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Identification of Design Drivers through Technology Feasibility Studies of First Wall Protection Systems

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The Limiter (LIM) System of a port-based tokamak like the EU-DEMO encompasses different kinds of limiters for first wall protection purposes. Although the limiters' position and poloidal surface extension are driven by plasma physics inputs and verified under charged particle heat loads by means of field line tracing, they should also be designed to be easily and independently handled through vacuum vessel ports. Among the four identified types of limiters, four Outboard Lower Limiters (OLL) and four Inboard Midplane Limiters (IML) – when the inboard protection is conceived as a standalone component – do not have dedicated ports for their maintenance, as no vacuum vessel openings are foreseen in the lower outboard first wall, precisely behind the OLL, and behind the IML in the inboard equatorial first wall. On one hand, limiters should be designed to protect the first wall against energy depositions following plasma disruptive events; on the other side, though, it is important to ensure that the protection system is designed under realistic constraints to be easily handled and realistically maintained. Therefore, integration and remote maintenance requirements and needs become an important factor affecting both the OLL and IML integrated engineering design, for which a dedicated handling strategy becomes one of the main drivers, together with physics needs.

The paper presents the rationale followed for addressing the integration issues which drive the design of limiters with no dedicated ports behind them, and the remote maintenance strategy supporting their design concept. The definition of the handling strategy will help identify robust design drivers that apply to the entire lifecycle of the OLL and IML and improve the feasibility of achieving a practicable design solution compatible with its remote maintenance at every stage.

Keywords: EU-DEMO limiters, integration issue, handling strategy.

1. Introduction

The port-based EU-DEMO tokamak relies on a Limiter (LIM) system [1] as first wall (FW) protection strategy against the foreseen plasma-wall contact events in [2]. The LIM system encompasses four different types of poloidal limiters spread over the outboard and inboard wall (see Fig. 1 and Fig. 2, respectively), as well as across the 360° torus, as described in [1].

Limiters are primarily devoted to preventing plasma from contacting the wall during events that bring the plasma to lose its stable position and start drifting towards the FW. As limiters are meant to be damaged more frequently than the FW, they require an independent maintenance strategy from the rest of the In-Vessel Components (IVCs), as they should be the last components to be installed in-vessel and the first ones to be removed. For this reason, where possible, they should be located within the projection of the vacuum vessel ports, allowing them to be handled through single axis translations. This is valid for the Outboard Midplane Limiter (OML, highlighted in red in Fig. 1) and the Upper Limiter (UL, in green in Fig. 1), while it does not stand for any protection of the lower outboard and inboard FW, meaning the OLL and IML. Currently, two different inboard protection configurations are under feasibility study, i.e. the first one focused on the IML as standalone component (see Fig. 2, LHS), whereas the second one is looking at feasible ways of implementing a reinforced armor into the breeding blanket (see Fig. 2, RHS), which could potentially overcome some of the handling challenges of the standalone IML, if proved to be a feasible solution.

The present study is focused on tackling the integration challenges related to the design of FW protections lacking any vacuum vessel opening for feasible handling, precisely IML and OLL. It is important to account for them since the first preliminary design phase, as Remote Maintenance (RM) considerations can have a massive impact on the identified technological solutions for steering the design towards a realistic handling procedure, after meeting the physics needs. The RM challenges for the IML are particularly pronounced as the only feasible handling point for the IML is the first wall, owing to the current port configuration of the EU-DEMO tokamak. The combination of independent maintenance needs and unfavorable locations for maintenance results in influential design integration challenges that are highlighted in this paper.

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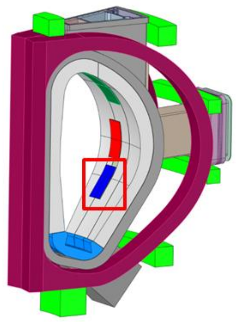

Fig. 1. Outboard configuration of the limiters in one sector, with focus on the OLL location.

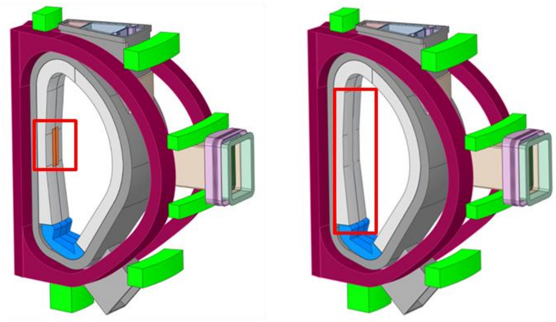

Fig. 2. LHS: IML as a standalone inboard protection component; RHS: protection integrated within the breeding blanket.

2. Rationale driving the LIM System design

As a general approach, two different kinds of drivers can be identified for conceiving and steering the engineering design of limiters, which implicitly define the rationale behind the design conceptualization. Hence, it can be assumed that the design is:

1. Driven by transient events. This implies a more demanding design, as the off-normal events are usually considered as part of the normal operation, and the power plant can continue operating after one or more off-normal events. This choice increases the plant availability and works towards the plant investment protection.

2. Driven by normal operation. This implies a less challenging design, as it can be conceived under normal operation loading conditions. However, it requires the limiter performance and structural integrity to be verified under off-normal events, as large deformation and damage of the component might be allowed under a single off-normal event loading condition, provided that the plant safety is not undermined. This implies the limiter replacement after every disruption and, hence, the decrease in the availability of the plant.

At present, lacking data on the frequency on the off-normal transient event occurrence, the rationale chosen for the engineering design of the limiters in [1] assumes as design drivers the loading conditions arising in the component during off-normal events. Considerations on how off-normal transients are approached in the design of limiters has an impact on the lifetime and maintenance of the limiter system.

3. Identification of the main integration issues

The design of limiters entails close cooperation among three different fundamental aspects: physics, integration and technology. Plasma physics provides information on plasma transients, which are critical for identifying the poloidal locations of the wall needing protection, as well as the poloidal spanning of the protection. Charged particles heat load calculations help identify the minimum number of toroidal limiters effectively protecting the 360° torus wall. Driven by plasma physics needs and inputs, the engineering design of the limiters require them to be realistically handled and maintained throughout the plant operation, hence the remote maintenance needs are driving the design from this point onwards, under much more constraining requirements dictated by the time the handling equipment can survive in harsh conditions, therefore requesting the designers to simplify kinematic constraints and reduce operations. In parallel, the technological choices and development of the material and configuration of the armor takes place between physics and maintenance needs. Different transient heat loads faced by different limiters require different design solutions for their first wall.

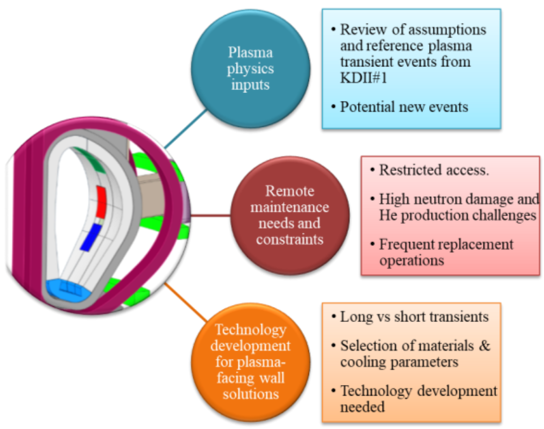

Fig. 3. Interaction between key aspects defining the limiter design, i.e. physics, maintenance and technology.

The main integration challenges identified for both IML and OLL are the handling strategy and their pipe routing. The most RM compatible handling strategy would involve dedicated port openings in the line-of-sight of every limiter (as highlighted in the "unconstrained RM" option in Fig. 4, LHS); however, this creates challenges for other aspects of the plant. Therefore, the current scope is to develop RM strategies within the constraints imposed by the plant architecture (see Fig. 4, RHS). Equally the requirement for an independent maintenance approach (no other IVCs than limiters are removed during maintenance) limits the RM strategy choices. In the independent approach the limiters cannot be integrated as captive protection to the blanket armor and simply maintained through the upper port as a whole unit together with the blankets. Hence,

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the maintenance strategy of OLL and IML must be developed through the equatorial port, due to the independent maintenance approach and the lack of dedicated openings behind them. OML is removed prior to removal of OLL or IML to facilitate access.

As the physics inputs driving the limiters ‘poloidal location have already been defined in [2], which have driven the definition of the limiter front face shaping, the following sections report preliminary considerations on handling strategy for both the limiters, and the implications that RM choices and interfaces have on the engineering design of such limiters.

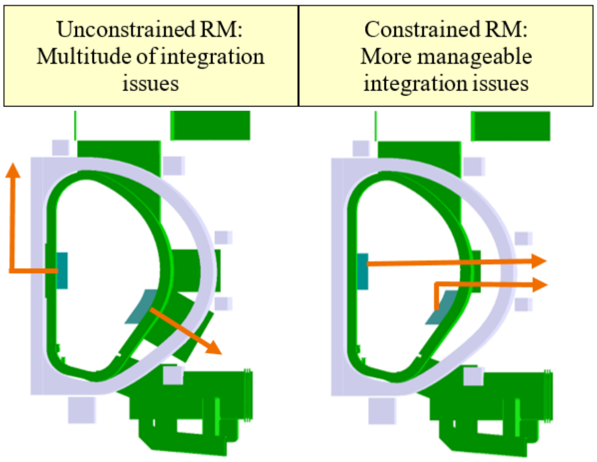

Fig. 4. Unconstrained vs constrained RM strategy.

3.1 Inboard Midplane Limiter

The IML lies between two inboard blanket segments, with a misalignment of ≈5° with respect to the radial direction of the port. This is highlighted in Fig. 5.

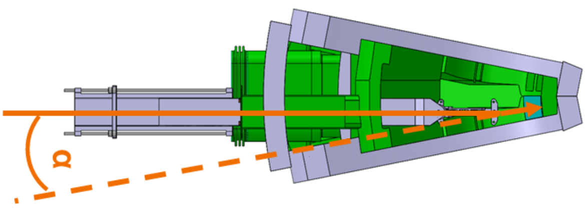

Fig. 5. Misalignment between the IML and the equatorial port.

Due to the restricted space and the independent maintenance requirement, the IML should be handled from the front face. As a point of reference, the FW of blankets in ITER include RM access penetrations which are shadowed from the plasma by shaping of the FW panels to reach acceptable temperatures [3]. However, in the development work for DEMO, IVC integration issues are anticipated on penetrations for front-side RM access and the thermal performance of the first wall therefore the approach is considered impractical due to the small spacing of FW cooling channels [4]. The following introduces an initial concept for penetrations on the first wall of IML from the perspective of RM while the effects on the performance of LIM remain uncharted. Rigorous set-based concurrent engineering and integration activities including the perspectives of RM handling and the thermal performance of IML FW including local modifications to the spacing and geometry of the cooling channels near the penetrations can be expected to further explore the design space to determine the feasibility of the approach. The RM Equipment (RME) identified for IML handling is an equatorial Port Rail Based Mover, as shown in Fig. Fig. 6. Equipped with end effectors, this tool has been identified for handling the installation and removal of the IML through a sequence of radial translations. The set of operations is sketched in Fig. 7. The interface between the IML plasma-facing wall (PFW) and the end effectors is by twist locks, shown in Fig. 8. The twist locks interface with appropriately sized receiving features on the IML and establish a load path between the RM equipment and the IML. These two connection points should be reflected in the design of the IML PFW, as the twist locks would need this space reservation within the first layers of the limiter body. Fig. 8 gives an idea on how the IML front face should be modified for hosting the two twist locks.

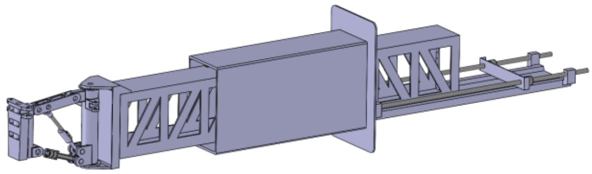

Fig. 6. RM tool: Equatorial Port – Rail Based Mover and End-Effector

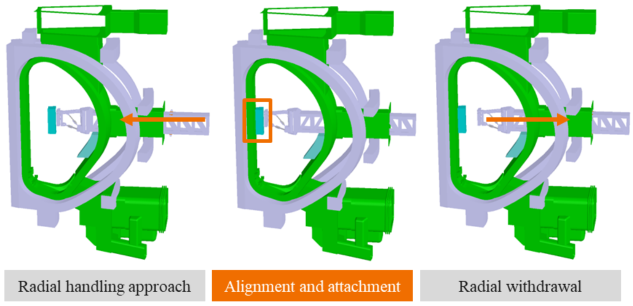

Fig. 7. RM handling strategy sequence for the IML.

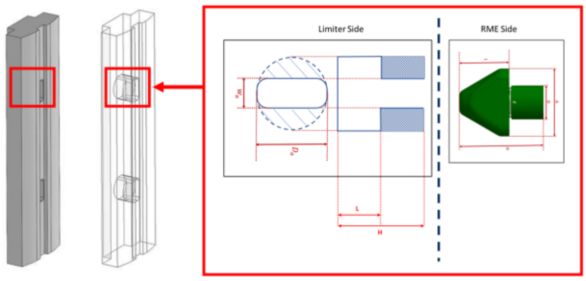

Fig. 8. IML PFW interfaces for the interlock system.

Analysis on pipe routing

Routing of the IML cooling pipes is of emphasized interest as there is no port for pipe routing in the near vicinity of IML. The three pipe routing options

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sketched in Fig. 9 (Upper port, Lower port, Vertical pipe chute) for the IML were qualitatively assessed with six RM feasibility criteria (Loading, Duration, Clearances, Accessibility, Kinematics, Radiation). Explanations of the RM feasibility criteria and the results of the assessment are presented in Table 1. The Vertical pipe chute option remains the RM preferred option as was also concluded in earlier assessments [5]. However, if we highlight the impact on other systems and the required design modifications the Upper port option is preferred.

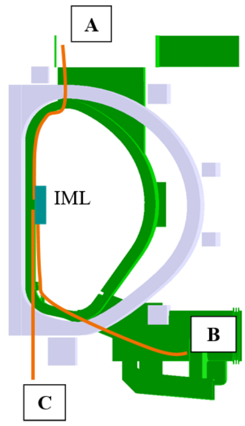

Fig. 9. Pipe routing options.

Table 1. IML pipe routing assessment. Legend: (+) RM preferred option; (-) RM challenging option.

IML pipe routing options	**RM loading** The mechanical load (moment, stress) on RMW caused by pipe module mass	**RM Duration** Maintenance duration of pipework replacement. Maintenance duration to open and seal the access to the vessel is assumed to be similar in all the scenarios.	**RM Clearances** Clearances between the combination of pipe module and RME and other systems during handling	**RM Accessibility** Accessibility to pipe module RM interfacing (handling, inspection, fixation, service connections)	**RM Kinematics** Simplicity of pipe module installation trajectories	**RM Radiation** Radiation accumulation of RME during pipe module RM operations	**Impact to RM systems beyond IML RME**	**Impact on IVC Systems**
A Upper port	Cantilever handling of pipe module increasing loading. (-)	The deployment, operation and retraction of the RM system is more time consuming for a more complex trajectory. (-)	Clearances depend on IML pipework and RME integration with other systems.	All pipe modules are not directly visible from the port due to bends in the pipework. (-)	Dextrous manipulation required. (-)	Radiation accumulation is higher for a longer maintenance duration. (-)	Blanket envelope and interfaces change affecting the upper port blanket RM approach and RM feasibility.	Requiring Upper Port piping system integration, and Blanket hosting the pipe routing.
B Lower port	Cantilever handling of pipe module increasing loading. (-)	The deployment, operation and retraction of the RM system is more time consuming for a more complex trajectory. (-)	Clearances depend on IML pipework and RME integration with other systems.	All pipe modules are not directly visible from the port due to bends in the pipework. (-)	Dextrous manipulation required. (-)	Radiation accumulation is higher for a longer maintenance duration. (-)	Blanket and divertor envelope and interfaces change affecting the upper port blanket and lower port divertor RM approaches and RM feasibilities.	Requiring modifications to Vacuum Vessel, Blanket, and Divertor systems. Big Impact on diverted central module, affecting its installation sequence; its attachment to the vacuum vessel; vacuum vessel pedestal and space claim for pipe replacements (only with a
C Vertical pipe chute	Pipe module can be supported under the center of gravity. (+)	The deployment, operation and retraction of the RM system is less time consuming for a simpler trajectory. (+)	Clearances depend on IML pipework and RME integration with other systems.	All pipe modules are visible from the port. (+)	Linear installation trajectory. (+)	Radiation accumulation is lower for a shorter maintenance duration. (+)	Blanket and divertor envelope and interfaces change affecting the upper port blanket and lower port divertor RM	

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approaches and RM feasibilities.	vertical pipe chute).

3.2 Outboard Lower Limiter

The OLL handling strategy through the equatorial port requires the OLL to be somehow connected to the equatorial port. (see Fig. 10). Considering that the current OLL poloidal spanning gives the minimum surface required for FW protection against high heat loads, this can be achieved by extending the current OLL up to the bottom of the equatorial port. This increase in OLL poloidal extension, which is now taller than the port height, forces a more complex handling pattern than the single rigid translations preferred by RM during the handling operations. Hence, the new OLL space envelope requires 60° max rotation by RM equipment to fit through the port, given that the port dimensions do not change.

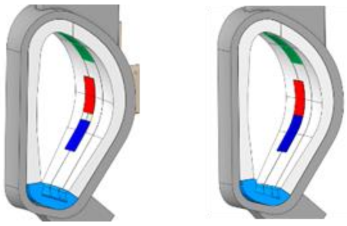

Fig. 10. Lhs: OLL minimum poloidal spanning needed for FW protection purposes. Rhs: OLL extended up to the bottom of the equatorial port for RM purposes.

The increase of the poloidal extension of the OLL introduces the benefit of an accessible top surface of the OLL after the OML has been removed. This enables us to avoid the issues with FW penetrations for RM interfaces like the IML as they can be positioned on the top surface of the OLL. An illustration of positioning interfaces on the OLL top surface pictured in Fig. 11 however reveals that the top surface is a crowded area where integration activities are necessary to accommodate RM interfaces, pipe entry including compatibility with pipe cutting and welding tools and the internal structure of the OLL.

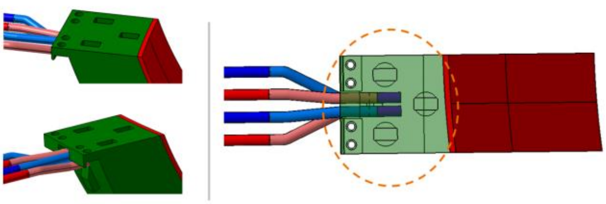

Fig. 11. OLL handling interface locations and pipe entry.

End-effectors

The main body of RM considerations for OLL described in this paper constitutes of illustrating initial approaches for transporting the OLL from in-situ location and orientation to a location and orientation where the OLL can be extracted radially through the equatorial port. This is achieved through the development of end-effector concepts for OLL handling. A potential OLL End-effector concept presented here assumes the use of a radial mover on rails accessing through the equatorial port.

Dedicated end-effector for OLL handling: The approach pictured in Fig. 12 is based on the use of a lifting platform and a rotating frame.

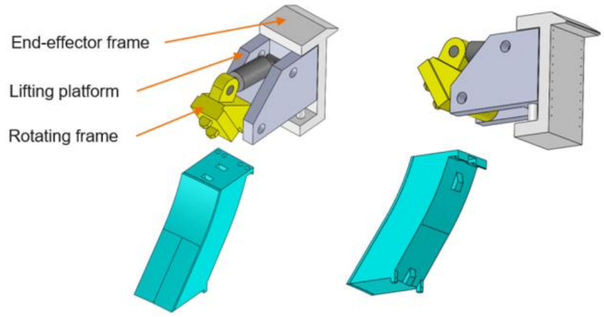

Fig. 12. Dedicated end-effector for OLL handling.

A potential removal sequence of OLL using the dedicated end-effector approach is pictured in Fig. 13.

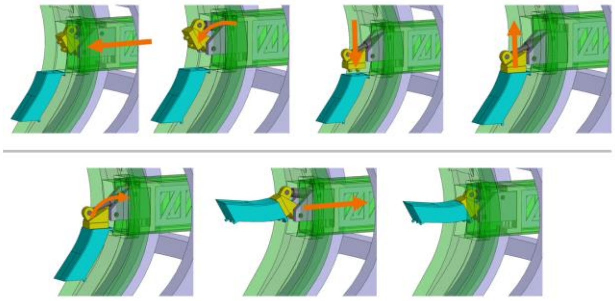

Fig. 13. OLL removal sequence.

Dedicated end-effector adapter for OLL handling: Dedicated end-effectors are replaced by one dexterous end-effector with dedicated changeable adapters for IML, OLL and OML.

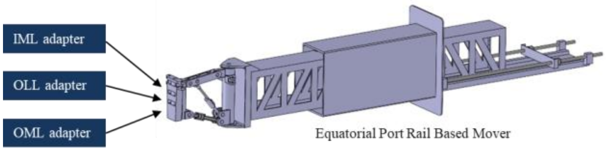

Fig. 14. Dedicated end-effector adapters for LIM handling.

Rail based OLL handling: A permanent rail is positioned behind the OLL. The OLL is handled from in-situ location to port by movers on rails behind the OLL. The rails are extended from the port area up to OLL. The benefit of this approach is avoiding cantilever handling as the OLL can be handled under the center of gravity. This reduces the load on the RME.

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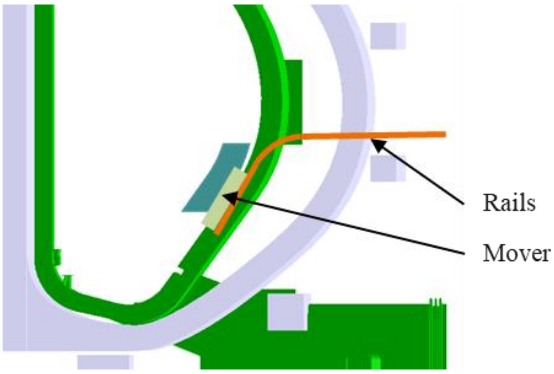

Fig. 15. Rail based OLL handling.

The presented concepts are by far not a complete set of possible options but an initial consideration of the main principles for OLL handling. The concepts are optimistic and describe providing kinematics for IVC transfer with a minimal number of joints in the end-effectors. The number of joints needs to be increased to provide adaptability to the position and orientation variations due to the tolerance chains of the tokamak systems. Design maturity of the concepts is low. Load calculations of frame structures and dimensioning of actuators are a necessity in defining a credible path for future development especially for the cantilever load cases of the dedicated end-effector and end-effector adapter as capability to account for the seismic load cases are one of the vital considerations for RME.

4. Conclusion

The design of the LIM system requires synergic cooperation among physics, integration and technology, as the need to protect the FW against plasma transient events cannot be detached from the need to design limiters that could be realistically and reliably handled. The design workflow does not have a trivial solution, as it must comply with both system-level and plant-level requirements at the same time.

The maintenance approach including the definitions of preventive and corrective maintenance scenarios are dependent on operational conditions driving the limiter design which impact the lifetime of the limiter system. Additionally, the combined effect of lack of ports behind the IML and OML and the requirement for independent maintenance is an increase of the RM system complexity and associated risks. The required capability for the combination of radiation hardness, reach, load capability, and welding capability of the RM equipment of in-vessel operations is more demanding compared to that of in-port operations.

The maintenance challenge is emphasized for the IML, where only the FW is accessible. If the requirement for an independent maintenance approach could be relaxed for the IML, the IML could be replaced by a reinforced armor of an inboard blanket and the maintenance approach could be that of accessing and removing the outboard and inboard blankets in four sectors from the upper ports. If the requirement for an independent maintenance approach cannot be relaxed a solution is needed to account for the poor RM accessibility. Initial considerations of FW penetrations for RM interfaces have been presented. Credibility needs to be increased by taking into account the requirements of limiter front face shaping. Alternatively, RM access routes behind the blankets to support more elaborate RM operations between multiple RM devices and IML fixation system can be envisaged. IML pipe routing options were presented where the weighing of impact on affected systems ultimately drives the design.

OLL handling approaches including end-effector, end-effector adapter and rail-based approach were investigated. New approaches can be innovated and loading of the RM system is to be considered to increase confidence in handling as the required OLL rotation during handling can result in cantilever loading depending on the handling approach.

This paper introduced the RM perspective to limiter design. Additionally, integration studies of the protection concepts involving the breeding blanket design are required due to the proximity of the limiter and breeding blanket systems and the impact of available space envelopes on the performance of the systems.

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