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European DEMO first wall shaping and limiters design and analysis status

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The anticipated heat flux limit of the European DEMO first wall is ~1MW/m^2. During transient and off normal events, the heat load deposited on the wall would be much larger than that the steady state heat load and exceed the first wall limit, therefore the breeding blanket first wall needs to be protected in such events. This involves dedicated discrete limiters in certain regions of the machine that would take the brunt of the heat load as well as adequate shaping of the first wall. The current concept envisages limiters at a few (3-4) equatorial ports to cope with the ramp-up of the plasma; upper limiters (in ~8 upper ports) are considered for upward vertical displacement events. Two design options have been considered for these limiters: a modular design where the limiter plasma facing components (PFCs) are attached to individual plates that are assembled together so that transient electromagnetic loads can be reduced, and in case of damage the plates can be replaced/repaired individually; and a divertor-like design where the PFCs are attached to a single Eurofer cassette. Other limiters considered include inner wall limiters in case of plasma contraction and lower limiters may be needed for downward vertical displacement events. The thermal hydraulic FE analysis results show that the integrity of the cooling pipes can be maintained during the anticipated transient events. The limiters are considered to be *sacrificial* and designed to be replaceable independently from the breeding blanket system. The design has to allow that installation, removal or replacement of the limiters can be performed remotely. Strategy to tackle outstanding issues and required R&D is also discussed.

Keywords: DEMO, First Wall shaping, Limiter, PFC, thermo-hydraulic analysis

1. Introduction

The EU DEMO breeding blanket (BB) first wall (FW) is capable of withstanding heat fluxes in the ~1 MW/m^2 [1]. The limited capability is driven by the requirement of tritium self-sufficiency, and thus the limited thickness of the FW (2 mm tungsten + 2 mm Eurofer). Analyses so far show that this limit can be respected during normal operation [2-3]. However, in case of normal and off normal transients the heat flux on the FW can exceed well the above-mentioned limits. The DEMO key design integration issue – 1 (KDII-1) is concerned with the performance and feasibility of limiters during these transients [4-5]. The envisaged worst plasma transients are:

- the ramp-up, which happens regularly at every single pulse;
- upward vertical displacement event (VDE);
- downward VDE;
- H-L transition (loss of confinement).

This paper focuses on the latest development in the engineering solutions to deal with these events. The physics behind the above transient scenarios in the EU DEMO is detailed in [6].

In order to protect the BB FW various limiters are proposed that can withstand the transient heat loads, or at least while providing protection to the BB FW the structural integrity of its own cooling system can be preserved.

The listed transient events affect different locations in the plasma chamber and therefore each event has its own dedicated limiter.

The naming convention of the limiters and the transient events they are designed for are in Table 1. The locations for the limiter are also shown on the schematic view (Figure 1).

Table 1: Transients and limiters

Transient event	Number on Figure 1	Limiter	Number of limiters
Ramp-up	1	Outboard Midplane Limiter (OML)	(3-)4
Upward VDE	2	Upper Limiter (UL)	8
Downward VDE	4	Lower Midplane Limiter (LML)	(3-)4
H-L transition	3	Inner Wall Limiter (IWL)	(3-)4

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Important to note is that the limiters are not toroidally continuous components, the envisaged number of each limiter is also included in Table 1.

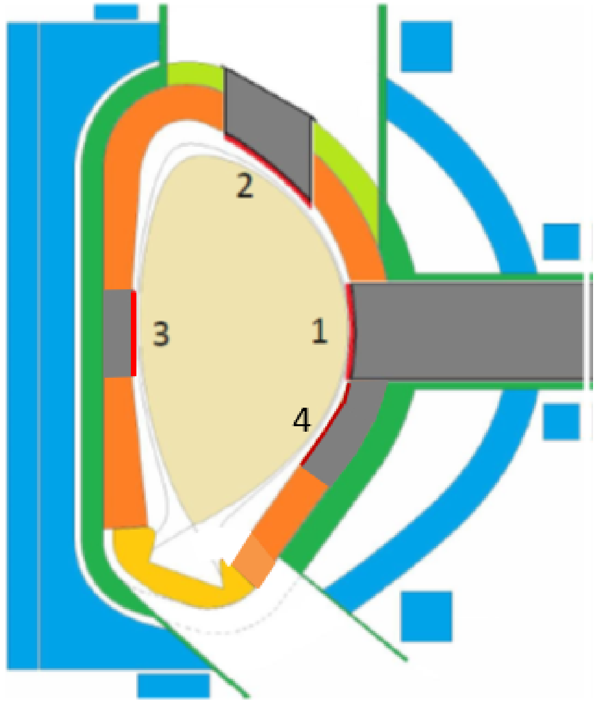

Figure 1: Schematic view of the EU DEMO indicating the positions which the limiters occupy.

The work presented here summarises the latest status of the limiter development for each of the limiters and identifies the design focus for the short-term future.

2. Limiter design options

Although their function is very different the technology of the limiters will be similar to the ITER and DEMO divertor technology [7-9]. Both the divertor and limiter components are designed to withstand high heat flux, however unlike the divertor which has to withstand a high steady-state heat flux, the heat flux for the limiters can be extremely high at the same time the duration of these loads are short (Table 2).

In fact, the thermal loads can be so large that the plasma facing tungsten monoblocs can be damaged (i.e.: melted, evaporated, cracked), therefore the limiters may require more frequent replacement than the BB system.

The tungsten monobloc plasma-facing components (PFCs) are cooled by CuCrZr cooling pipes, which according to our current knowledge is likely to have limited lifetime (to around 2 full power years) due to the high levels of irradiation [10]. This also indicates that the limiters will have to be replaced more frequently than the BB segments and therefore have to be designed so that they can be replaced independently.

Two design options have been considered in the development of the limiters. In both cases the PFCs are attached to a shieldplug: a water cooled Eurofer steel structure. The PFCs are tungsten monoblocs attached to CuCrZr water cooled pipes with a copper interlayer and Eurofer thermal break (Figure 2).

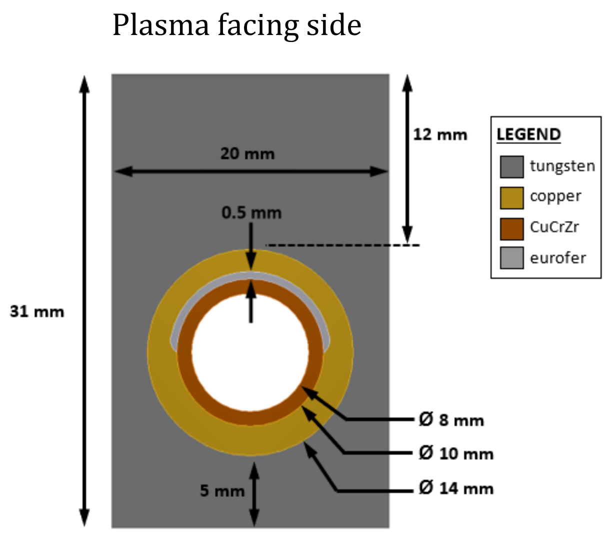

Figure 2: Monobloc cross-section for upper limiter.

Table 2: Typical heat loads for limiters

Limiter	Design heat load	Duration
OML	5-10 MW/m^2	20-60 s
UL	~25 GW/m^2	~4 ms
LML	~150 GW/m^2	~4 ms
IWL	10-20 MW/m^2	5 s

The shieldplug is not just a structural part to which the PFCs are attached to, but they also have to provide sufficient shielding to the structures (port plug, vacuum vessel) behind.

2.1. Plate-based design

The “plate-based” design follows the principle of the once proposed ITER port limiter [11] or the JET ITER-like wall tile design [12], where the components contain “cuts” so that the transient electromagnetic loads (eddy currents) can be kept as low as possible. The “cuts” are designed so that they prevent the possibilities of large current loops induced in the components during plasma disruptions. If the cuts run poloidally the poloidal current loops can be prevented, while dividing the poloidal extent into smaller section current loops due to toroidal field change (in the thermal quench phase, while the plasma is doing a poloidal inward shift due to shrinkage by loss of energy) can be reduced. Analysis so far confirmed that indeed the eddy currents (especially during the current quench) can be reduced this way [13].

Such shiledblock can be realised by manufacturing distinct Eurofer plates which are assembled together by attaching them to a back frame to form the shieldplug. The plates would be relatively easy to manufacture and would

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be used several hundred times in the whole reactor, with variants for each limiter (although this solution may not be viable for the IWL). This modular build would also offer flexibility and smaller component size that builds up the limiter. The modularity could potentially allow the repair or replacement of damaged monoblocs/monobloc sections, although handling an irradiated limiter at these sizes certainly would not be easy to maintain remotely.

The actual plates could be made from two parts using hot isostatic pressing (HIP). This would also allow bespoke internal cooling channel geometry inside the plates (Figure 7). This can be optimized for both to the desired plate temperature and shielding capability.

More work needs to be done on the attachment of these plates to make it a viable option. Estimated halo current loads could be large (especially for the UL and LML). Attaching the plates only in the back would challenge any attachment system. Attaching the plates together (for example by preloaded tie-rods) could increase the strength. This would have to be done via a high resistivity path, to avoid compromising the resilience against eddy currents. Concerns regarding the loss of preload require novel solutions. Work is ongoing to understand how the irradiation induced stress relaxation and creep in such assembly could be managed.

2.2. Divertor-like design

The divertor-like design is building on the information already learned from the divertor development. As said the technology will be very similar, even the coolant conditions are to be shared (180 °C/130 °C water, 3.5MPa/5MPa) in line with balance of plant requirements. Building on the divertor development could shorten the limiter development path, share resources for future R&D and ensure the consistency among the various components.

The size and shape of the limiters are different from the divertor (and from each other), the number of PFC cooling pipes the length of these pipes will also vary and therefore for each limiter the internal structure of the "cassette" will have to be optimised. The heat load on the cassette is driven by the volumetric heat load during normal operation due to the large volume and thus mass flow rate. The internal cooling layout is not trivial.

3. The Limiters

3.1. Outboard Midplane Limiter (OML)

Among the various plasma transient events the ramp-up is the one that occurs on a regular basis. The maximum envisaged heat flux is 5-10 MW/m^2 for tens of seconds (20-60s). During the ramp-up in the plasma will be leaned against the OML. We foresee 4 of such limiter periodically placed 90 degrees apart (alternatively it is studied to use only 3 to save equatorial ports). The limiter is attached to the port plug and sit in an equatorial port. The port itself would need to be offset in order to avoid having to split any blanket segment into two (Figure 3).

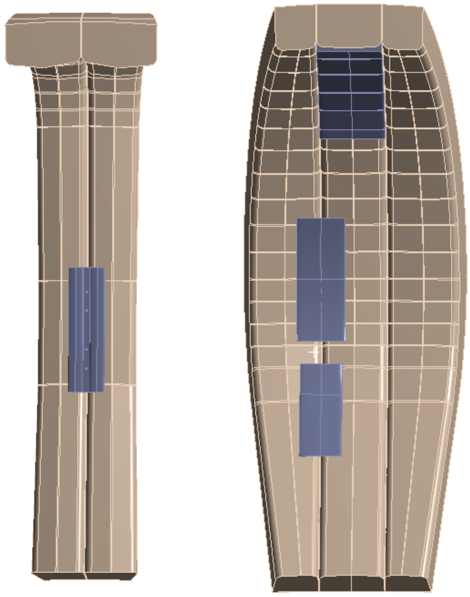

Figure 3: Limiters in a sector: left, inboard view, right, outboard view (without PFCs).

During ramp-up these limiters will have to be well aligned; a mechanism is envisaged that would allow the fine adjustment of the limiter (± 5 mm) to achieve this after assembly [14].

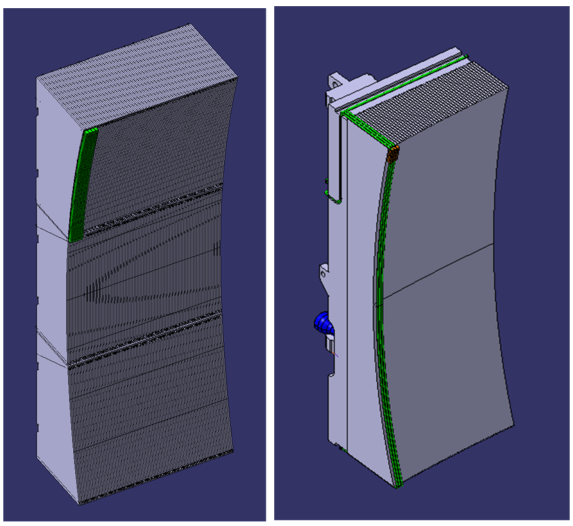

Figure 4: Outboard Midplane Limiter: left, plate-based design right, divertor-like design with attachments on the back side (both partially populated with PFCs for better understanding).

3.2. Upper Limiter (UL)

Avoiding disruptions and VDEs cannot be guaranteed based on present plasma scenarios. The energy released during the upward VDE is huge: ~1.3 GJ during the thermal quench in ~4 ms, followed by the current quench with ~1 GJ within ~250 ms. This enormous heat load would destroy the BB FW. To prevent this every second upper port would include an UL similarly attached to the central upper port plug [15]. The 8 ULs are replacing the top section of the central outboard blanket segments. This

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also means that the port plug has to provide a load path too towards the inboard segments.

The estimated heat load is so large for the UL that it seems to be unavoidable that the tungsten monoblocs would melt/evaporate. In the design the focus is on ensuring the integrity of the cooling pipe in such event, so that the coolant cannot leak into the plasma chamber. The limiter is likely to have to be replaced after such a serious event. In this sense, the UL is considered *sacrificial*: it would be sacrificed in order to protect the BB.

Previously a wide monobloc with complex cuts has been proposed [16]; recently it was reversed to a simpler monobloc (Figure 2) which is easier to manufacture and allows more flexibility in geometry. This is however at the price of having more cooling pipes in the vessel as the monobloc is narrower to achieve similar capability. The monobloc still features a Eurofer strip thermal break, to distribute the heat load more evenly in the CuCrZr pipe.

Analyses show that using the thermal break the CuCrZr pipe bore temperature stays in the region of ~300 °C and there is only a short period of time when the wall critical heat flux (CHF) is slightly exceeded (Figure 5). Increasing the tungsten thickness could reduce the pipe bore temperature. Analysis suggest that the tungsten thickness could be increased to 25 mm without reaching the recrystallisation temperature at steady state conditions.

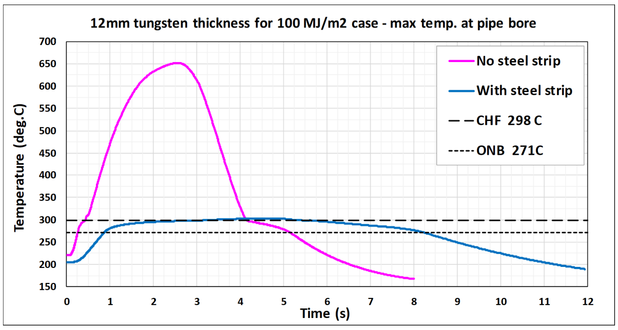

Figure 5: Comparison of pipe bore temperature with and without thermal break for 12 mm tungsten monobloc thickness.

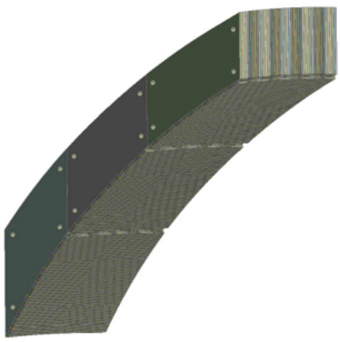

Figure 6: Upper Limiter plates and PFCs assembly.

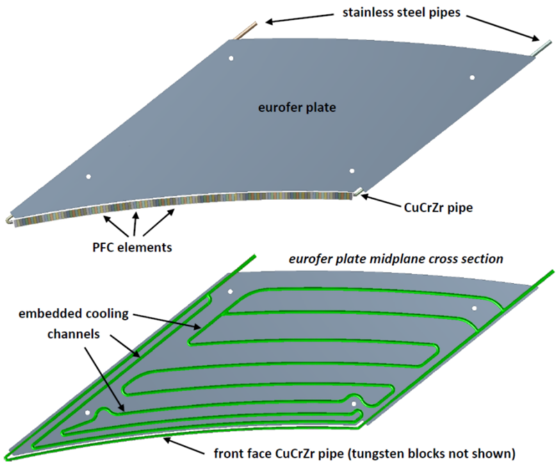

Figure 7: Upper Limiter plate and internal channels.

3.3. Lower Midplane Limiter (LML)

In case of a downward VDE a LML is being considered to protect the BB. This work is in the early stages, but due to the nature of the loads it needs to be similar to the upper limiters. They need to be located just slightly further down from the OMLs offering an opportunity to install/remove these limiters and provide coolant connections also through the equatorial port. The LML will need to be extended upward (compared to Figure 3) to achieve this. It also means that there will be only (3-)4 LML, meaning even higher heat loads than on the ULs.

3.4. Inner Wall Limiter (IWL)

Loss of confinement can lead to an H-L transition and the plasma would contract and touch the inner wall. Unlike any of the other limiters the IWL will have to be accessed from its front; offering the biggest challenge among the limiters. It is proposed to access the IWL from the equatorial port once the OML has been removed. This also means that the number of IWLs is the same as OMLs. To allow handling interface at the front of the limiter similar solution to that of ITER is sought [17], whereby the central part of the limiter, where the interface is located, would have to be shadowed by the PFCs.

The limiter would be attached directly to the vacuum vessel (VV) wall in between two inboard BB segments (Figure 3, left), again, to avoid having to split any inboard segments into two. The current concept envisages keys and load pads to the VV. The water coolant connection would be provided from the lower port direction. After installation and prior operation the limiter would be held in place via a structural pipe connection to withstand seismic load (Figure 4, right). During operation the ferromagnetic forces are radial and pointing to the centre of the machine and provide sufficient force to keep the limiter in place.

The eddy current loads on this limiter were scaled from the helium cooled pebble bed (HCPB) BB inboard segment loads and are quite high. Design modifications may be required to reduce these loads in the IWL so that the load from the ferromagnetic forces provides sufficient

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preload on the attachments to withstand the transient electromagnetic loads.

The limiter has also difficult maintenance issues: alignment to the hidden fixations; alignment to the pipework and pipe routing; rescuing of the limiter in a failure scenario (for example, unable to remove IWL from fixations).

The ongoing work aims to provide potential solutions in each of these areas.

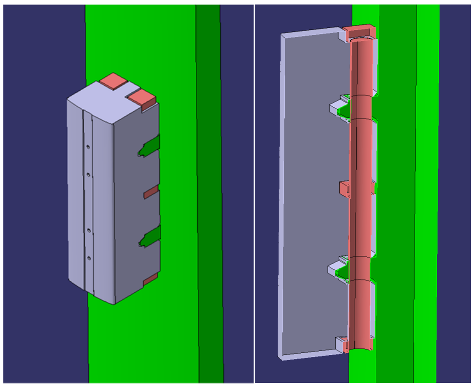

Figure 8: Inner Wall Limiter shieldblock (without PFCs). Left isometric view, right section view.

4. Wall and Limiter Shaping

Unlike in ITER the DEMO FW will not be a limiter wall. During flat top operation the distance from the plasma will be ~225 mm [18]. Despite that the FW panels have been shaped following a similar procedure to that of ITER [19-20] to optimise the heat load from charged particles. The shape of the BB FW front face has been set to match the flat top operation far scrape of layer (SOL) length.

As well as the FW the limiter surface has been shaped in a similar manner. However, each limiter surface has been optimised for the far SOL of the case against which they are intended to protect. Simulations have been run to check their heat load during flat top operation as well.

Initially, the limiter shape also included a 100 mm radius rounded edge just like the BB FW. Due to their protrusion the limiter edges see higher heat flux. The shape of these edges can be changed; however, a balance needs to be found that would not compromise the optimised shape but protect the edges too within the relatively short toroidal extent of the limiters.

Understanding the impact on misalignments between blanket segments and limiters is crucial. The misalignments have various sources: manufacturing, assembly, operational differences, magnetic field lines etc. An initial study has been presented for multi-module segments as used until recently [22]. As the leading concepts are currently single module blanket segments a new study has been started which considers blanket segments as well as limiters in the study [23].

Further work needs to be done to check the sensitivity of these shape to variance in the scrape of layer length, similar to misalignment studies. As a result of this exercise we may change the shape to a more resilient one even if that means going away from the optimised shape.

For the limiters the shape can be implemented in different ways: either by the monobloc heights or the cooling pipe shape or the most likely the combination of the two. A sensitivity study is under way to find out the impact of varying monobloc heights. So far, the study shows that tungsten thickness ranging from 12 to 25mm can give adequate flexibility with regards to FW-shaping, especially at the rounded-edges of the limiters. Furthermore, the range of working front face thickness will allow the limiter to maintain its capability under erosion over long life time.

5. Fabrication tests

A development plan has been proposed in order to validate functional principles for DEMO Limiter and to acquire experience in all the processes required during the cycle of life for manufacturing and testing.

The industry infrastructure will have to be upgraded/created for fusion applications. It is one of the main objectives within this development plan to explore the market and the industrial capacities that are or will be needed to support fusion manufacturing and testing.

Currently, the mock-up fabrication tasks are on the way and they cover the PFC joining techniques. The main goal at this state for WPBB is to validate the feasibility of the concept based on P91-steel layer as thermal break in order to decide if it is worth to pursue. P91 is a type of ferritic-martensitic steel micro alloyed with vanadium and niobium and with controlled nitrogen content.

Several filler metals (Orobraze™ 950, Orobraze™ 1025, Pallabraze™ 950, NBLM™, H-Bronze™) are tested in order to develop a rational process of requirements and results with the possible PFC base materials (tungsten, P91, OFHC copper, CuCrZr), defining matrix decision process that become lineal.

The two main requirements that drives this preselection are to guarantee the structural integrity during the service life of the component and to guarantee the proper brazing filler metal-base metal interaction.

6. Summary

The status of the EU DEMO limiter concept has been presented. Two design options have been explored for the limiter components, due to the maturity of the divertor concept the divertor-like concept has been chosen for the limiters too. The OML and UL are advanced while more work needs to be done for the IWL and especially LML, although solutions found for other limiters can be re-used. Work is still ongoing, both in CAD design as well as at the analysis front. Optimisation of the limiter cassette internals from thermo-hydraulic point of view as well as interfaces with the port plugs and remote maintenance equipment are the next priorities.

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Analyses of charged particle heat flux based on the FW and limiter shaping show promising results that the limiters can protect the BB FW as well as have acceptable heat loads during steady-state operation. The limiter PFC shaping implementation has yet to be decided. The most likely solution for the PFC shaping is a combination of monobloc height and cooling pipe shape.

PFC joining fabrication and testing tasks are also ongoing.

Acknowledgements

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