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D Wolff et al.

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The Impact on Remote Maintenance of Varying the Aspect Ratio and Number of TF Coils for DEMO

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As part of the conceptual design studies for a European DEMO, different tokamak geometries are being considered. As identified in the EFDA Roadmap to the realisation of Fusion Energy, 2013: "*The integration of the Remote Maintenance system within the DEMO plant is an essential task within the DEMO CDA phase. This will involve establishing requirements, functions and interfaces with many other systems to ensure that plant availability and maintainability are considered from the outset.*"

In order to fulfil this integration requirement different geometries of DEMO have been assessed for their impact on remote maintenance (RM). The aspect ratio and number of TF coils have been identified as the pivotal variables, driving the tokamak geometry, with significant effects on remote maintenance both in terms of technical feasibility and speed of operation. Tokamak geometries with aspect ratios from 2.6 to 4.0 and 16 or 18 TF coils have been compared. The results of this evaluation show that higher aspect ratios and lower numbers of TF coils are beneficial to RM both in terms of technical feasibility and speed of operations. To deliver a maintainable DEMO, efforts must be made to maximize its aspect ratio and minimize the number of TF coils.

Keywords: Integration, Optimization, Systems Engineering, Remote Maintenance, Holistic Design, Tokamak Geometry

1. Introduction

In defining the concept design of the DEMO Remote Maintenance (RM) system it has always been apparent that the number of TF coils and the aspect ratio specified for the DEMO tokamak will have a major impact. This paper sets out to quantify the effect of varying the number of TF coils and the aspect ratio of DEMO on its RM system, in terms of technical feasibility and speed of remote maintenance operations. It compares tokamak geometries with aspect ratios from 2.6 to 4.0 and 16 or 18 TF coils.

2. Tokamak geometries considered

The basis of the analysis was to compare alternative tokamak geometries to Eurofusion's 2015 baseline. The four other geometries considered were; Eurofusion's 2014 baseline, a 16 TF coil variant with the 2015 baseline aspect ratio (2014-15 Intermediate) generated by RACE, a reduced aspect ratio / 18 TF coil variant (Reduced AR (TF 18)) generated by the Programme Management Unit (PMU) of Eurofusion, and finally the same reduced aspect ratio variant but with 16 TF coils (Reduced AR (TF 16)) generated by RACE. The top level parameters of the five tokamak geometries considered are shown in table 1 and the relative sizes in figure 1. All geometries followed the same blanket segmentation, with two inboard blanket multi-module segments (MMS) and three outboard MMS per sector.

Table 1. Dimensions of the geometries considered.

[PFS – Plasma Facing Surface] Dimension	2014 Baseline	2014-15 Intermediate	2015 Baseline	Reduced AR (TF 16)	Reduced AR (TF 18)
Aspect Ratio	4.0	3.1	3.1	2.6	2.6
Number of TF coils	16	16	18	16	18
Inboard PFS Radius at Mid-plane (m)	6.6	5.9	5.9	5.6	5.6
Outboard PFS Radius at Mid-plane (m)	11.4	12.2	12.2	13.3	13.3
Height from Mid-plane to Top PFS (m)	3.9	5.2	5.2	7.0	7.0

3. Factors considered

Tokamak geometries were compared in terms of the speed and technical feasibility of carrying out RM operations, using key performance related parameters,

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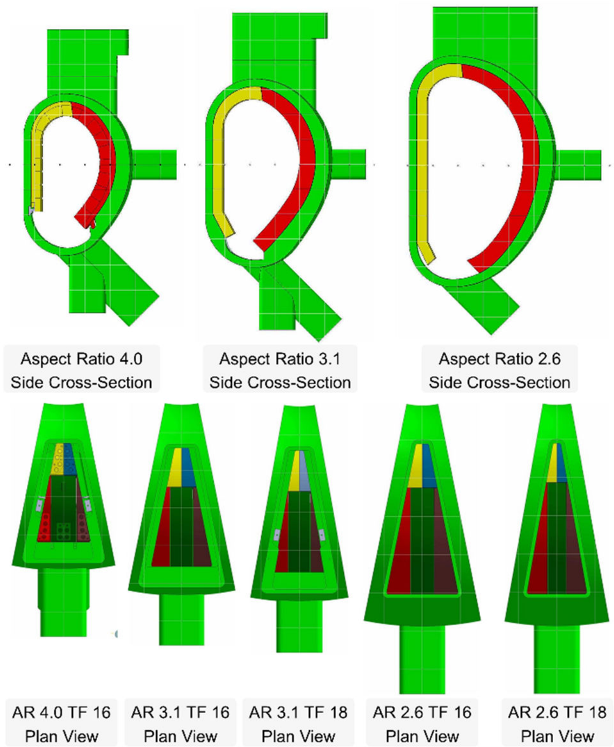

Fig. 1. Comparative sizes of the DEMO geometries considered.

with appropriate weightings applied, as defined by RM experts from RACE. The parameters focus on the removal and replacement of the blanket multi-module segments (MMS) through the upper vertical ports, as this is deemed to be one of the main drivers for the speed and technical feasibility of the RM in DEMO. The following key parameters were used to compare the different geometries:

- **Total number of Blanket segments.**

The total number of blanket segments correlates strongly with the overall time required to carry out maintenance of DEMO.

- **Blanket manifold slenderness ratio.**

The blanket manifold slenderness ratio is a measure of how flexible the MMS is. It was calculated by dividing the Blanket segment length by the minimum radius of gyration of the MMS manifold. It is assumed that all structural loads in the MMS are taken by the manifold. A more flexible MMS requires slower RM speed and more complex collision avoidance controls.

- **Number of kinematic steps to remove a Blanket segment.**

This is the number of distinct movements (translations or rotations) that each MMS will need to go through in order to be extracted from the tokamak. This has been determined from a first pass look at the likely routing for the MMS, ignoring minor clashes which have yet to be resolved and not taking into account any movements that may be driven by tooling geometry. If a greater number of translations and rotations are required to remove an MMS, removal (and replacement) will be slower and require a more complex control system and tooling.

- **Equivalent tooling stress.**

This is a measure of the load the MMS removal/replacement tooling will carry, relative to the space to package that tooling. It was calculated by dividing the approximated gravitational load of the blanket segment being considered by the cross-sectional area of upper port in which the lifting and manipulation tooling must be housed. A higher stress equates to, more challenges in the design, packaging and operation of the RM tooling for MMS removal and replacement.

- **Equivalent stress at the Blanket lifting interface**

This specifically considers the stress at the interface between the MMS and the lifting tooling. Higher stress here will make designing and operating the removal/replacement tooling more difficult. It was calculated by dividing the approximated gravitational load of the blanket segment being considered by the cross-sectional area of the same blanket segment that is accessible through the upper port.

- **Torque at the Blanket lifting interface.**

Another key parameter affecting the tooling design and operational envelope will be the moment arm from the lifting point to the MMS centre of gravity – assuming a homogeneous mass distribution. Here this is coupled with the approximated gravitational load of the blanket segment being considered to give a torque figure. The higher this torque value, the more difficult it will be to design, package and operate RM tooling in the required space to manoeuvre the blanket segments.

- **Area ratio between the Blanket being handled and the aperture through which it must pass.**

This is the total cross-sectional area of the MMS being considered when viewed from above divided by the cross-sectional area of the upper vertical port available for that MMS to exit/enter through, also viewed from above. As the area ratio reduces, the room for manoeuvre of the MMS increases, making extraction easier and clashes less likely. Greater clearance for the MMS during removal and replacement will lead to a simple movement control system and scope for faster moves.

4. Relative weighting of comparison parameters

In order to ensure the relative effect of the different parameters on RM Speed and RM Technical Feasibility was properly captured, the Analytical Hierarchy Process (AHP) was applied. First, a pairwise comparison of all parameters was carried out by a group of RM experts from RACE, separately in terms of both RM Speed and RM Technical Feasibility. The relative effect of each pair of parameters on the two criteria was determined using a scale from 1 (equal) to 5 (strong difference). This generated a pair of matrices from which the eigenvectors were then calculated. Which the AHP shows are representative of the relative importance of the parameters [1]. These were then applied in the calculation of the RM Speed Index (RMSI) and the RM Technical Feasibility Index (RMTFI) for each geometry being considered.

Tables 2 shows the relative effect of the different parameters on speed of RM operations and technical feasibility of RM.

Table 2. Speed and technical feasibility weighting calculated using the Analytical Hierarchy Process (AHP).

Parameter (see Sec. 3 for details)	RM speed weighting	RM technical feasibility weighting
Total number of blanket segments	0.40	0.03
Manifold slenderness ratio	0.18	0.14
Kinematic steps to remove MMS	0.12	0.05
Equivalent Tooling Stress	0.04	0.19
Equivalent Interface Stress	0.04	0.19
Interface Torque	0.06	0.30
Area ratio	0.14	0.09

5. Comparison methodology

In order to compare the different geometries in terms of both RM technical feasibility and speed using the identified parameters the proceeding methodology was followed:

First, all parameter values were determined from the CAD models of the five different geometry variants. In the case of Eurofusion's 2015 baseline, this involved first applying previously agreed changes to the blanket segmentation to ensure that the kinematics of each MMS removal were feasible. For all the other geometry variants the blanket segmentation was established based on the same principles.

Having gathered all parameter variables for each variant, the approach differs for the speed and technical feasibility. To compare the speed of RM operations the aim was to get an overall evaluation of the relative time taken to remove a full set of blanket segments. However, for the technical feasibility the intention was to compare the worst case for each parameter type.

5.1 Remote Maintenance Speed Index (RMSI)

The RMSI is a measure of the impact of each geometry variant on the speed with which RM operations can be completed. A higher RMSI equates to faster RM operations.

In order to compare the speed of RM the next step was to normalize each of the parameters to a dimensionless figure relative to the values for the 2015 baseline. This was done by dividing each parameter value for each MMS type by the corresponding value for the 2015 baseline. This gave an unweighted index value for each parameter of each geometry variant.

The speed weightings in table 2 were then applied separately to each unweighted index value to take account of the magnitude of the effect of the parameter on RM speed. This gave a weighted index value for RM speed for each parameter of each geometry variant.

For each geometry variant the weighted parameters were then combined to give an RM Speed Index (RMSI) for each MMS type. This was calculated by finding the inverse of the product of all individual parameters, weighted for speed, related to each MMS type. This gave an RMSI for each MMS type of each geometry variant.

Finally, the average of the MMS type RMSIs was calculated for each geometry variant. These values can now be used to compare each geometry variant considered and any future variants in terms of their effect on RM speed.

5.1 Remote Maintenance Technical Feasibility Index (RMTFI)

The RMTFI is a measure of the impact of each geometry variant on the technical feasibility of designing an RM system capable of carrying out the required maintenance. A higher RMTFI equates to a geometry that is more technically feasible to maintain.

To compare the technical feasibility of maintaining the different geometries with RM, first the worst case for each of the parameter types described in section 3 was found for each geometry variant. As, for all the parameters considered, lower values correlate with improved technical feasibility the worst case was the maximum value from the five MMS types. The next step was to normalize each of these worst case values relative to the values for the 2015 baseline. This gave an unweighted index value for each parameter of each geometry variant.

The technical feasibility weightings in table 2 were then applied separately to each unweighted index value to take account of the magnitude of the effect of the parameter on RM technical feasibility. This gave a weighted index value for RM technical feasibility for each parameter of each geometry variant.

For each geometry variant the weighted parameters were then combined to give an overall RM Technical Feasibility Index (RMTFI). This was calculated by finding the inverse of the product of all individual parameters, weighted for technical feasibility, for that geometry variant. These RMTFI values can now be used to compare each geometry variant considered and any future variants in terms of their effect on RM technical feasibility.

6. Results

The calculated values for RMSI & RMFTI are shown in tables 3 & 4. They show that both RMTFI & RMSI increase with increasing aspect ratio (physically smaller machines) and decreasing number of TF coils.

Table 3. Remote Maintenance Speed Index (RMSI) values for the five geometry variants considered

RMSI		Aspect Ratio		
		2.6	3.1	4.0
No of TF coils	16	0.97	1.06	1.13
	18	0.93	1.00	

Table 4. Remote Maintenance Technical Feasibility Index (RMTFI) values for the five geometry variants considered

RMTFI		Aspect Ratio		
		2.6	3.1	4.0
No of TF coils	16	0.90	1.04	1.12
	18	0.86	1.00	

7. Conclusion

Having reviewed the results of this investigation the following conclusions can be drawn:

- Those EU DEMO geometries with a higher aspect ratio are faster to remotely maintain than geometries with lower aspect ratios. This is logical as higher aspect ratios equate to a smaller machine with shorter, lighter MMS, enabling quicker movements and shorter path lengths for those MMS to travel along.
- Remote Maintenance of EU DEMO geometries with a higher aspect ratio is more technically feasible than lower aspect ratio geometries. Again this follows as the shorter, lighter MMS of a smaller, higher aspect ratio machine make design of the tooling and control system to manipulate it, easier.
- EU DEMO geometries with a lower number of TF coils are faster to remotely maintain than those with more TF coils. This is very simply down to there being less parts to be maintained and hence overall shorter maintenance durations.
- Remote Maintenance of EU DEMO geometries with a lower number of TF coils is more technically feasible than for higher numbers of TF coils. This can be largely attributed to the relative increase in the size of the upper port allowing more space in which to package the RM tooling.
- From a remote maintenance perspective, both in terms of technical feasibility and speed, of the geometry variants considered, the Eurofusion 2014 Baseline is the optimum design. This is owing to the fact that this is the geometry variant with the smallest number of TF coils and largest aspect ratio.

In order to deliver a DEMO machine that can be maintained, efforts must be made to maximise the aspect ratio of the device and minimise the number of TF coils. Should the ability to alter these parameters be limited by other overriding considerations, then significant resources must be allocated at an early stage to developing RM solutions. Different alternatives should be developed and evaluated making use of proof of principle tests to drive up the Technology Readiness Levels of candidate solutions. However, this will not guarantee that a suitable RM solution can be achieved.

Through- life cost is a key element of proving the viability of a future Fusion Power Station. It is therefore vital that efforts are made to ensure that the cost of operating DEMO is minimized. If an RM solution can be found that is sufficiently robust, the primary maintenance cost driver becomes the speed with which RM operations can be carried out. Therefore, from a maintenance perspective, minimizing the number of TF coils and maximizing the aspect ratio of the DEMO machine will also reduce the through life cost.

Maintenance however cannot be considered in isolation and is only one aspect that must be taken into account when trying to develop the optimum design of DEMO.

8. Future work

Thus far only a limited range of geometries have been considered. This methodology could be used to explore a wider range of geometries, different geometry parameters and alternative blanket segmentation.

Currently the Indices are solely focussed on the blanket replacement aspects of RM. Other RM activities could also be considered, with relative priorities.

Ultimately this work should form part of wider decision making process to decide the optimum DEMO geometry taking account of the needs of all the various stakeholders.

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