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Poloidal distribution of penalty factors for DEMO Single Module Segment with limiters in normal operation

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ABSTRACT

The charged particle heat load expected for the DEMO Single Module Segment first wall (FW) during current off-normal plasma scenarios indicates that protection is needed for avoiding/reducing damage to the breeding blanket FW due to the deposition of a huge amount of energy in a small timescale [1].

Within the EUROfusion framework of heat load analysis and design of DEMO wall and FW protections during plasma transients (identified as "Key Design Integration Issue 1" [2]), extensive reworking has led to FW and limiter designs that keep the flat-top maximum heat load on both the FW and limiter plasma-facing surfaces within engineering limits. The limiter strategy appears promising for both normal and off-normal plasma events, therefore the study will be focussed on a FW equipped with limiters.

As a continuation of the work started in [3], which has highlighted the weakest point of the older FW design and led to the new FW layout, the impact of misaligned segments and limiters on the charged particle heat flux pattern is investigated for the "limited" FW (i.e. FW protected by limiters). The study is carried out by 3D field line tracing codes SMARDDA/PFCflux [4,5] and covers normal operation scenarios (ramp-up and steady-state) with the aim of producing heat flux penalty factor distribution to identify the worst case scenarios. As far as the normal transient events are concerned, the results in [3] are updated. In addition, during steady-state operation, deformation of in-vessel components due to mechanical loads such as ferromagnetic forces acting on EUROfer and different thermal expansion of adjacent segments, leads to the exposure of edges that are shadowed in the FW undeformed configuration. As a novel approach, flexible geometrical transformations simulating this kind of normal operation misalignment are implemented for studying the impact on the charged particle heat load of the induced differential deformations.

1. Introduction

Any break in the continuity of the plasma-facing surface increases the chance of edge-localized hot spots due to charged particle power deposition. The presence of openings on the first wall (FW) due to diagnostics, ports and the introduction of limiters provides only a few examples of unavoidable FW discontinuities. The exposure of these edges to magnetic field lines may be accentuated by small deviations (within specified tolerance) in manufacture and installation, plus they deform under loading conditions of Normal Operation (NO). During NO, indeed, the DEMO Single Module Segments (SMS) experience distortions arising from:

- mechanical loads (i.e. gravity, ferromagnetic forces) acting on in-vessel components;
- differential thermal expansion along the poloidal extension of a single segment as well as between adjacent segments due to spacial temperature gradients.

Manufacturing, assembly, and installation tolerances will result in a positional misalignment of the FW. As the different kinds of misalignment may combine adversely, it is important to study the contribution of deformation under NO (hereinafter referred to as "flexible deformations") to keep the Maximum Heat Flux (HF_{max}) within acceptable limits. This assessment is also useful for evaluating the effectiveness of

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different designs used for modelling connections and segment attachment systems, as an example.

Misalignment studies on the DEMO SMS have already started. The methodology is explained in the companion paper [3], which also includes some preliminary results highlighting a few required modifications of the adopted FW design for keeping the charged particle HF_{max} below 1 MW/m^2 during NO and allowing segments to have larger tolerances on misalignment. In the present paper, the study is updated to use the new FW layout, and the effect of limiter misalignments on the HF pattern is investigated as well. In addition to this, the novel case presented here is related to the study of segment misalignments under flexible deformations induced by a combination of loads as gravity, ferromagnetic forces and temperature gradient typical of a NO scenario.

2. Misalignment cases

2.1. Assumptions

The present misalignment study presumes that:

- the nomenclature used for the five segments included in a 22.5° DEMO sector is explained in [3];
- all the segments have been clustered by poloidal locations in modules (1–30) that have different penalty factor values. Penalty factor poloidal maps containing penalty factors per module are provided, highlighting the highest penalty factor among the related misaligned modules;
- misalignments of the divertor are ignorable for present purposes;
- only one component misalignment has been considered at once, while the rest of the geometry is untouched;
- all the calculated heat flux values (HF_{output}) are rescaled for retrieving the power balance between the power crossing the separatrix (Q_{sol}) and the integrated power deposited on the FW (Q_{output}). The new heat flux values ($HF_{rescaled}$) are obtained according to Eq (1):

$$\mathrm{HF}_{\mathrm{rescaled}} = \mathrm{HF}_{\mathrm{output}} \cdot \frac{Q_{\mathrm{sol}}}{Q_{\mathrm{output}}} \quad (1)$$

Following the methodology explained in [3], the results obtained for the most relevant cases will be provided in terms of penalty factors (f) defined as in Eq (2):

$$f = \frac{\mathrm{HF}_{\mathrm{max}_{\mathrm{misaligned}}}}{\mathrm{HF}_{\mathrm{max}_{\mathrm{reference}}}} \quad (2)$$

The investigated misalignment cases are listed below, and the results of the study will be presented in Section 3.

2.2. Radial and vertical misalignments

Under the Ramp-up (RU) and Start-Of-Flat top (SOF) phases characterizing NO condition, the effect of segment misalignments in the radial and vertical directions on the reference charged particle heat load pattern is investigated. As far as the limiter misalignments are concerned, only the Outboard Midplane Limiter (OML) radial displacements are investigated during RU since the OML is the only limiter involved during this transient, while the radial misalignments of Upper Limiter (UL), Outboard Lower Limiter (OLL) and OML are studied under SOF conditions. Although the Inboard Midplane Limiter (IML) is included in the geometry, no studies about its misalignment have been carried out as the decision to include the IML in the final DEMO FW layout is still pending. The misalignment test matrix has been identified, to include the following cases:

- FW segments displaced radially and vertically by $\pm$20 mm, $\pm$10 mm, during both RU and SOF;
- OLL and UL displaced radially by $\pm$10 mm, $\pm$5 mm, $\pm$2 mm. Those are sacrificial limiters to mitigate disruptions (facing HF $\geqslant$ 100 MW/m^2 in a short time, $t \leqslant$ 300 ms), for which, at the present, are not foreseen alignment adjustment actuators (also because of the possibility to have asymmetric Vertical Displacement Events – VDEs);
- OML displaced radially by $\pm$5 mm, $\pm$2 mm. This limiter is intended to manage normal plasma transients like RU (i.e. for HF $\leqslant$ 10 MW/m^2, and tens of seconds), for which are foreseen alignment adjustment actuators.

2.3. Flexible deformations during SOF

If radial and vertical rigid transformations can be used to model displacements due to manufacturing or installation processes, the same cannot be said for distortions that every segment experiences under loading conditions typical of NO. According to the way they are attached to the vacuum vessel, as an example, every segment can experience differential deformations in different poloidal locations, which can change the layout of the reference FW configuration. For modelling the effect of operational misalignments among segments, "flexible deformations" are introduced. It has to be underlined that the effects of flexible deformations on the heat flux pattern are here analysed only during SOF as this is meant to be the steady-state phase whose duration is longer than the RU, which is, by definition, a normal transient event. Furthermore, the displacement data during RU, which should result from a transient structural analysis, are not available yet. This does not limit the validity of the procedure, which can be applied to every scenario provided that there are available solutions, in terms of displacements, coming from the mechanical analysis of the system.

The methodology used here is based on direct manipulation of node coordinates included in geometry VTK input file format [6] through python scripts. The flexible deformations implemented for this study result from the DEMO blanket attachment system static-structural analysis under gravity, spatial thermal gradients and ferromagnetic forces acting on blanket segments during NO. Averaged radial (Fig. 1) and vertical (Fig. 2) displacement values are calculated from the two edges of each segment in three different locations (top, equatorial midplane and bottom) and linearly interpolated along every segment poloidal direction for ensuring the continuity of the input geometry. Although the DEMO blanket attachment is still not fully finalized, the results shown in this paper are considered usefully indicative for demonstrating the capability of considering flexible deformed misalignment cases.

3. Penalty factor poloidal maps

3.1. First wall segment radial and vertical misalignment

The results of the study carried out have highlighted that only segment misalignments within $\pm$10 mm are acceptable. Although during SOF the up-to-date FW configuration can handle HF_{max}< 1 MW/m^2 in presence of $-$20 mm displaced segments, the upper limit on admissible tolerances in NO is defined by the RU. This ensures that the charged particle HF_{max} on segments is below the engineering limit in case of deviation from the reference configuration. As the current OML protrusion is 20 mm, the outboard segment radial misalignments have to be less than 20 mm to avoid the segments acting as a "limiter" during the RU phase. An increase in misalignment tolerances would require a review of the OML protrusion. Therefore, the penalty factor poloidal maps reported below will be referred to radial/vertical misalignments of $\pm$10 mm. Where not explicitly stated, penalty factors should be taken as unity.

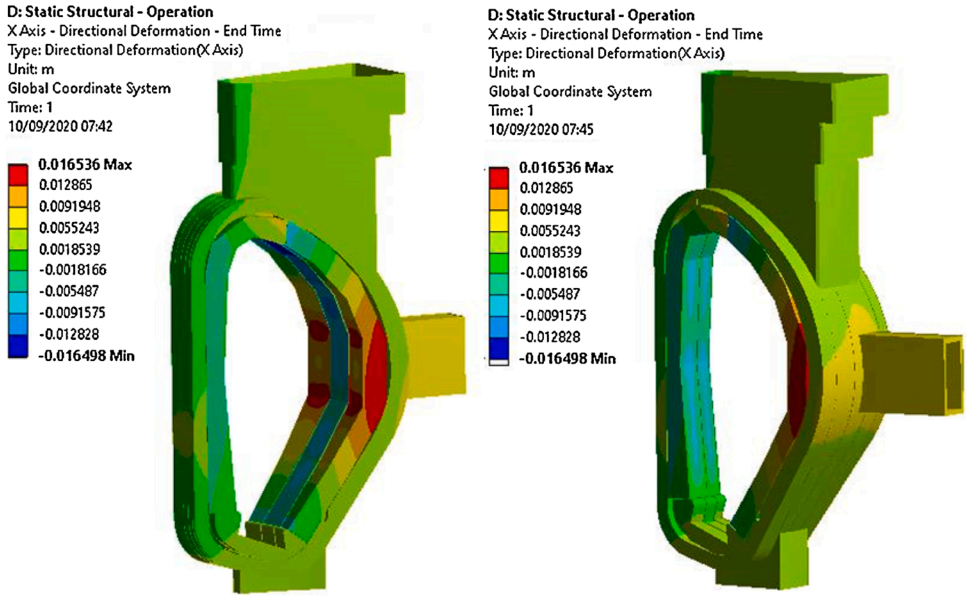

Fig. 1. Radial displacements of the DEMO blanket attached system under loading conditions typical of NO.

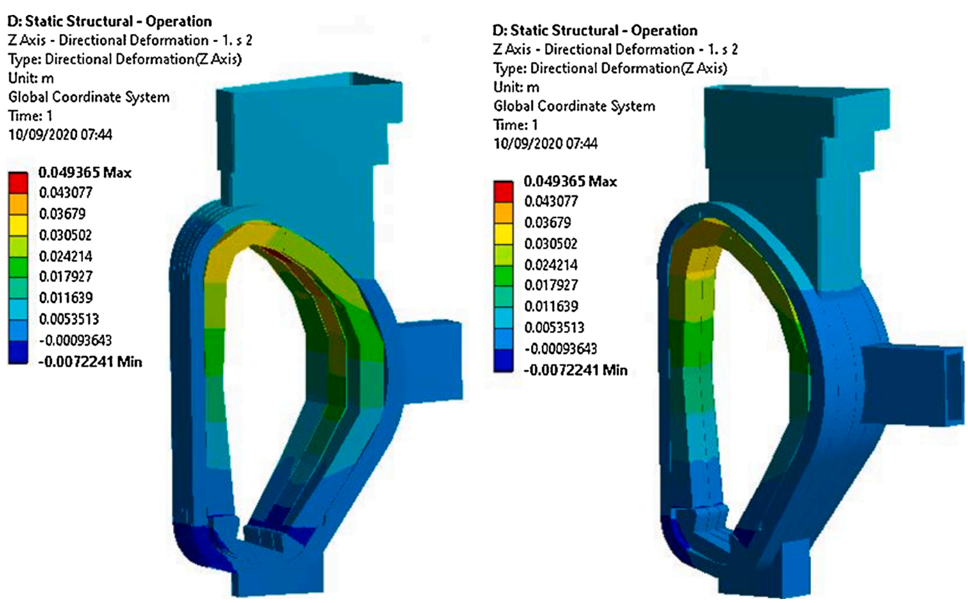

Fig. 2. Vertical displacements of the DEMO blanket attached system under loading conditions typical of NO.

3.1.1. RU

The results are reported in Fig. 3. During RU, the inner wall is shadowed as the plasma-wall contact is expected to happen in the outboard wall. Therefore, the inner wall radial/vertical misalignment does not change the HF pattern on the rest of the wall. The same consideration is valid for the vertical misalignments of the outboard segments, hence the poloidal map needs account for only radial misalignments. If the outboard segments were displaced by −20 mm, the HF_{max} on m23 would be 3.74 MW/m^2.

3.1.2. SOF

The results are reported in Fig. 4. During SOF, inboard segment misalignments have no effect on the reference heat load pattern. As vertical and radial displacements of segments produce similar results in terms of penalty factors, the worst ones have been selected for every module of the outboard segments.

3.2. FW segment flexible deformations under SOF

The results are reported in Fig. 5. As the deformations in the toroidal direction are small, they are neglected and only the radial and vertical ones are implemented in every segment. Considering that the segment deformations during the loading conditions analysed are such that the top and bottom ends are pushed outwards while the equatorial region moves inwards, the UL is the only component experiencing an edge-localized HF_{max} = 1.85 MW/m^2 as it is not shadowed anymore by the Right Outboard Segment (ROB). Under the loading condition analysed, inboard and outboard flexible deformations do not increase the HF_{max} on the wall.

3.3. Limiter radial misalignments

The study carried out on limiter radial misalignments has shown that allowable misalignment tolerances are in range ±10 mm during SOF for

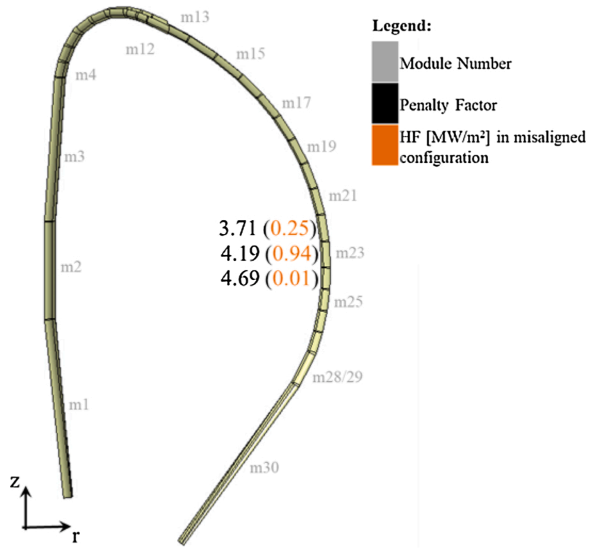

Fig. 3. Penalty factor poloidal map for ±10 mm misalignment during RU. Only penalty factors greater than 1 are shown.

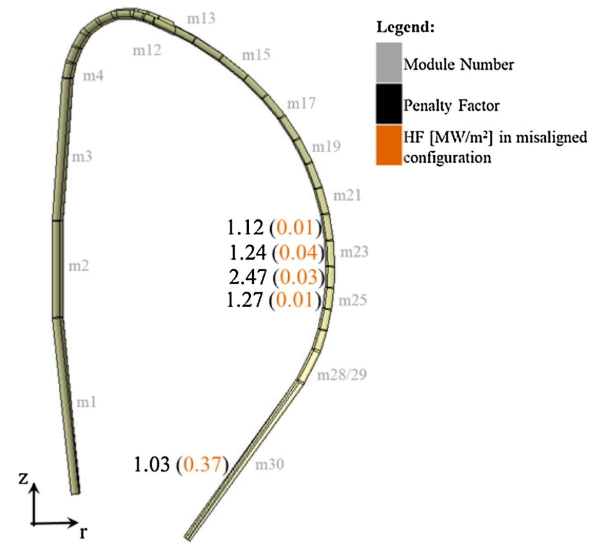

Fig. 5. Segment penalty factors for the loading condition analysed during SOF (i.e. flexible deformations). Only penalty factors greater than 1 are shown.

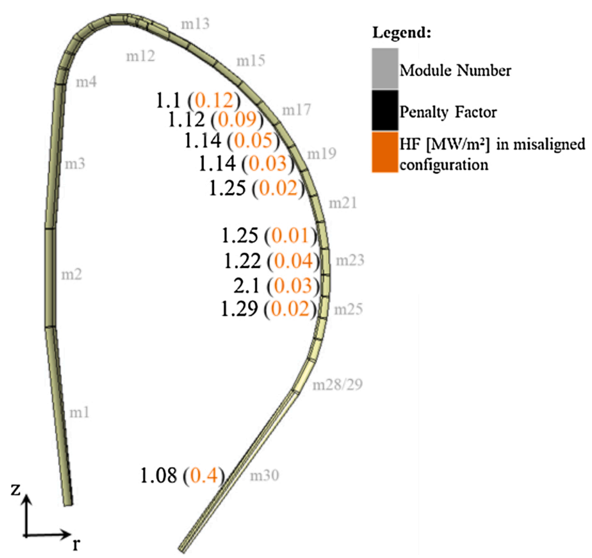

Fig. 4. Worst values of penalty factors (per module) between the −10 mm radial and vertical displacements during SOF. Only penalty factors greater than 1 are shown.

Table 1
Penalty factors for all the analyses of OML radial displacements during RU.

Rad. Displ.	f	HF_{mis}
−5	1.62	3.72
−2	1.24	2.83
2	0.78	1.80
5	0.51	1.18

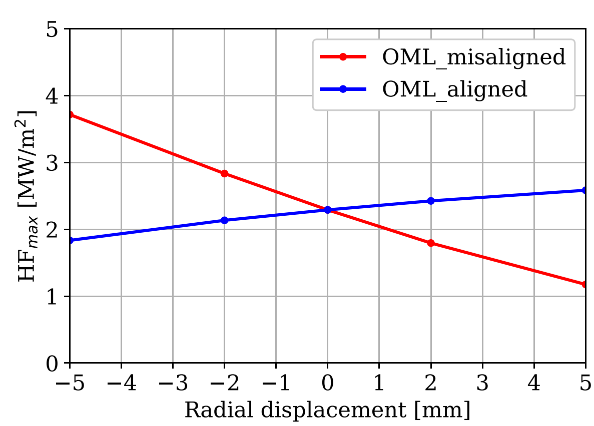

Fig. 6. Variation of the power deposition peak values on the misaligned OML (red trend line) and on the three aligned OMLs (blue trend line) for every OML misalignment case during RU. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

all the limiters but the UL, for which the admissible range is ±5 mm taking as acceptable the criterion $HF_{max} \leq 1$ MW/m^2. During NO, the range of analysed displacements for limiters does not have any effect on the segment HF pattern.

3.3.1. RU

During RU, the plasma-wall interactions are concentrated on the OML, therefore only the OML misalignments are here taken into account. It has to be noted that only one of the four OML limiters located in the 360° DEMO wall geometry is radially displaced, while all the others are kept in their aligned position. According to the OML range of adjustability once installed, the range of radial displacements is within ±5 mm. The obtained results are collected in Table 1, where displacements are expressed in mm while HF_{mis} (i.e. HF_{max} on the misaligned component) in MW/m^2.

Fig. 6 shows how the power deposition peak magnitude varies in the displaced OML for every analysed misaligned case. Furthermore, for every value of misalignment, the graph shows the related value of the power deposition peak in one of the three aligned OMLs (blue trend line in Fig. 6).

3.3.2. SOF

During SOF, all the limiters but the IML receive power coming from the plasma. Therefore, the radial displacements of all the limiters will be here analysed. For every radial displacement value taken into account, the results obtained in terms of penalty factors are reported in Table 2, where the displacements are expressed in mm while the HF_{mis} in MW/m^2.

Fig. 7 shows the variation of the maximum heat flux value on both the misaligned OML (red line) and the aligned OMLs (blue line) for every

Table 2
Penalty factor summary for all analyses of limiter radial displacements during SOF.

Rad. Displ.	OML		OLL		UL	
	f	HF_{mis}	f	HF_{mis}	f	HF_{mis}
−10	–	–	1.17	0.13	2.34	1.98
−5	1.09	0.64	1.08	0.12	1.61	1.35
−2	1.03	0.61	1.03	0.11	1.01	0.85
2	0.97	0.57	0.97	0.1	0.99	0.84
5	0.92	0.54	0.92	0.1	0.98	0.83
10	–	–	0.86	0.09	0.96	0.81

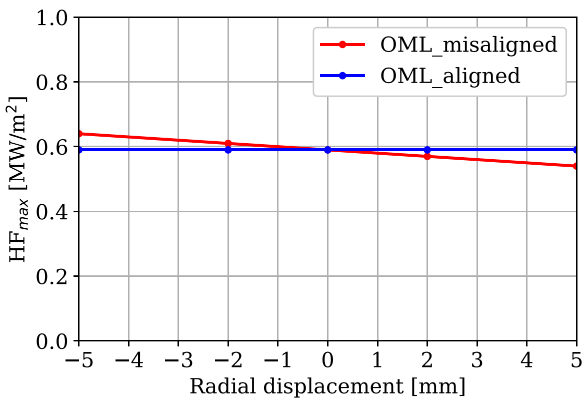

Fig. 7. Variation of the power deposition peak values on the misaligned OML (red trend line) and on the three aligned OMLs (blue trend line) for every OML misalignment case during SOF. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

OML radial displacement. Since during SOF the plasma is meant to be ≈225 mm away from the wall [7], the HF_{max} on the misaligned OML increases less in magnitude than during the RU as the inward radial displacement increases.

4. Conclusions

The latest design of the FW equipped with limiters, which has been released in early 2020, works safely in NO and copes well with small radial misalignments under charged particle heat loads.

Radial and vertical segment displacements, together with radial misalignment of the limiters, have been analysed for understanding the way they affect the reference heat load pattern due to charged particles. Furthermore, a novel approach for implementing differential deformations along the poloidal direction of segments due to loads typical of NO has been developed with the aim of studying the impact on the charged particle heat load of the induced flexible deformations.

The misalignment study is a powerful means through which assessing the design effectiveness, as well as the usefulness of mechanical constraint modelling. As far as the present study is concerned, its main outcomes can be summarized by the following conclusions:

- any misalignment of the inner segments does not affect the reference power deposition pattern during SOF. This is also valid during RU as the plasma-wall interaction occurs on the outer wall, leaving the inner wall completely shadowed;
- during NO, allowable segment misalignment tolerances are in the range ±10 mm, limited by the results obtained for the RU as a −20 mm misalignment causes the outer segments to act as a “limiter”, which raises the HF_{max} above 1 MW/m^2. If the ±10 mm misalignment range is too challenging from manufacturing, assembly, and operational point of view, increasing the protrusion of the OML might offer a solution, however the impact of the OML increased protrusion should be first studied;
- during SOF, admissible misalignment tolerances are in the range ±10 mm for all the limiters except for the UL, for which the admissible range ±5 mm keeps the HF_{max} below 1 MW/m^2;
- the methodology adopted for implementing differential deformations along the poloidal segments provides an opportunity to investigate the heat load pattern on the wall due to operational loading conditions that temporarily deform the layout of the FW, thereby providing support to the FW design and modelling activities in its optioneering phase.

CRediT authorship contribution statement

M.L. Richiusa: Conceptualization, Methodology, Formal analysis, Software, Validation, Investigation, Visualization, Writing – Review & Editing.
W. Arter: Methodology, Formal analysis, Software, Validation, Investigation, Visualization, Writing – Review & Editing.
M. Firdaouss: Methodology, Formal analysis, Software, Validation, Investigation, Visualization.
J. Gerardin: Methodology, Formal analysis, Software, Validation, Investigation, Visualization, Writing – Review & Editing.
F. Maviglia: Supervision, Project administration.
Z. Vizvary: Conceptualization, Methodology, Formal analysis, Software, Validation, Investigation, Visualization, Writing – Review & Editing.

Declaration of Competing Interest

The authors report no declarations of interest.

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