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Issues of the Vertical Blanket Segment Architecture in DEMO: current progress and resolution strategies

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Due to the limited irradiation lifetime of the structural material used for in-vessel components in DEMO, and subsequent future fusion power plants, it will be necessary to replace all breeding blankets within the given planned maintenance window in order to meet DEMO availability targets [1, 2]. It is assumed that failure of in-vessel components cannot be excluded, whilst in-situ repair is unrealistic. Hence the replacement of individual breeder blankets must be technically feasible. As such, remote maintenance replacement of the breeding blankets is a mission critical operation. The baseline concept utilises vertical segment architecture to aid in the removal of the blankets [3]. This choice impacts on the tokamak and plant architecture and also affects operational maintenance strategy. Within the EUROfusion PPPT program efforts have been made to perform cross work package investigations on eight Key Integration Issues needed to show the feasibility of the DEMO pre-concept design [4]. Key Design Issue 4 is an investigation into the feasibility of the Vertical Segment Architecture blanket feasibility.

The present work documents the approach, current progress and developments within this investigation. This includes the strategy, identified risks and proposed solutions. An alternative variant, an Equatorial Divided Blanket Segment is also proposed. A design overview and the impacts, both positive and challenging, on the design of the affected systems are provided and evaluation criteria are proposed. The removal of breeding blankets and replacement with new or refurbished components is a complex operation. It will require the interfacing and developing of multiple systems and components. Due to the performance trade-off between the operational performance of in-vessel components and the remote handling suitability, the interrelationships and possible interacting challenges of extracting breeder blankets needs to be consider at the pre-concept design stage.

Keywords: DEMO, tokamak, design integration, plasma-wall interaction, breeding blanket.

1 INTRODUCTION

The purpose of the Key Design Issue no. 4 is to consider the *vertical maintenance* approach as a system of components. Originally one configuration of design was considered. Now, due to newly identified issues and technical challenges centred on the extraction of the breeder blanket (BB) segments, an alternative variant is also being investigated. This has been combined with new opportunities from adjacent Key Design Integration Issues (KDII) KDI#1(*Design, performance and feasibility of wall protection limiters during plasma transients*) and KDI#3 (*Advanced Magnetic Configurations*) [5].

2 MOTIVATION

A power plant like fusion reactor such as DEMO must address the challenges of maintenance. Maintenance will be necessary to replace in-vessel components (IVCs) due to the degradation of the structural materials by high energy neutrons produced by the plasma [4] and possible IVC failures. Due to many of the components and volumes within the facility becoming irradiated, it will be necessary to perform maintenance using RM systems to protect human operators from radiation streaming and contaminated particulates.

Present fusion devices must perform maintenance activities in order to maintain the operation of a reactor for experiments, thus provide adequate operational time deemed acceptable by stake holders. In the case of DEMO, which will have to demonstrate a closed tritium cycle [1], the maintenance operations will be bounded by achieving high plant availability and therefore become mission critical to success of DEMO [2].

The KDI#4 approaches the challenge of vertical maintenance from a system level. Ownership of vertical segment architecture is by the Power Plant Physics and Technology (PPPT) team as a Lead System Integrator (LSI). The KDI4 is being developed for consideration as one of eight KDII [5]. Transport corridors and the Active Maintenance Facility (AMF) are considered out of scope for this investigation. The total mass of IVCs between the variants will not change substantially to warrant the inclusion of an analysis of the AMF and transport options. This would strain available resources and implementation time to the effect of reducing the clarity of results to non-satisfactory resolution.

3 STRATEGY

Development of power plant like reactors has been focused on either Vertical Segment Architecture or Large Port Maintenance Systems [6]. Alternatives forms of vertical maintenance architecture have been investigated before [3], but the currently considered configuration is that of the Large Vertical Port configuration [7]. The KDI#4 approaches the feasibility of the vertical segment architecture by breaking down the study into, **Ports**, **In-vessel Components**, **Operations** and **Safety**. The in-vessel components focus on development of the BB segments and the Divertor cassettes. The three **Ports** to be considered are the **Upper Port** [8], **Equatorial Port** [9], and **Lower Port** [10]. Considering the ports is as important as the IVCs, essential tokamak services will require routing through the ports, as well as the ports providing the transport flight paths. Upper Port dimensions are constrained by the toroidal and poloidal magnets [8], **Operations** refer to the development of equipment that will perform any maintenance operations. **Safety** is a critical aspect of the vertical segment architecture feasibility in order to allow the plant to gain license to operate. These are replicated for both investigated variant configuration, which are described below.

4 VARIANTS

Another purpose of the KDII is to capture the variants of the design space currently being considered. For the KDI#4 the following variants are considered shown in *Table 1*. This gives three variant configurations that will be considered; 1) Full Blanket Segment Single Null (FBSSN), 2.) Equatorial Split Blanket Double Null (ESBDN) shown in Figure 1, 3.) Equatorial Split Blanket Single Null (ESBSN), (not shown). It can be noted that the ESNSN configuration employs an inner divertor target integrated into the BB segment, and separated small 'keystone' outer cassette body (A).

The first two variant configurations are to be considered in the program, the third is not to be actively investigated, although due to overlaps in the designs, issues, risk and solutions that apply will be captured by the other two. The aim of the assessment is to develop workable solutions for each variant configuration with identified technical issues and system readiness level to inform the engineering stage planning.

Table 1. Design Variants within KDI#4

System or Work Package	Variant Title
Segmentation of Breeder Blanket (major)	Full Inboard/Outboard segment
	Half Poloidal Inboard/Outboard segment
Divertor Configuration (major)	Single Null, Large Upper Port
	Double Null, Larger Upper and Lower Port
WPBB - Breeder Blanket Type (minor)	Helium Cooled Pebble Bed (HCPB)
	Water Cooled Liquid Lithium (WCLL)
WPRM - Blanket Transport Maintenance Cell Options (minor)	Cask Transport Option
	Hot Cell Transport Option

Full Blanket Segment Single Null (FBSSN)

The FBSSN is the currently considered DEMO configuration shown in [7]. The BB segments comprise of two inboard (LIB, RIB) and three out board segments (LOB, COB, ROB) [11].

Identified challenges to be addressed here (highlighted in Figure 2) include the structural suitability of the BB segments (A) and BB lifting interfaces (B) when lifted and suitability of the VV as a primary confinement boundary in drop load scenario (C). The time required to complete all RM operations must be considered to meet availability requirements (D). Integration of essential plant systems (plasma limiters, heating and current drive systems, diagnostics, and Services) through all **Ports** must also be addressed (E). BB segments to VV attachments must also be considered as well as to

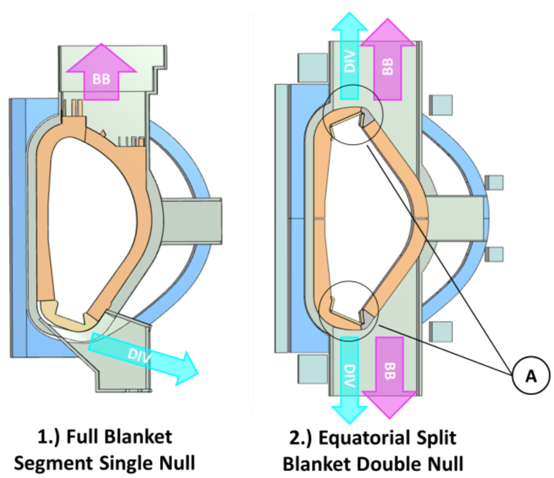

Figure 1. Variant Configuration with in-vessel component extraction paths shown. (A) – key stone outer divertor leg.

ensure suitable first wall alignment (F). RM systems are being developed to service pipe connections in confined and radioactive environments (G).

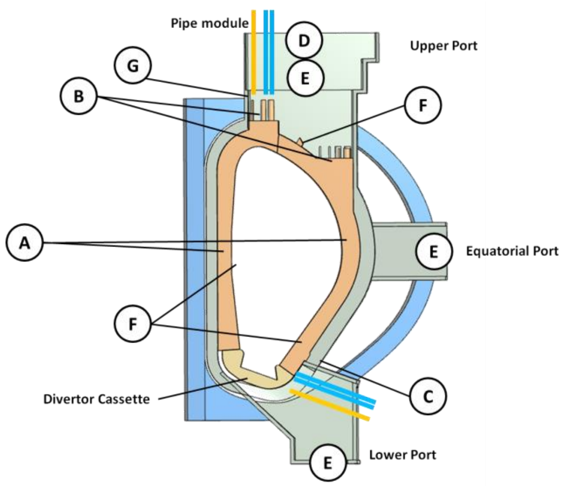

Figure 2. Design Issues Highlighted on FBSSN configuration

The BB Transporter is the key RM system for removal of BB segments via the vertical port. Due to the high radiation field (1000Sv/h) [4] the use of in-vessel movers as the primary extraction method for components would limit the device lifespan. Instead, the strategy is to have large components that can be manipulated by RM equipment whilst remaining in the port space which has a lower radiation field. Still, there are technical challenges [12] to RM equipment such as high tolerance movements (20mm alignment), complex kinematics with slender, deforming payloads (up to 10mm) and challenging RM operational scenarios.

The BB Transporter has evolved to a Hybrid Kinematic Mechanism [13] selected for further development. A Proof of Principle (PoP) concluded that the FBSSN was driving challenging design requirements on to the BB Transporter. Peak stresses have been shown to be high without accounting for dynamic effect and safety factors. These challenges are driven by the BB removal kinematics and the high BB payloads (≈90 tonnes). Possible solutions have been identified to prevent or mitigate the fault scenarios, but they require further engineering substantiation [14]. There is a need to identify components that can be integrated into the design that are available on the market or investigate the requirements of developing modified or bespoke components. Bespoke items would require testing to gain confidence (no backup expertise). Input from external experts considers that the design complexity will only increase as the solution is 'nuclearized' and represents a significant risk to the viability of the solution [15].

Alternative solutions for BB transporter were also considered [16] comprising of a Counterweight Mechanism and an L-shaped lifting arm. The intention of using a counterweight mechanism is to reduce complexity of BB removal kinematics and thus eliminate the bending moment induced on the BB transporter by the lifting interface. An overhead travelling crane would then provide the lifting capability of the BB segment, but only resolve the vertical forces as this interface would not transfer horizontal or bending moment forces. This concept generates other technical challenges however. Even when the payload is balanced with the centre of gravity below the lifting of the BB segment, rotation of the BB segment about the lifting point will occur in the toroidal plane. This will either require a dynamic counterweight to adjust to the movements or actuators positioned in the maintenance hall above. As identified in [16] there are two main uncertainties that cannot be confirmed which load the BB segment during transport; a) Low certainty of BB deforming dynamics after operation. b) Residual magnetic fields.

A following task will be for the WPRM team to perform a *sensitivity analysis* on the main load driving requirement of the BB extraction and replacement. It was recommended by the DEMO Technical Advisory Group [on review of KDI#4 strategy] that a poloidal de-optimized machine be investigated to allow for a larger vertical port to be designed, simplifying the kinematics of BB extraction. This is an attractive solution, although considering the upper port is constrained by the toroidal and poloidal magnets [8] the size increase will be limited, thus the kinematic improvement opportunities is limited as well. Due to limited resource allocations, this activity will be planned for the concept phase when more data will be available from the BB transport loading *sensitivity analysis*.

The review also highlighted a load drop scenario when lifting the BB. A dropped BB (≈90tonnes) from the height of 9.0m will have a kinetic energy of order magnitude 7.9MJ. The Vacuum Vessel (VV) must be able to withstand such an impact and remain an intact primary confinement boundary. Mitigation activities could potentially include dual load path safety cables on payload, the insertion of sacrificial impulse reducing cassettes (given that the divertor cassettes are removed during BB replacement) or temporary relocating of the primary confinement boundary outside of the VV during maintenance operations. The DEMO safety team will lead the classification of accident scenarios to assess the worst case load drop scenario in vessel. The load drop scenario must be addressed at the design stage [17] to allow the DEMO program to develop.

The seismic response was shown to be a driver of high loads within the BB transporter. Tasks within the PPPT will investigate ways to reduce seismic response frequency on the VV and upper ports. Adjacent KDII activities KDI#1 and KDI#3 have proposed the variant of a double null configuration. For KDI#1 the double null may improve plasma vertical stability [18] From KDI#3 the DN concept may improve machine performance in power distribution to top and bottom divertor targets, as in [19]. If both presumptions hold true, it will still be necessary to show that a DN configuration is feasible from an RM stand point as well. Modifications to the component configuration created by a using a DN divertor will also require further investigation to assess RM feasibility.

Further, this may allow for improved kinematics and smaller payloads, which will be key to resolving BB transporter design issues. It was considered that as the program is at the pre-concept stage, the program should capitalize on the opportunity to investigate different configurations that still used vertical maintenance.

Equatorial Split Blanket Double Null (ESBDN)

Splitting of the BB segments about the mid plane equatorial level will thus result in 10 separate BB segments per VV sector. Extraction of all of these BB segments through the upper port would require a long reach transporter to engage with the lower BB segments. This would create increased moments on the BB transporter arm. Instead, lower BB segments will be extracted through a lower vertical port. This will require reconfiguration of the reactor to allow for movement of the IVCs. The design shows radially decoupled inner and outer divertor targets. The inner is integrated into the inner BB segment and the outer into a 'keystone' component design. This will be investigated to consider impacts on RM durations.

The ESBDN design creates new technical issues that will be addressed. Many of these issues were already highlighted in work completed prior to the KDII in [20] and the RM evaluation the alternative configuration [21]. Figure 3 shows the following technical issues highlighted on an in-vessel cross section.

Dividing of the components within the reactor will require additional pipe services to supply in-vessel components with coolant or LiPb/helium purge gas, depending on the BB concept. More service connections will need to be disconnected and reconnected creating an increased burden on RM operations to remove in-vessel components in a timely manner (A) [Figure 3]. Secondly, the increased number of pipe services will have to be routed through the ports and out of the machine creating increased configuration challenges, these will be investigated further (B). It could be concluded initially that due to sub-division of components, individual segments will require smaller bore pipe services as they will demand lower flow rates. However, the minimum pipe bore diameters and bending radii are limited by the use of in-bore cutting and welding RM systems [22], driven by environmental conditions, space constraint, and plant availability.

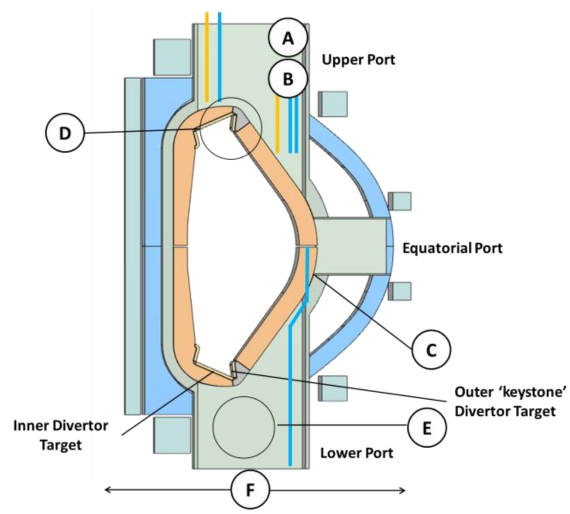

Figure 3. Design Issues Highlighted on ESBDN configuration

Sub-division of the BB segments will be investigated to assess the impacts on the feasibility of the BB operation. WCLL BB segments will require LiPb draining before removal. This is done via a drainage pipe routed through the lower port. For the upper BB segments in the ESBDN drainage will still be required. This will require an alternative drainage means (C). Either a separate drainage pipe running down along the VV inner shell or routing through (all) equatorial ports are options that could be considered. The former creates the aforementioned challenges of extra services and the latter the challenges of service maintenance in-vessel or via the equatorial port which will have very limiting spatial constraints on RM systems and increase the number of ports to be accessed and hence the overall complexity of the operation. BB to VV attachment will be reviewed to consider any required design updates (D).

The handling of the lower in-vessel components will undergo redesign to now considering lowering of in-vessel components via a large vertical lower port. This will require the development of new handling systems to react the loads of 40+tonne components through challenging kinematics with the payload positioned above the mechanism (E).

To accommodate a re-configured lower vertical port and lower port RM operations the tokamak complex basemat must be lowered It also creates new design challenges to be investigated, in particular the integration of the magnet feeders and torus vacuum pumps and the development of RM transport systems and corridors, which will be a focus of KDI#4variant work plan (F).

There will be a challenge to evolve the DN split segment concept to this level of maturity of design resolution, due to timescales and available resources. To aid this, system readiness levels have been proposed to aid in comparison between variants.

5 CONCLUSIONS

Cross collaboration and opportunity capitalisation has been implemented between adjacent KDII. Following newly identified BB transporter challenges the KDI#4 was redefined; hence the question of vertical maintenance is now better understood. Issues that could have fallen between the gaps of parallel work packages have been identified and allocated in accordance with the KDII approach. With the exploration of new variants new technical issues were identified. The KDI#4 work plan now addresses these on the run up to the 2020 Pre-Concept Gate Review.

Acknowledgments

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