UKAEA-RACE-PR(21)03

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This is a preprint of a paper submitted for publication in
Fusion Engineering and Design

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DEMO is a key part of the EU fusion roadmap, where the programme is reaching the end of the pre-conceptual phase with a gate review in 2020. As part of the work to complete this phase, eight Key Design Integration Issues (KDIIs) have been identified as critical to the programme [1]. Within KDII#1 (Wall protection to withstand plasma transients) the feasibility of the Inner Mid-plane Limiter (IML) is assessed from a remote maintenance perspective.

The IML is an actively cooled component attached to the inner ring of the tokamak torus, with access for removal and installation only possible from the plasma facing side. The IML service life is less than that of the Breeder Blankets (BBs), due to the foreseen transients and/or the CuCrZr cooling pipes that have limited irradiation lifetime. This drives the need to change the IML with the BB in position. When replacing the IML, the pipework is expected to be too highly irradiated to allow re-welding. This drives the need to change the pipework to the IML, a challenging task when the BB are in their installed position.

This paper presents the preliminary development of a maintainable IML concept, including: the development of the IML fastening for remote maintenance; a proposal for a new IML cooling pipe chute; and the rationale for the options selected.

Keywords: DEMO, Limiter, Remote maintenance.

1. Introduction

The replacement of the BB segments will require a considerable maintenance campaign. There is a risk that the blanket modules can be damaged by the plasma in transient events. The Single Null (SN) with discrete limiters concept intends to protect the breeder blanket front wall from all foreseeable normal and off-normal plasma transient events via a limited number of discrete high heat flux components. The purpose of the IML is to protect the breeder blanket front wall against off-normal events characterised by an uncontrollable “loss of confinement”. The position of these limiters can be seen in figure 1-1 where item 3 is the IML.

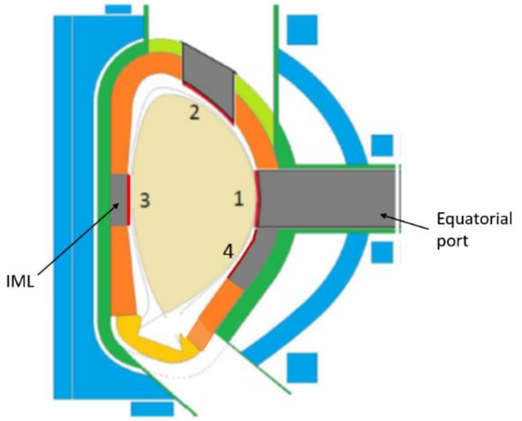

Figure 1-1: Schematic view of the Single Null EU DEMO indicating the positions which the limiters occupy [2]

Four of the IMLs are intended to be located on the inner ring of the torus, at the tokamak vertical mid-plane, allowing maintenance radially through the associated equatorial port. The maintenance approach is simply depicted in figure 1-2. The End Effector (EE) is supported by a straight first link and physically connects to the IML.

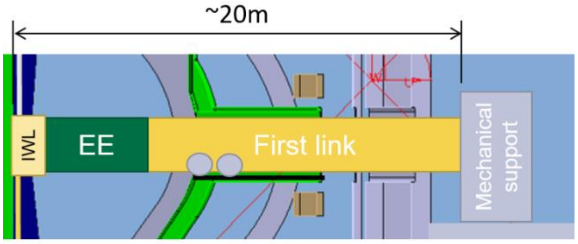

Figure 1-2: Diagram showing the IML and the intended maintenance equipment approach through the equatorial port

This paper provides a summary of the development of a remote maintainable IML. This has involved the concept design of the limiter itself, its pipework, and the Remote Maintenance Equipment (RME). The work required in the short-term future is also noted.

2. Limiter concept development

The concept development of the IML has been performed through a very close collaboration between component and remote maintenance engineers. This close collaboration was essential to produce a feasible concept for a remote maintainable IML due to the significant design challenges faced.

Several key design considerations were taken into account. Firstly, the differential thermal expansion of the surrounding breeder blankets to the limiter, which when mounted directly to the Vacuum Vessel (VV) sees an estimated change in blanket clearance of 28mm between plant shutdown and tokamak operations; and 92mm between plant shutdown and a Loss Of Coolant Accident (LOCA) in a BB. As shown in figure 2-1.

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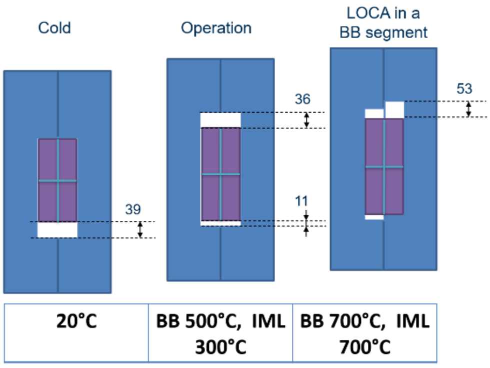

Figure 2-1: IML and BB varying clearances with temperature (view towards the tokamak centre)

Secondly, the restricted access to the IML is considered, as this is only possible from the front surface of the limiter which is plasma facing, and hence has the potential to be damaged during a plasma transient event. The interface to the RME needs to ensure a successful physical connection is possible following a transient event, hence it needs to be resistant to damage.

Thirdly, the IML is expected to require maintenance more frequently than the BBs, removing / installing the IML with the BBs in situ reduces the IML surfaces which can be used to connect to the RME.

Finally, significant compressive loads and bending moments that are placed upon the limiter during operation and H-L transition events are considered.

The use of bolted joints is assumed to not be acceptable due to irradiation and subsequent loss of preload, as well as the likelihood of seizure. It is also assumed that the IML will be changed approximately every two full power years, which is a similar replacement frequency as the DEMO divertor cassettes.

Several workshop meetings were held in which ideas for the IML attachment to the VV and RME were discussed and many initial sketches were produced. These initial sketches were rationalised based upon their technical feasibility and three concepts were developed.

Concept A can be seen in Figure 2-3. The limiter is divided into two main components, a large component (shown in light blue) which is physically fastened to the VV wall (shown in green) through the use of four components (shown in dark blue) which feature short pipe sections which can be welded from within the pipe bore. These components are held within pockets on the VV wall and are removable, in order to prevent the need to re-weld irradiated material. An example of a in-bore pipe welding tool can be seen in figure 2-2.

Figure 2-2: DEMO in-bore laser welding tool

The large forces placed upon the limiter are transferred to the VV wall through two horizontal and two vertical shear keys, while the large moments applied are transferred through the mounting pads with a small amount of assistance from the in-bore welded components. A plasma facing component is fastened to the main component through the use of a single in-bore welded location. The RME access to the single central connection can be protected somewhat from plasma strike damage by shaping the plasma facing surface to shield this entrance point. The horizontal shear keys are close fitting in the vertical direction, and have clearance to the VV interface in the horizontal direction (the opposite is true for the vertical shear keys).

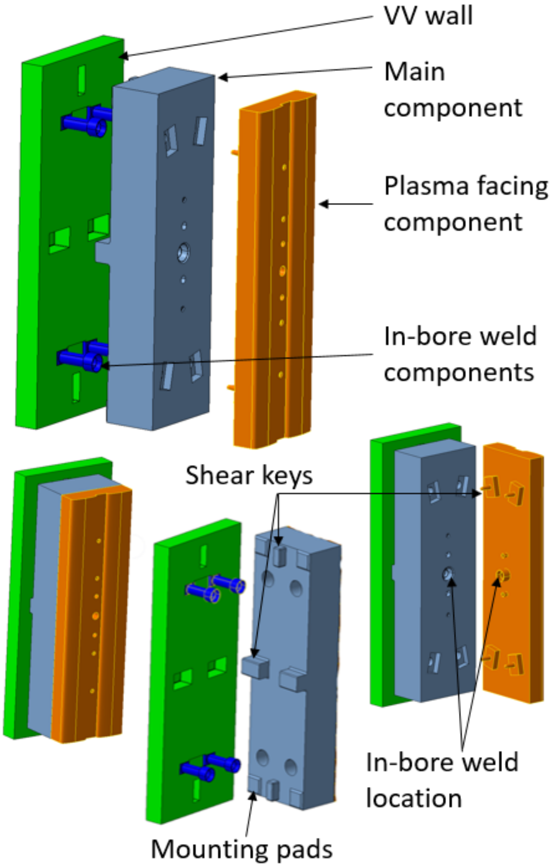

Figure 2-3: Concept A – Two-piece limiter

Concept B can be seen in figure 2-4. This simplified design has only one main limiter component. Shear keys and mounting pads to transfer mechanical loads to the VV are used, as in concept A. However only one central in-bore welded connection is present, compared to a total of 5 for concept A. This change is made for the following reasons: reducing the number of weld connection points improves the ease of alignment and hence allows for a more robust and simpler maintenance strategy; and the welded connections are not affected by the thermal expansion of the limiter. The addition of a second in-bore weld location is suggested in order to remove the possibility of a single-point failure, this change can be made whilst considering the ease of alignment to reduce the impact of a secondary weld location. Also included in this concept is the addition of hooks which the limiter is hung from, which provides a level of redundancy in the event of the in-bore welded joint failing, and also allows for the RME to be released from the limiter if required during limiter installation / removal.

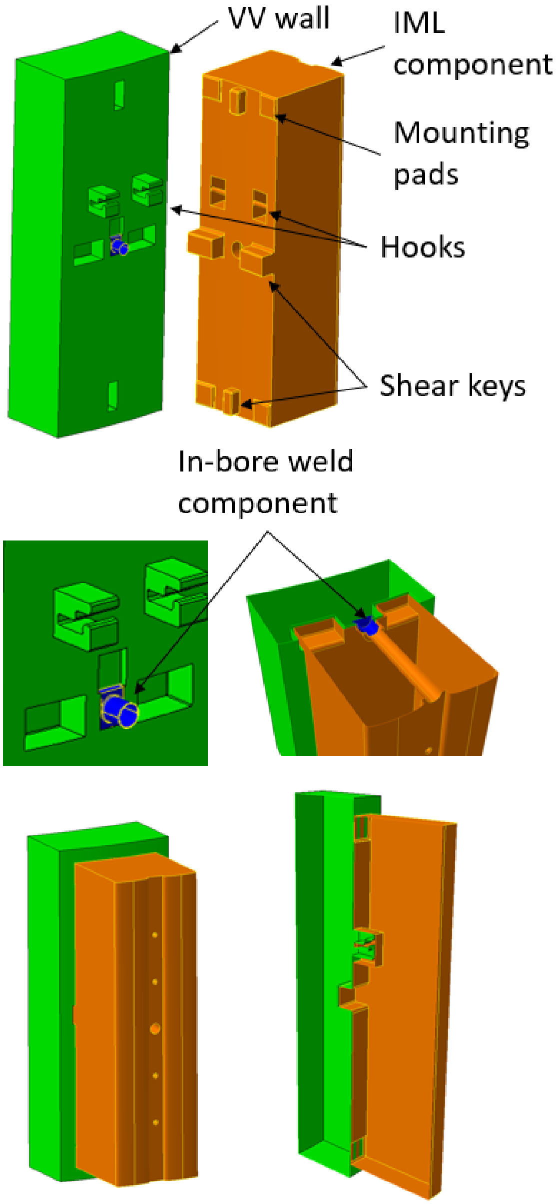

Figure 2-4: Concept B Single piece limiter

Concept C can be seen in figure 2-5, this concept features a ‘thin’ IML which is mounted directly to <u>a single</u> inner breeder blanket segment. Hence, for this concept the location of the IML is altered slightly in the toroidal direction. The use of shear keys, mounting pads, hooks, and a single central in-bore weld location is carried across from concept B.

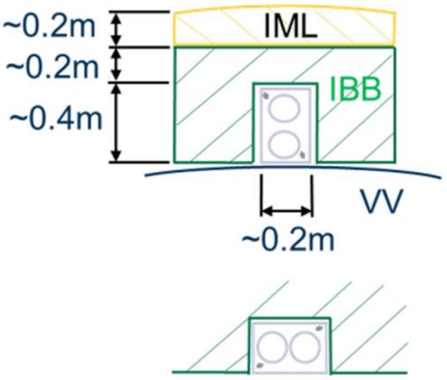

Figure 2-5: Concept C - Blanket mounted limiter (section view from underneath. Alternative pipe arrangement shown)

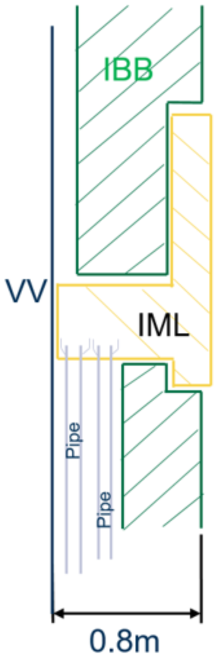

Figure 2-6: Concept C - Blanket mounted limiter (section view from side)

The position of the IML would change as the IBB expands under thermal loading, and the ability for the IBB to act as a load path for the loads which are imparted into the IML under a plasma transient event have not been assessed. Hence, if this concept is to be progressed then both of these areas need to be considered.

While the current leading concept under development is B, the combination of concepts B and C is preferable from an RM approach, as this is estimated to reduce the mass of the IML by approximately 50% and hence the loads placed upon the RME. This concept also removes the need to include large (~36mm) gaps between the limiter and the surrounding blankets, which are required in concepts A and B to accommodate the differential thermal expansion.

3. Limiter pipework concept development

The same close collaboration that has been previously noted has allowed for the development of limiter pipework concepts.

Several key design considerations were taken into account. Firstly, a neutronics study was performed (shown in figure 3-1) which found that the level of irradiation over the expected limiter operational life of two full power years would be result in a helium concentration of 1.66 appm (at point A). The DEMO RM team understand that re-welding of austenitic SS with 1appm Helium results in a factor of 4-5 reduction in weld fatigue life **[3]**. Hence, welding material which contains 1appm of Helium or more is deemed not possible. Also, the welding of irradiated material which contains less then 1appm of Helium must be treated with great care, the need to reweld material in this state should be avoided if at all possible, if this cannot be achieved then significant testing will be required to determine whether a suitable weld can be achieved.

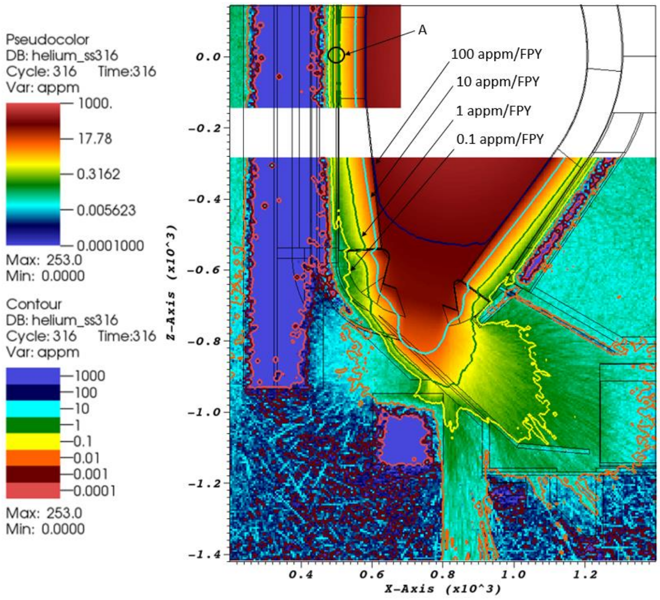

Figure 3-1: Helium production in SS316L(N) (units: appm/Full Power Year)

Secondly, the thermal expansion of the pipework, VV and BBs must be taken into account. Thirdly, the space available for the pipework is limited. Note the pipework will be routed behind the breeder blankets which remain in position during the removal and installation of the pipework. Finally, the limited space available for the pipe cutting and welding tooling must be considered. Extremely space efficient in-bore laser cutting and welding tools are being developed for DEMO, which are planned to be used for DN80 diameter pipes, although the tools require certain design constraints, such as: a minimum pipe bend radius of 1.5m; a pipe cuff with an approximate outer diameter of 150mm; a 0.5m straight length of pipe is necessary on both sides of the cut / weld location; and approximately 2m depth is needed underneath the pipe chute to allow for the in-bore tool launcher, additional space will be required for the associated RME (such as an automated ground vehicle).

The use of two DN80 pipes is assumed to be suitable for the limiter cooling based on experience from other limiters. At this stage of concept development, the cooling requirements had not been calculated, design development of the IML Eurofer box may be needed along with thermal analysis in order to ensure the Eurofer material operates within a suitable temperature range. It is also assumed that an amount of space underneath the VV is accessible for maintenance purposes. The use of shielding to limit the amount of neutron damage on the pipework has not yet been considered as part of this work.

An initial concept routed the pipework through the lower port, this concept can be seen in figure 3-2. Pipework “section 2” is removed to allow for the removal / installation of the divertor. Pipework “section 1” can only be replaced when the breeder blankets are removed (which may be 2-3 times less frequent then the divertors or the inner mid-plane limiter). Hence, the re-welding of irradiated pipework is required in this concept. As discussed previously, rewelding of irradiated material carries significant risk and is not thought to be acceptable. This is especially apparent under the divertor where the level of helium generation is very high. This concept is not recommended due to: the complexity of assembling the pipe sections within the vessel; the tooling requirements for the task; and high risk associated with rewelding of irradiated material.

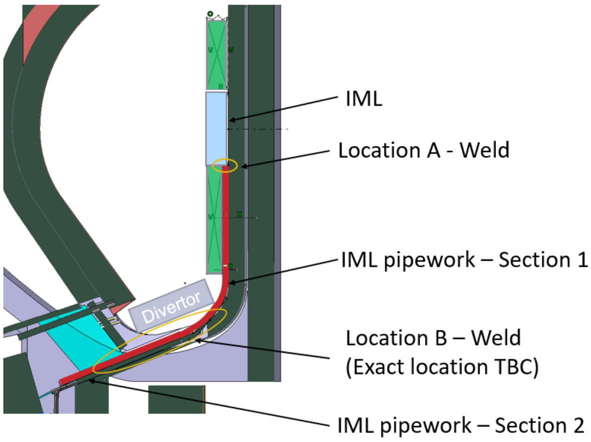

Figure 3-2: Multi-piece limiter pipework

A second concept utilises a small amount of space available between the Toroidal Field (TF) coils and the bottom Poloidal Field (PF) coil to route the pipework from the limiter straight vertically down and out of the VV. The sketch of this concept can be seen in figure 3-3.

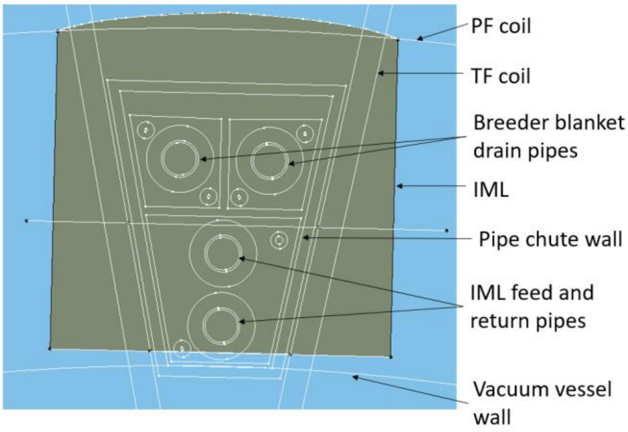

Figure 3-3: Vertical pipe chute sketch – bottom view (with a toroidal cross-section)

The pipe chute includes two DN80 pipes for the cooling of the limiter. The two DN80 drain pipes, one from each of the in-board BBs (which are required to drain lithium lead from the BBs prior to their removal) are also included in the pipe chute design. This is expected to improve the divertor maintenance strategy. The two limiter pipes can be installed and removed without interfering with the BB drain pipes.

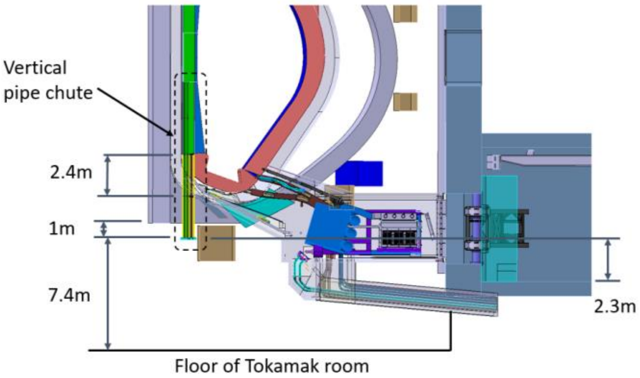

Figure 3-4: Tokamak side view with vertical pipe chute

The pipes are intended to be installed in sections, as shown in figure 3-4. This is due to the limited height available between the estimated floor position and the pipe chute exit. Four sections are shown, however this may be reduced to two. The two limiter pipes are assembled together through the use of end plates, which do allow a small amount of movement to allow for pipe alignment. The end plates are also fitted with alignment and mating features (such as alignment pins) in order to allow for gross alignment. Fine alignment is achieved through the independent pipe movement and their pipe cuffs.

A vertical pipe run requires a new pipe chute which is not currently included in the DEMO SN design. This pipe chute would require a modification to the VV to allow for the pipe routing and to provide the pipe chute structure, which is sealed using a closure plate, possibly a smaller version of the closure plates envisaged for the upper and lower ports.

The pipe sections would be pushed up into the chute from below by RME, where they can be joined together using the same in-bore welding tool which is used to connect the pipework to the limiter. Similarly, the same in-bore cutting tool which is used to remove the pipework from the limiter can be used to cut the pipework into sections, allowing for its removal.

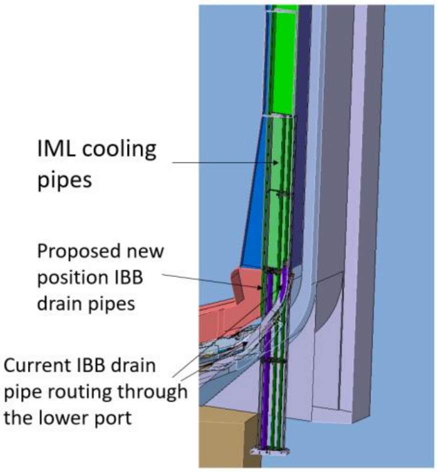

Figure 3-5: Vertical pipe chute

The remote maintenance preferred concept is the vertical pipe chute, as it is envisaged that this concept has far fewer operational risks when compared to the lower port pipework concept. Additional work is required to understand whether neutron shielding can sufficiently protect the pipework, which may then negate the need to replace the pipework with the breeder blankets in position.

4. Remote Maintenance Equipment concept development

The use of four equatorial ports for in-vessel maintenance is envisaged during maintenance periods. A concept design for an in-vessel device with an envisaged payload of 1,000kg has been produced as part of a separate DEMO remote maintenance work package. This device is called a Multi-Purpose Deployer (MPD) and can be seen in figure 4-1.

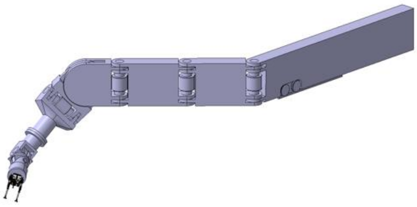

Figure 4-1: Multi-Purpose Deployer concept

The MPD is a ~30m long articulating boom, rectangular in section with a mechanical support in the equatorial containment cell with additional support from rollers which physically connect to the equatorial port in order to limit deflection. This device must reach much further into the vessel than is necessary for the maintenance of the IML, and the payload requirement for the IML is 6,500kg, significantly higher than the MPDs payload capacity.

Hence a variant of the MPD has been produced as an early concept. This shorter version allows for a higher payload capacity and allows for specific degrees of freedom to allow for the installation and removal of the IML. The RME can be seen in the following figures. This concept has not undergone any substantiation and requires significant further development.

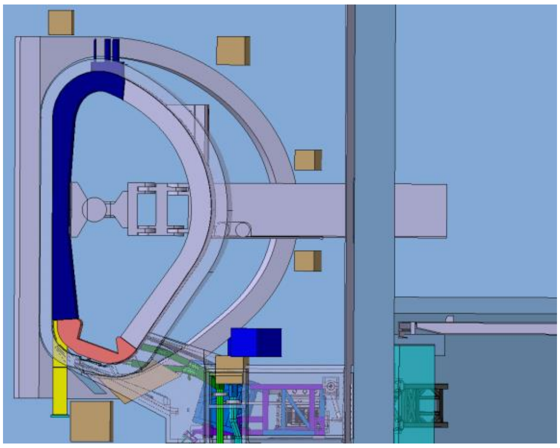

Figure 4-2: RME concept for the IML side view

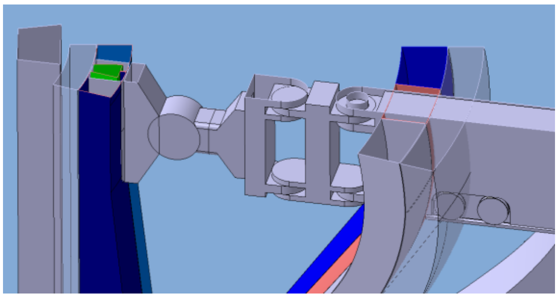

Figure 4-3: RME concept for the IML

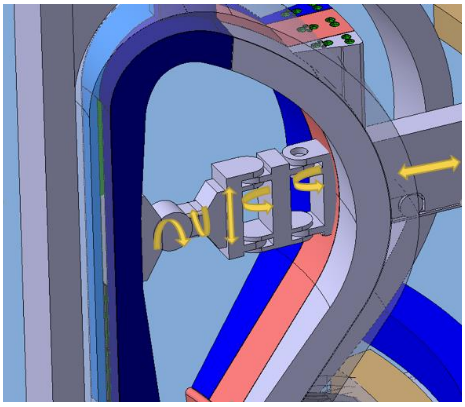

Figure 4-4: RME degrees of freedom

5. Conclusions and further work

The IML pipework is particularly challenging, primarily due to two reasons. Firstly, the high irradiation environment causes neutron damage and subsequent helium production, which significantly lowers the fatigue life in the weld. This is expected to make the welding of irradiated pipe material unfeasible. Secondly, the need to change the IML more frequently than the breeder blankets. Two concepts have been produced for the pipework. However, only the vertical pipe chute is seen as feasibly maintainable for the following reasons: the concept does not require the re-welding of irradiated material; and the remote maintenance is expected to be more feasible compared to the lower port pipework concept. The use of neutron shielding to protect the pipework from damage requires investigation as this may remove the requirement for the pipework to be renewed at the same time as the IML.

The design of the IML itself is challenging due to the restricted access to the IML, as only one surface is accessible for maintenance. Further difficulty is added as the available surface is plasma facing, which may become damaged following a plasma transient event. The ability to provide a load path for mechanical loads through the use of mounting pads and shear keys is seen to be advantageous. Three concepts for the IML have been produced and discussed, concept C is the current RM preference although concept B is also potentially acceptable for RM.

A concept design for the IML RME has been produced, this work has been based upon the MPD, which is in the initial stages of development (Technology Readiness Level 3). Significant further development and substantiation is required in order to ensure this IML RME concept design is feasible.

Areas requiring further development are listed below:

- The addition of the vertical pipe chute into the DEMO baseline;
- The potential to shield pipework from irradiation damage, which may allow for welding of used pipework;
- Alignment features for the IML to its mating surface;
- The preferred limiter concept requires development, discussion and integration with the breeder blanket design team;
- The IML design has been frozen at the end of 2019 awaiting better understanding of the physics of the H L transition in DEMO;
- An additional weld location is required to secure the IML in position removing the potential for a single point failure;
- Detail design development required for the shear key interface;
- The need for electrical earthing / electrical isolation at mounting points;
- The remote maintenance equipment requires significant further design development and substantiation;
- A full study of the electromagnetic loads applied to the IML is required, this should include the VDE, ramp up and ramp down loads.
- The effect EM loads which act to accelerate the IML and could result in damage to the IML, the VV and their interface needs to be assessed and mitigated.

Acknowledgment

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 and 2019-2020 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

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E. Flynn and A. Wilde from RACE have provided design support in order to ensure the IML concept can be feasibly maintained remotely. P. Cooper and Z. Vizvary from CCFE are responsible for the design development of the IML.