out space has been established based on the dimensions of the largest tools that require access to the pipework when fitted to the pipework. The results show that, at least for the IB section of the DSC, where space is a premium, the task of cutting/welding these WG pipes will be hard to achieve, as these tools require a quite generous keep out diameter. Unless this task would be left for after the fluid pipes have been cut and removed, so as to make room for these tools to work. But, in that case, the WG pipes would have to be cut at a level above the cutting of the fluid pipes and, in addition, the WG pipes and the fluid pipes would have to be grouped into two independent pipe modules that would be handled separately: first the fluids pipe module, then the WGs pipe module. However, this would go against the conclusion above that the pipes for the BB and DSC ought to be grouped into a single pipe module.

Note that, for the SJS in-bore laser cutting/welding tool the pipes that carry the

Table 2. Maximum deformations [mm] for the DSC on fixed support by 2 and 3 contact points.

	Max. deformations [mm]	
	2 CP	3 CP
Inboard	1.12	0.99
Outboard	2.10	1.87

BBs fluids, which are essentially hollow—besides a more or less thin wall that has to be fully cut—must be provided with appropriate cuffs on the two sections to be cut which, when mated, create a cavity that traps the debris resulting from in-bore cutting/welding, preventing this waste from entering the Tokamak [10] (which adds to constrain the space around them). However, the pipe concept presented in figure 16 to group the WGs, which is very preliminary, is not that hollow and could present its own challenges to cut/weld, e.g.: how to deploy the tools; how to protect debris resulting from cutting/welding to end up falling inside the machine; how to avoid jamming the socket from cutting/welding.

It should be highlighted that no concept has been developed yet for the interface of the DSC cooling with the ex-vessel, which could add to overcrowding even more the reduced space in the "chimneys", unless the cooling is shared with the BB cooling.

4.5.4. Preliminary structural analysis of the DSC A preliminary structural analysis was performed to provide a first estimate of the stability and deformation that might happen during RH operations, if the DSC has to be manipulated independently from the blanket at some point. The analysis considers the DSC as an independent slim cassette (presented in section 3.3), the Tricept as the RH tool, and the dimension of the DSC as the dimension constraint to consider all possibilities of RH manoeuvre needed for the DSC. The boundary conditions considered for the analysis are:

- 2 contact points (CP) and 3 CP (like in the Tricept manipulator), as shown in figure 21;
- Fixed support applied to each contact point (to model the RH operation);
- Standard earth gravity acceleration applied to each component.

The results for the total deformations along the DSC on fixed support by 2 CPs and 3 CPs are depicted in figure 22, whereas the corresponding maximum deformations are presented in table 2. Noting that the OB section of the DSC is a 12 m long component, a maximum deformation of 2.1 mm can be considered negligible, which means that the DSC is able to sustain its own weight. The results in figure 22 represent the deformation that might arise during RH of the DSC, which should occur in the elastic region of the EUROFER stress-strain diagram. In this region, the deformation will revert back to normal after the load (the deadweight of the DSC) is released (i.e. when the DSC is in its support position attached to the VV). Furthermore, assuming

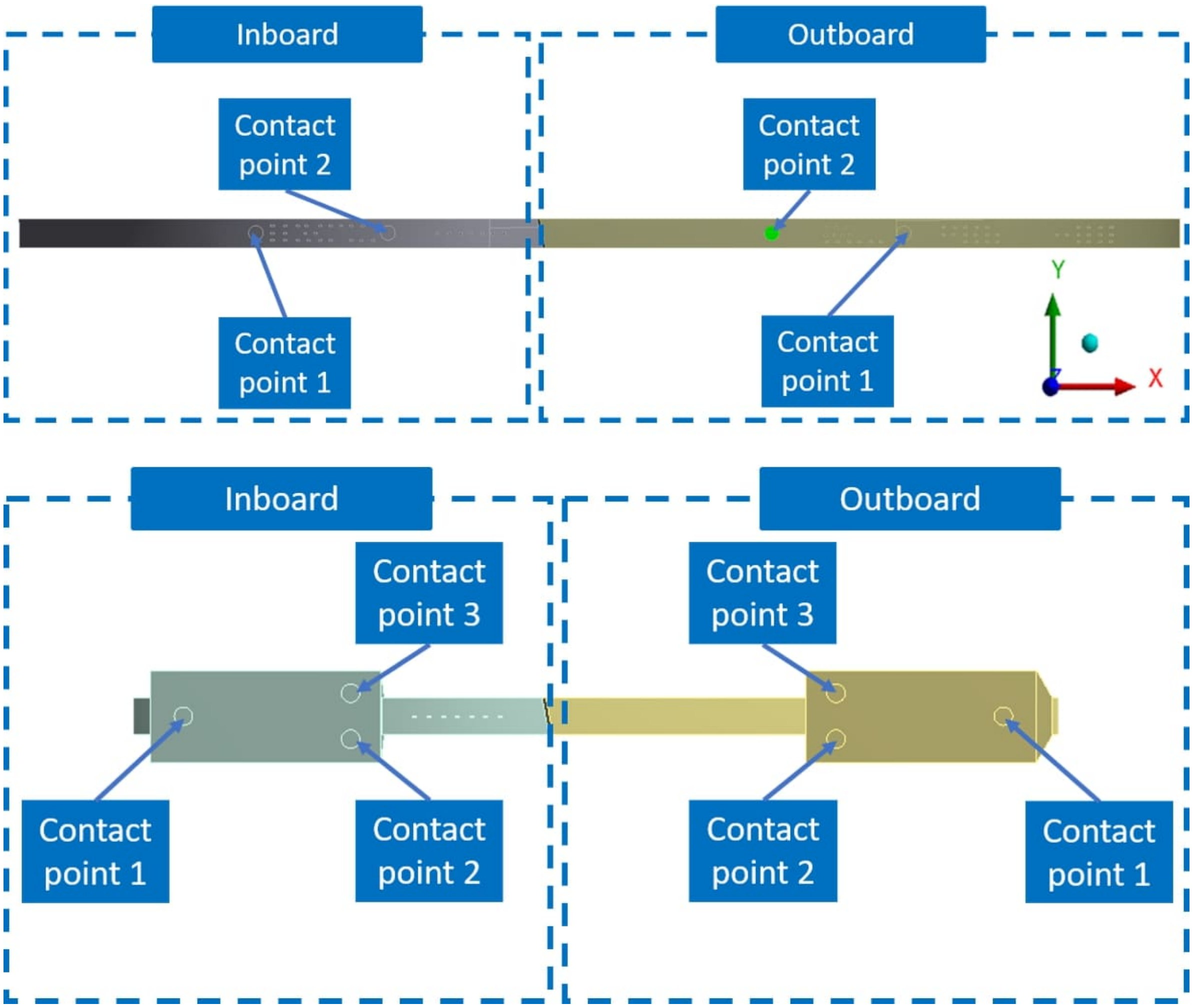

Figure 21. Position of the contact points used in the preliminary structural assessment of the DSC (top view): using two contact points (above) and using three contact points as in the tricept manipulator (below) from the Z+ point of view.

Table 3. Moments [N m] for the DSC on fixed support by 2 contact points.

		Moments [N m]		
		X-axis	Y-axis	Z-axis
Inboard				
	CP 1	−332.48	1030.90	30.78
	CP 2	−80.14	1148.00	−0.49
Outboard				
	CP 1	35.14	−37.62	−12.12
	CP 2	5.76	121.79	−2.55

that the gap between neighbouring BB segments to enable installation is 20 mm [14], this means that the 2.1 mm deformation of the DSC will not make an immediate contact with other IVCs. The resulting moments for the DSC on fixed support by 2 CPs and 3

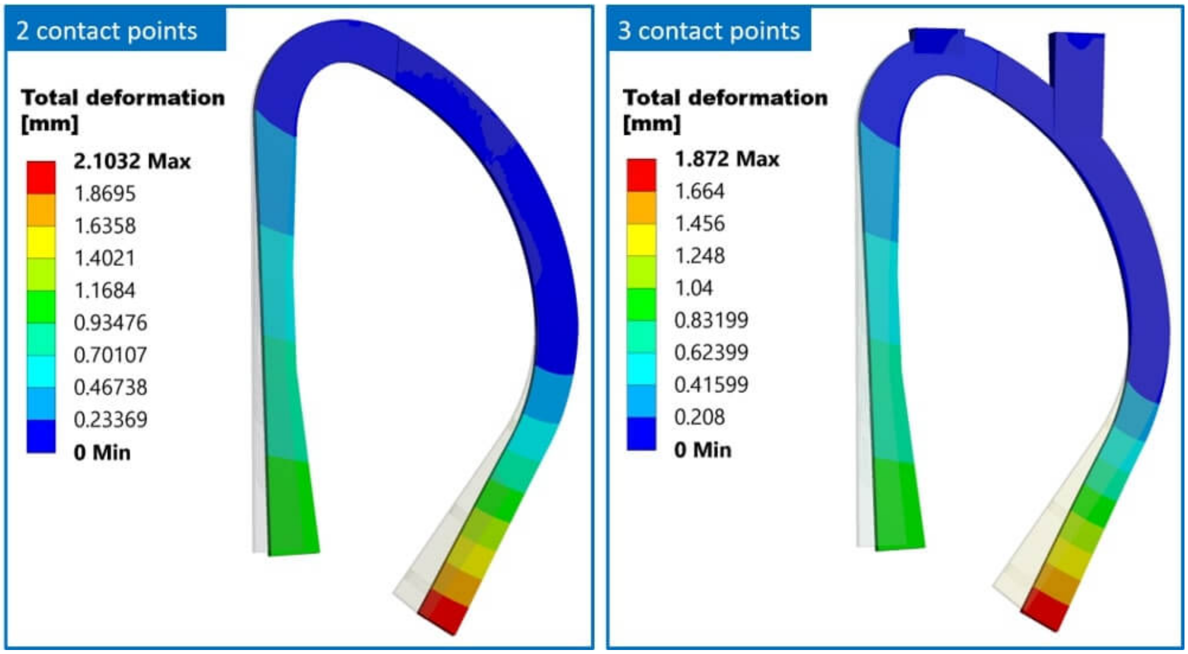

Figure 22. Deformation (mm) for the DSC on fixed support by 2 and 3 contact points, scale: 500 (see figure 21).

Table 4. Moments [N m] for the DSC on fixed support by 3 contact points.

		Moments [N m]		
		X-axis	Y-axis	Z-axis
Inboard				
	CP 1	−101.96	733.69	20.50
	CP 2	−1.20	955.11	31.32
	CP 3	23.08	910.18	−21.54
Outboard				
	CP 1	−7.24	−232.75	2.66
	CP 2	−41.66	−390.68	−19.35
	CP 3	16.77	−396.06	25.03

CPs are summarized in table 3 and table 4, respectively. These results show that even for the 3 CPs—which are distributed in the radial-toroidal direction to minimize the moment—, there will be instability caused by the asymmetries of the DSC geometry, in which the 16 clusters of antennas and the respective WGs are distributed in different planes in the toroidal direction (see section 3.3 and figure 10).

For the 3 CPs the results show that the DSC has more stability and smaller deformation. Yet, the downside of this concept is the need of additional area for both the RH interface and the supporting modules in the UP, which is unlikely to be granted. In the case of the 2 CPs, even if the DSC does not need additional space for the RH interface, the support modules will still ask for additional space. Moreover, the 2 CPs DSC needs a different (non-standardized) end-effector. Thus, in summary, these results are unfavorable to the concept of a DSC independent of the blanket.

4.5.5. Sequence of procedures to extract and install the DSC According to [9], the "keystone" neutron shield needs to be removed through the UP before the removal of the blanket modules and, consequently, of the DSC. Therefore, the "keystone" part of the DSC is assumed to be integrated with the neutron shield and follow the same procedures of the neutron shield removal.

The WGs extension of the DSC shall be integrated with the existing pipe modules of the BB, especially at the IB side. As such, the procedure of extraction and installation of the IB DSC will follow the procedures of the extraction and installation of the IB BB. For the OB, the possibility of independent pipe modules on the OB is not yet ruled out and is considered in this section.

Assuming the WGs extension concept for the OB presented in figure 17, the support module is divided into two sections: the vertical WGs extension and the horizontal WGs extension. In this case an alignment feature such as the pin/hole arrangement depicted in figure 15 would only be used to connect the vertical section of the WGs extension to the BB "chimneys", whereas to connect the vertical to the horizontal WGs extension it could be envisaged, for instance, a MPC (as shown in figure 4), and the two sections joined following the pipe modules concept—a customized end-effector to interface with the RH tool for the manipulations of these items would have to be developed, as well as the RH procedures. The procedures for removal of the vertical WGs extension, shown in figure 23, are:

(1) the tricept (assumed as the RH tool) approaches the WG module and stops above the WG module;

(2) the tricept is lowered into the WG module RM interface;

(3) the twistlock pins on the tricept are rotated to secure the connection between the tricept and the WG module;

(4) (5) (6) the tricept is lifted in the vertical direction, removing the WG module;

(7) the RH tool transports the WG module to the hot cell.

It is assumed that the horizontal WG extensions are fixed to the VV. If not, then, similar to the vertical WG extension removal, the horizontal part of the WG extension could be removed using the tricept as the main RH tool. In this case the sequence of actions to remove it, shown in figure 24, are:

(1) the tricept approaches the WG module and stops above the WG module;

(2) the tricept is lowered into the WG module RM interface;

(3) the tricept twistlock pins are rotated to secure the connection between the tricept and the WG module;

(4) the tricept manoeuvres the WG module on the horizontal direction to remove the extension module completely (assuming the permanent WG connectors are outside the UP, which may not be the case);

(5) (6) the tricept is lifted in the vertical direction, removing the WG module;

(7) the RH tool transports the WG module to the hot cell.

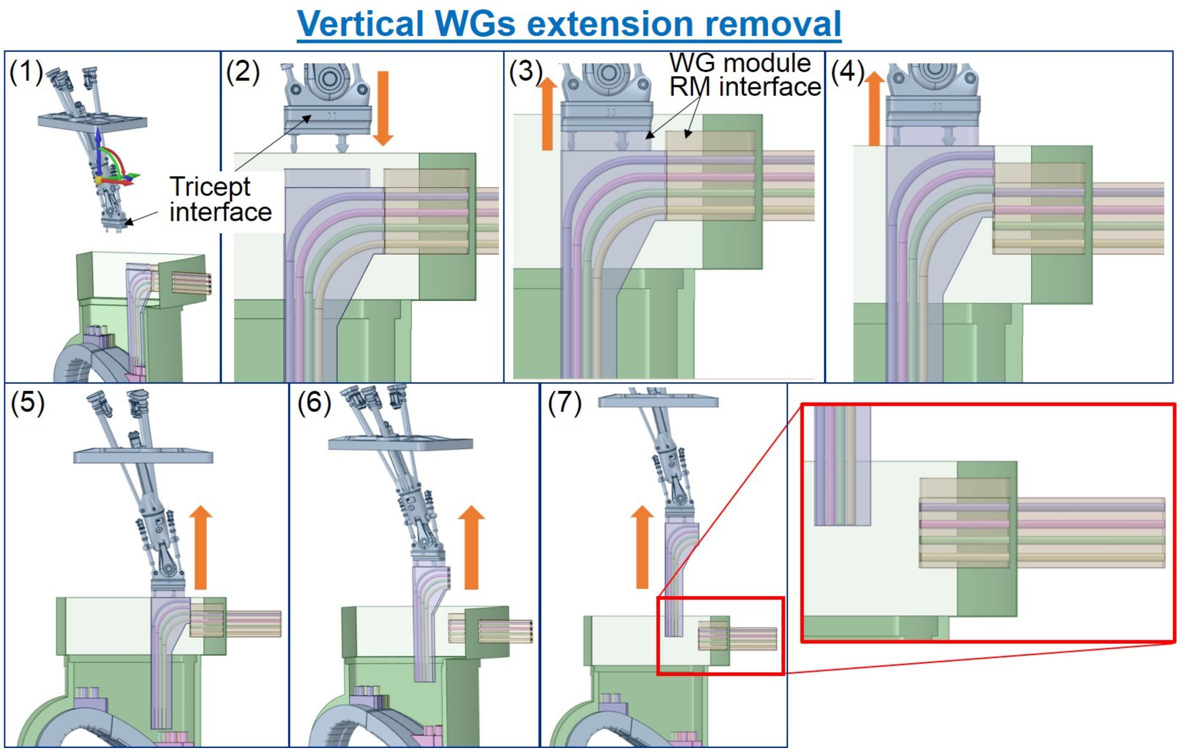

Figure 23. Possible removal sequence of the OB vertical WG extension of the DSC.

4.5.6. Required space to remove/install the DSC Since the DSC is designed with the same baseline geometry of the blanket, the space required for the DSC is compliant with the space required for the maintenance of the BB, given that the DSC inboard and outboard sections (independent or attached to the blanket) do not exceed the envelope of the RIBS and COBS, respectively.

The difference is in the "chimneys", as the DSC interface connector will require the allocation of some space and the existing "chimneys" do not take the diagnostics interface into account. The interfaces proposed here are the 154 mm diameter cylindrical pipes, presented in figure 16. Though a concept for these interfaces is presented, further discussions with the WPBB and WPRM work packages are required to define it. Note that the space required for the support structure of the interfaces in the vertical direction will have to follow the space required for the pipe modules, i.e., the interface shall be integrated into the pipe module.

There is an additional concern related to the available space on the IB, as even before the integration of the WG extensions in the UP it did not allow the installation and removal of the IB blanket pipe modules. The space between the neighbouring UP has been suggested as a viable space to expand into [9], as shown in figure 25.

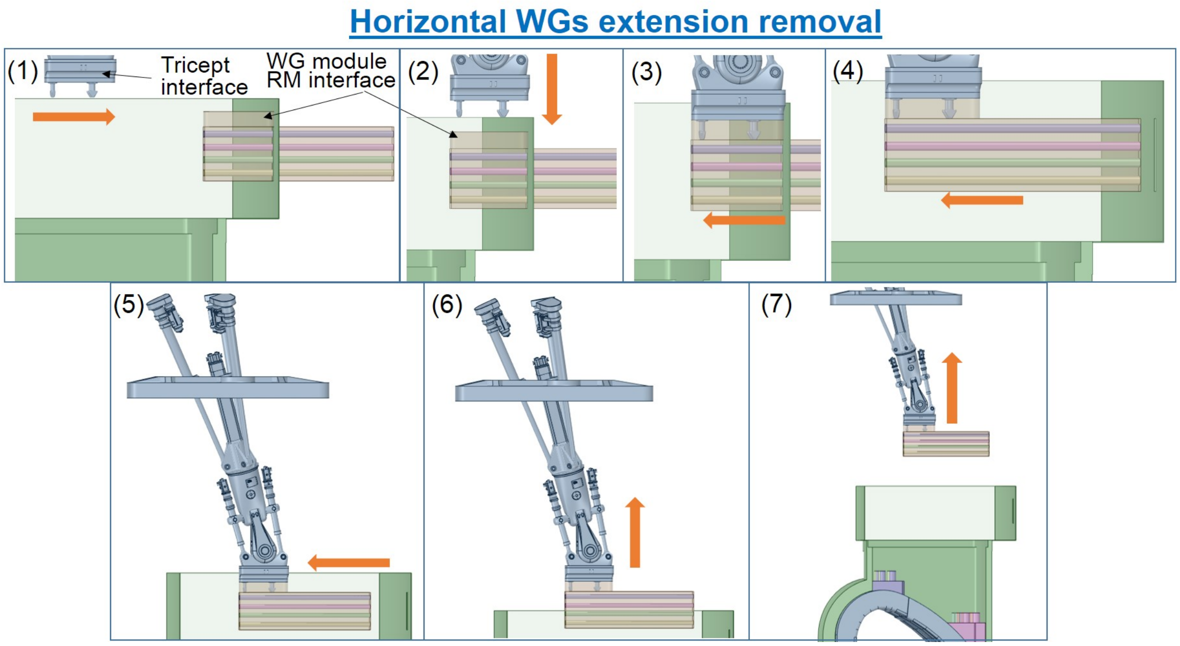

Figure 24. Possible removal sequence of the OB horizontal WG extension of the DSC if not fixed to the VV.

4.5.7. FMECA and risk assessment of RH operations with the DSC FMECA is a methodology to identify, analyse and provide the means to avoid the failures, and/or mitigate the effects of the failures on the system. A preliminary FMECA of the RH operations with the DSC was carried out based on the occurrence (O) and severity (S) ratings of failures, which are considered herein with three levels: low (L), middle (M) and high (H) [50]. Table 5 presents the identified failure modes of RH operations with the DSC, and the respective O and S before and after the mitigation actions.

The risks with high criticality levels are related to the drop and clash during the lift operations of the DSC parts and other components in the vicinity of the DSC. It should be pointed that the damage caused by the contact/clash of equipment is assumed not affecting the structure and, hence, the equipment can still be removed for ex-vessel repair, whereas in the case of dropping the structure may be affected and, ultimately, compromise all the Remote Handling extraction operations. Therefore, in table 5 the severity of the damage caused by contact/clash is considered lower than that caused by dropping. These types of risks are also present in the extraction operations of the blankets or other components; thus, similar mitigation actions can be used. For instance, electrical winches installed on the structure of the building, outside the vessel, and wires/cables/chains connected to the target load to mitigate the risk of dropping loads and guidance system to avoid clashes [51]. Further work is required to extend the FMECA with more detailed and quantified ratings levels, such as the ones adopted in ITER Reliability, Availability, Maintainability, Inspectability (RAMI) [52].

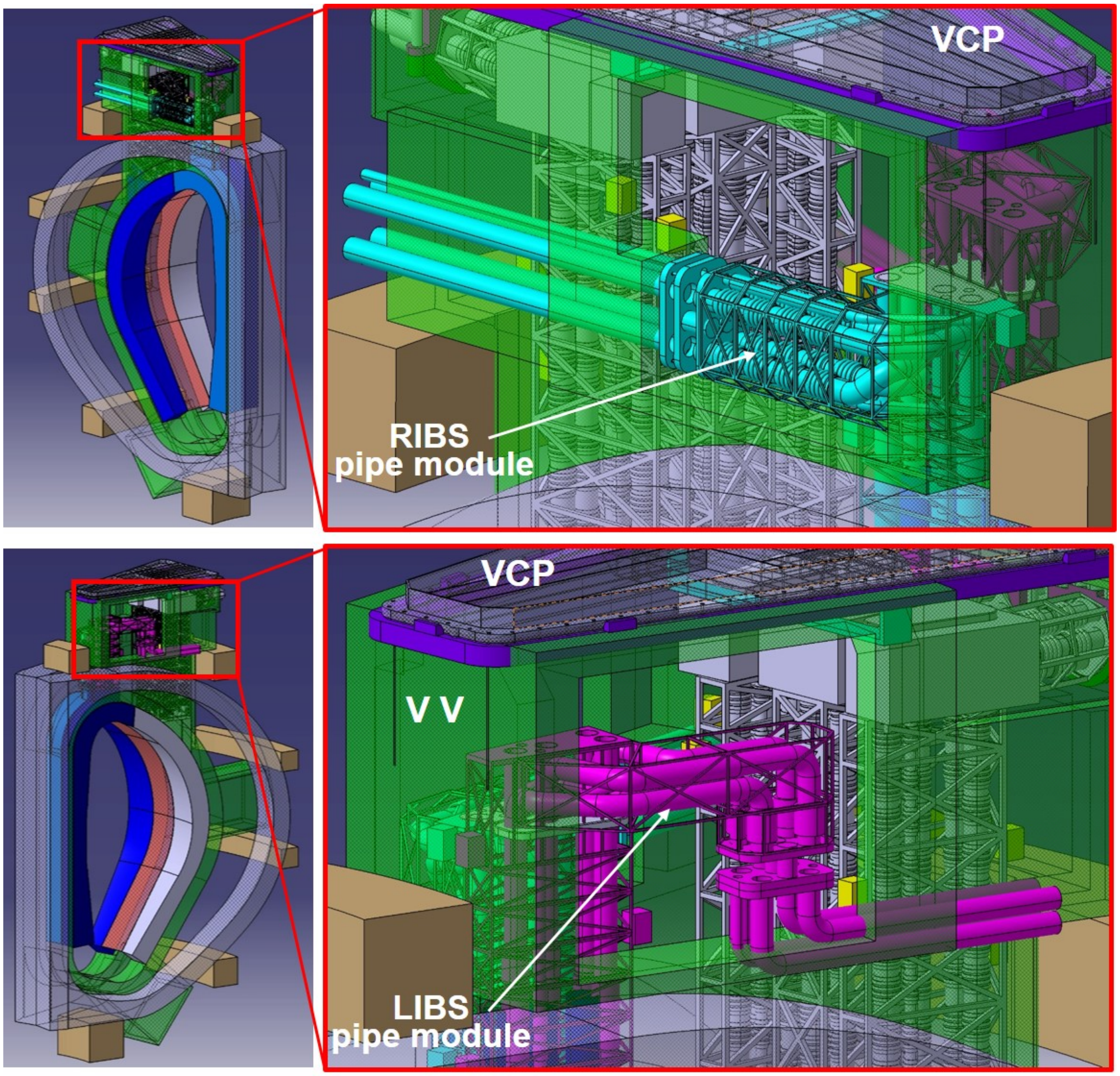

Figure 25. Space between the neighbouring UP to expand into both inboard pipe modules (CAD model from [6]).

4.5.8. FMECA open issues The FMECA presented above is a first iteration, where some failure modes were not addressed. For instance, the possible failure resulting from the difficulty to remove DSC parts caused by seismic conditions, requires further studies related to the oscillation of the DSC and the respective interfaces.

4.6. Recovery and rescue

In case of a failure, the current operation must be interrupted and the following situations may occur: i) resume the current operation if possible, ii) start another planned operation, iii) start a recovery operation or, in the worst situation, iv) start a rescue operation. In the first three cases, no additional equipment is required. In the last one, additional RM systems are required to support the (rescue) operation.

Table 5. Preliminary FMECA for RH operations with the DSC.

Possible failures	Before mitigation		Possible mitigation actions	After mitigation	
	O	S		O	S
Risk of dropping any part of DSC or other element with impact to DSC during the lift operations.	H	H	This risk exists in all lifting loads in-vessel and during ex-vessel transportation along galleries. Mitigation could follow [51]: use electrical winches installed on the building, outside the VV, and wires/cables/chains connected to load.	L	H
Risk of clash with DSC: 1) during removal/installation of a DSC part; 2) during removal/installation of another component in the vicinity of a DSC part.	H	M	Risk also during removal/installation of in-vessel components with a high and heavy profile, mainly the BBs [9, 45]. Thus, mitigation used for BBs can also be used for DSC: increase precision of RH manipulator (e.g. tricept) and/or integrate guidance tools to avoid risk of clash.	L	M
Risk of misalignment of DSC parts during installation caused by precision of RH tools and swinging with heavy parts.	M	M	Design update in the DSC and in surrounding parts to include guidance structures, such as guidance pins, dowelling arrangements and flanges.	L	L
Failure of RH tools during operations with the DSC.	M	M	Mitigation used for risk of dropping loads can be adopted, and the DSC shall be moved to a safe configuration. During non-lift operations RH tools can be removed and replaced by another similar RH tool.	M	L
Difficulty to remove DSC parts due to thermal changes	M	M	New studies must evaluate if compensation is required to accommodate thermal expansion of DSC + BBs + pipes + pipe module. Increasing space for compensation decreases occurrence and severity.	L	L

The planned operations, which are the extraction/installation and transportation, were already addressed in section 4.5.5. The recovery and rescue operations must be planned to take into account all the possible failure situations. In the particular case of rescue operations, it is necessary to identify the additional RM systems and the impact in the design of the DSC to accommodate possible additional anchor points for handling and manoeuvring.

4.7. Blanket attachment concept (blanket support structure)

As already pointed above (section 2.5.2) the BBs will need an attachment to the VV. This attachment should satisfy various requirements, among them: (1) provide a sufficiently precise positioning of the BB; (2) withstand all relevant loading conditions; (3) be compatible with the BB removal kinematics; and (4) be suitable for engagement and release by RH tools.

Attachment systems have been designed for DEMO around the concept of keys that interact with a purposely designed counterpart, the housing, in which the keys are set in various places on the blanket BSS, whereas the corresponding housings are placed on the VV [53, 54]. More recently, a concept for the BB attachment has been developed taking advantage of the ferromagnetic force that acts on the ferromagnetic BB material EUROFER, caused by the radial decay of the toroidal magnetic field, which pulls each BB towards the inboard with a large radial force [55]. This concept relies on a set of vertical, toroidal and radial supports (see [56] and [57]), and is claimed to result in a significant reduction of in-vessel design complexity and RH operations. Figure 26 depicts this concept, where it is illustrated with the 200 mm wide DSC (in pink). Note that, as this figure shows, these supports will have an impact on the design of the DSC, given that they are located on the back of the IB and OB sections of the DSC. Therefore, this is another issue that must be taken into account for a successful integration of the DSC in DEMO, in a process that should develop in close proximity with the owners of the work packages involved.

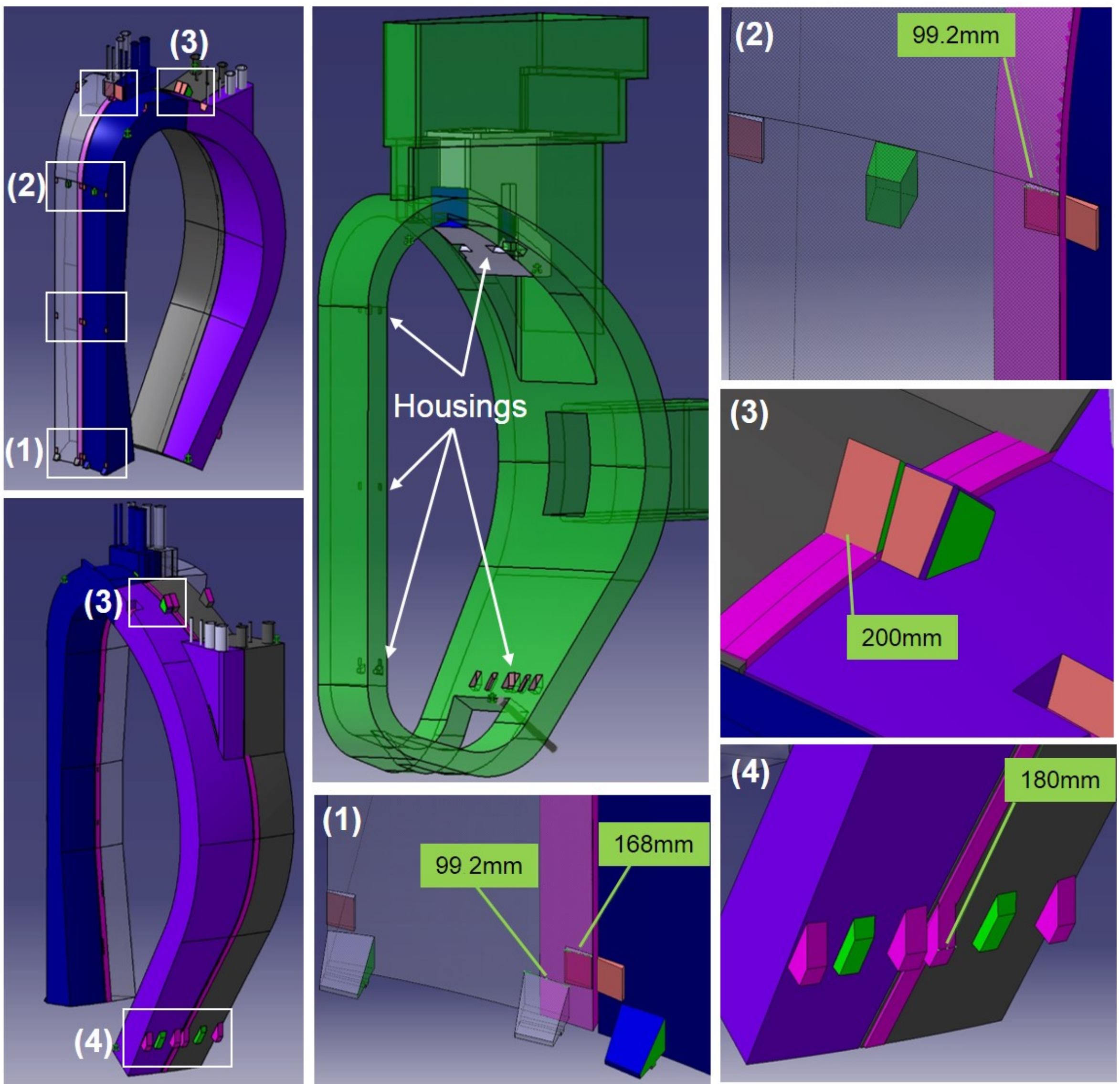

Figure 26. BB support structure concept with keys on the BB and housings on the VV, where the width of the keys is compared with that of the DSC (depicted in pink) in detailed views of the 4 key regions numbered on the left figures (CAD model from [58]).

5. Conclusions

A MW reflectometry diagnostic system for DEMO is being developed with the ability to provide much needed electron density information with high spatial and temporal resolutions. It has a twofold objective: i) to provide the radial edge density profile at several poloidal angles and ii) to provide data for the feedback control for plasma position and shape, acting as a backup for the magnetics—the main tool for plasma behaviour real-time monitoring in DEMO.

Its primary integration approach is based on the DSC, a concept using a dedicated poloidal section that is to be integrated with the BB segments considered in this work, the WCLL. With a thickness of 20 cm to 25 cm in the toroidal direction, this DSC is envisaged to contain up to 100 antennas, distributed in clusters at 16 locations (gaps) and arranged vertically in each gap. Presently, 2 DSCs are foreseen for MW reflectometry—and 4 for magnetics if the DSC is chosen to host the magnetics sensors—, although their toroidal locations are not yet defined, except for the condition that in the UPs with a limiter there will be no DSC.

The DSC is assumed to be removed and installed from the UP, through which the maintenance of the BBs segments (5 per UP/sector: the RIBS, LIBS, ROBS, COBS, and LOBS) will be also carried out. Taking into account the RM operations required for the BBs and the space available in the UPs the possible locations of the DSC relative to the BB segments were studied in detail. From six possible combinations, the one with the most advantages from the RM point of view foresees a DSC no longer aligned in the same poloidal plane but in two different vertical planes: inserted to the left wall of the LIBS and COBS. With the DSC handled attached to the BB, this configuration would still allow the removal of the OB section of the DSC in the first removal operation (that of the COBS) and the removal of the IB section of the DSC with the LIBS and LOBS still in place. Thus, the removal of the full DSC would involve operations with only 3 of the 5 BB segments. It is important to underline that this toroidal misalignment between the IB and OB sections of the DSC would not compromise the performance of the diagnostics.

Regarding the integration of the DSC within the WCLL blankets, and with a fully independent DSC option facing numerous difficulties—including the need for independent pipe modules in the UP, which would be virtually impossible at the IB (due to lack of space); the need to develop a non-standardized end-effector for RH manipulation; and routing of the DSC pipes through the already overcrowded BB "chimneys" in the UP—the two remaining approaches are: the DSC is attached in front of the BSS (BB and DSC share a common BSS); and the DSC is attached to the side of the BB. These approaches shall be studied in more detail in the near future, in close collaboration with the WPBB work package.

Considerations related to the BB pipe modules in the UP, as well as the neutron shield plugs and the ULs lead to the division of the DSC into three parts: i) the IB section (high-field side), ii) the OB section (low-field side) and iii) the "keystone". As the DSC WGs are expected to be routed through the BB "chimneys" to the UP, a conceptual design of an interface between the DSC and the UP is proposed, in which several WGs are grouped inside pipes with 154 mm of diameter. These pipes are designed to be routed through the "chimneys" and integrated with the pipe modules of the BB.

The sequence of procedures to extract and install the DSC were evaluated considering the existing pipe modules of the BBs, mainly for the IB, and the procedures for the extraction and installation of the BBs. The required space to perform the extraction and re-installation of the DSC (IB and OB sections and interfaces) was evaluated and shown to be compliant with the space already defined for the maintenance of the BBs, i.e., the DSC IB and OB sections (whether independent or attached to the BB) do not exceed the envelope of a RIBS/LIBS and COBS, respectively. The space required for the interface in the "chimneys" is not defined yet and needs more discussion with the WPBB team.

A preliminary FMECA analysis of RH operations was performed for the DSC, including the identification of potential failure modes, the effects these failures may have on the system and how to avoid the failures and/or mitigate the effects of those failures on the system. The risks with high criticality levels are related to the drop and clash during the lift operations of DSC parts and other components in the vicinity of the DSC. Mitigation actions may include, for instance, electrical winches installed on the structure of the building, outside the VV, and wires/cables/chains connected to the target load and guidance systems to avoid clashes.

The concepts presented here are subject to many uncertainties arising from the different design stages of each DEMO component. Among these, the CAD models for the "chimneys" in the WCLL BBs and for the pipe modules in the UPs have the largest impact on the assumptions made throughout. Nevertheless, most of the concepts discussed here can be adapted to different BB and UP configurations.

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