UKAEA-CCFE-CP(21)01

J. Keep, T. Berry, S. Budden, B. Chuilon, B. Colling, E. Flynn, S. Ha, C. Jackson, G. Keech, W. Leong, G. Mathew, E. Organ, C. Shaw, A. Wilde

DEMO Double Null architectural study

DEMO Double Null architectural study

J. Keep, T. Berry, S. Budden, B. Chuilon, B. Colling, E. Flynn, S. Ha, C. Jackson, G. Keech, W. Leong, G. Mathew, E. Organ, C. Shaw, A. Wilde

This paper has been submitted to
31st Symposium on Fusion Technology (SOFT), Dubrovnik, Croatia, 20 - 25 September 2020

DEMO Double Null architectural study

J. Keep, T. Berry, S. Budden, B. Chuilon, B. Colling, E. Flynn, S. Ha, C. Jackson, G. Keech, W. Leong, G. Mathew, E. Organ, C. Shaw, A. Wilde

RACE, UKAEA, Culham Science Centre, Oxfordshire, United Kingdom

DEMO is a key part of the EU fusion roadmap, and the programme reaches the end of the pre-conceptual phase with a gate review in 2020. As part of the work to complete this phase, eight Key Design Integration Issues (KDII's) have been identified as critical to the programme. Two of these KDII's identified a requirement for a more detailed architectural study. Within KDII#3 (advanced divertor configurations) a double null configuration has been developed; in parallel KDII#4 (vertical segment architecture) identified a need to evaluate a split breeding blanket architecture. These two requirements were combined into a single study that assesses the in-vessel architecture for a double null DEMO featuring split breeding blankets.

This paper presents the configurations developed and an evaluation of their feasibility with respect to integration of key in-vessel components (breeding blankets, divertors), port hardware (service pipes, shielding, vacuum pumping), and maintenance strategy. Furthermore, wider considerations such as the impact of the port orientation on the building architecture are also included. Finally, this paper will identify the risks and further work required to advance the double null configuration.

Keywords: DEMO, Double Null, Remote maintenance,

1. Introduction

Eight Key Design Integration Issues (KDII) have been highlighted as critical to the DEMO programme [1,2]. KDII#4 concerns the feasibility of the vertical segment based architecture that has been used within the DEMO baseline. This architecture leads to large blanket segments that must be removed through a vertical port. The size of the port is mostly constrained by the space between the TF coils. The manoeuvres and manipulation required are seen as a major challenge for maintenance [3,4]. One possible approach to address the issue could be to split the breeding blankets, reducing the mass and size, with the aim to reduce the loads on the blanket transporter and simplify the kinematics.

Within KDII#3, which is evaluating alternative divertor configurations, a Double Null (DN) divertor concept has been studied. Initial evaluation has been completed to give a magnet configuration and initial feasibility [5]. The symmetry of the double null design lends itself to a split blanket solution. This provided an opportunity to combine an extended study for the DN configuration with an evaluation of the maintenance of a split blanket tokamak configuration.

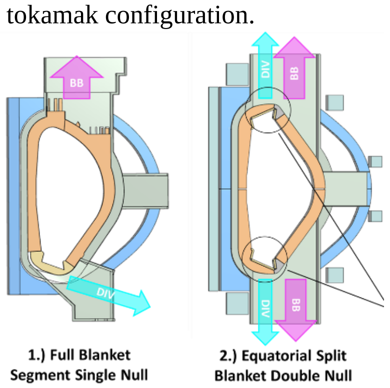


Figure 1-1: Initial split blanket double null configuration

The initial proposed configuration is shown in figure 1-1. Once the study was completed it was clear that by studying this configuration in comparison to the existing DEMO baseline design, further results could be extrapolated to other configuration options as shown in figure. 1-2:

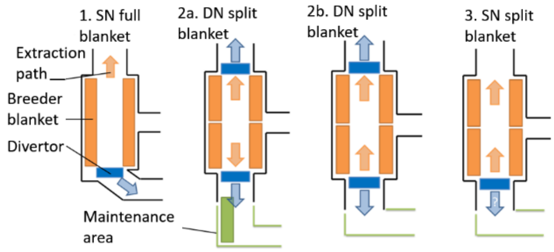


Figure 1-2: Potential blanket and divertor configurations

This paper provides an overview of a short agile study carried out to evaluate the options for a double null design featuring poloidally split breeding blankets. This study was carefully bounded, looking for initial feasibility and identification of risks rather than aiming to provide detailed analysis of every element of the design – allowing rapid progress within the study. This was enabled by three main actions:

1. Clear identification of design scope
2. Identification of a short list of key requirements, assumptions and constraints
3. Selection of high technical risk items as main areas of assessment

An initial assessment of the maintenance of the proposed configuration with equatorial splits provided an insight to the problem, enabling a number of different concepts to be developed. These were down selected yield four candidate configurations. One of these enabled more detailed exploration of some novel aspects that were significantly different to the existing DEMO baseline design.

Using the knowledge developed during the detailed study, and prior work completed for the DEMO baseline it was possible to complete an initial evaluation of the four candidate configurations and provide recommendations for future work.

2. Design scope and requirements

The main objective was clearly defined at the outset of the project – to develop a split blanket double null design based on the proposed DN concept that had been previously developed [5]. This design includes the assumption that the reduced heat loads on the inner

author's email: jonathan.keep@ukaea.uk

divertor targets could allow use of materials that may have a longer life, enabling the inner target to be integrated with the inner blanket segment.

The previous work [5] had evaluated the magnetic equilibrium defining one of the main constraints for the work – the magnet configuration would be fixed and the port intersections with the vessel couldn't be enlarged any further (due to the impact on the passive stability function that, in DEMO, is provided by the vacuum vessel). Furthermore, it was assumed that the initial layout was appropriate for either of the current breeding blanket technologies and the divertor targets would use the current monoblock design.

These assumptions and constraints provided a suitable level of boundary to the study and started to define the design scope. Further design details were identified that could be carried forward from the existing DEMO baseline. These 'out of scope' items are:

- Equatorial port design integration
- Radial design/thickness of blanket and vacuum vessel
- Limiter design and integration
- Diagnostics/plasma control systems
- Wider systems such as heating and current drive, balance of plant, tritium processing etc.

In principle the DN design should be aligned with the existing DEMO requirement sets. The challenge was that many of these were either not appropriate or relevant to the scope of the study; either too high level, or design specific. Instead a limited set of high-level requirements were derived from a functional analysis, considering the assumptions, constraints and exclusions of the study. This resulted in 17 functional requirements being identified. These then were used to enable more detailed requirements to be derived for the main in-vessel sub-systems within the scope of work.

3. Initial studies

The main benefit of splitting the blankets poloidally is to reduce the size and mass of the blankets, potentially aiding the kinematics for removal. Using the initial layout with the breeding blankets split symmetrically at the equatorial plane, a 3D model was generated to enable initial Remote Maintenance (RM) studies to evaluate the blanket replacement kinematics. Unfortunately, the kinematics were still complex with similar requirements to the full blanket segments. Figure 3.1 shows the kinematics to remove the lower outboard blanket segment.

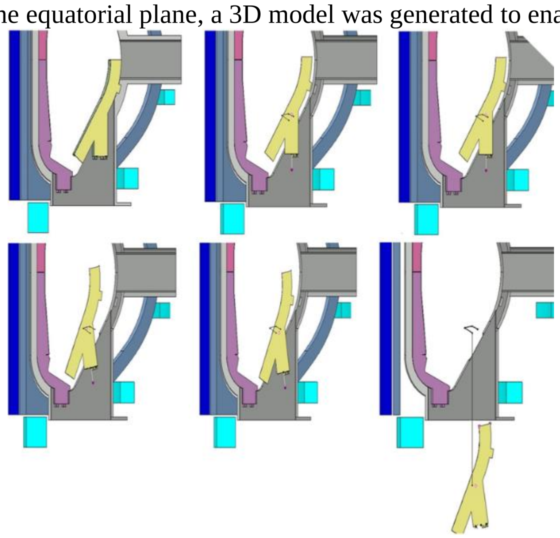


Figure 3-1: Lower blanket kinematics for initial equatorial split blanket configuration

To enable further work, it was recognized that the orientation of the ports and blankets splits could be optimized. A brainstorming session generated many options (over 30) that were compiled and grouped and rated against key functional requirements. Using some simple studies several ideas were eliminated and other ideas were merged leading to a short list of potential configuration options.

4. Down-selected options

Once the ideas were consolidated there were two 'families' of solution identified (see figure 4-1). An option featuring a horizontal lower port and three options featuring vertical lower port; the variation being found in the outer blanket split position.

It was noted that the horizontal port design had substantial similarities to the existing DEMO baseline design, which had already been extensively and analysed within the main DEMO programme. In contrast options with a vertical lower port have had minimal consideration within the programme. Furthermore, the upper port layout was common between all the options so this could be evaluated in any configuration. Therefore, the vertical port option (22D) was chosen to be developed further.This development would increase understanding of issues associated with a vertical lower port including:

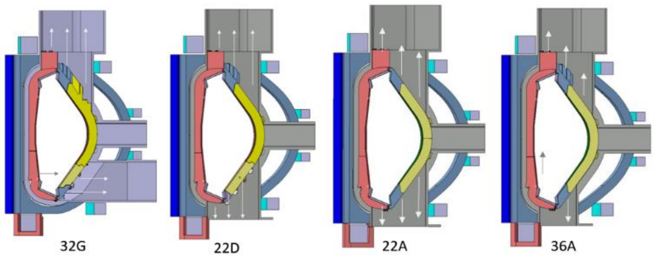


Figure 4-1: Double Null configuration options

- Impact on pipework and routing
- Requirements for maintenance 'basement' and impact on building layout.

The horizontal port option (32G) could be evaluated by extrapolation from the existing DEMO baseline

5. Design development

The work was focused on only addressing major risk areas for the configuration which were identified as follows:

1. Provide support for main in-vessel components (divertors and breeding blankets) under all conditions.
2. Ensure services for all in-vessel components can be connected and integrated into the relevant ports
3. Ensure adequate shielding and vacuum pumps can be integrated into the ports
4. Ensure all in-vessel components are maintainable.

5.1. Divertor

The divertor design assumes that the inner target can be integrated into the inner breeding blanket (as outlined in section 2). This leads to a simpler outer target that must be replaceable while the blankets and their relative pipework remains in place. The existing monoblock design for the DEMO baseline design [6] is assumed to be suitable for the outer target, based on the reduction in target loads associated with the DN configuration. The upper divertor has an extended section that creates space for the outer blanket segments to move into when these are removed, significantly simplifying the kinematics. This can be seen in figure 5-1.

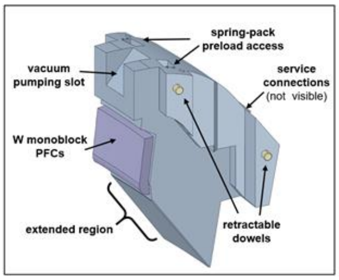


Figure 5-1: Centre outboard divertor design detail

The position of the divertor segments created the biggest challenge for the supports in that the centre segment was within the port area, so the rear structure needed to be extended to enable location and securing features (sprung loaded retractable dowels) to engage with the port wall, while allowing space for the left and right hand segments to be located and secured.

5.2. Breeding blanket

The breeding blanket development was focused on providing adequate support for the breeding blankets, whilst still enabling maintenance. The internal design of the breeding blankets was assumed to be consistent with the current DEMO baseline design [7]. It should be noted that the compatibility of the different blanket types with the proposed split solutions will need more detailed study on the internal details. This was outside of the scope of this work.

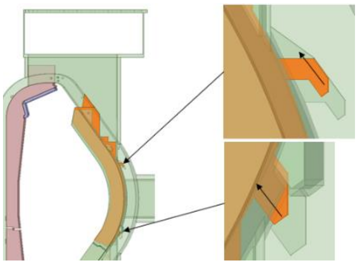


Figure 5-2: Upper centre outboard blanket support design

The key challenge was associated with the substantial difference in temperature between operation and maintenance (>250°c). The basic design principle adopted with the support was to ensure the vertical support was as close to the pipe interface as possible. This would minimize the pipe deformation and hence in-service loads. The significant vertical expansion for the upper blankets (~30mm) was exploited to enable installation with a larger clearance, which would close once at operational conditions.

Figure 5-2 shows an example of the detail of the support design, and the initial movement required to release the blanket from its supports; clearly the design is driven by the installation/removal kinematics.

5.3. Port integration

With an increase in the number of in-vessel components, both due to the extra divertor and splitting the blankets, the spatial design to accommodate all the pipes was a critical risk. Figure 5-3 shows the lower port installation.

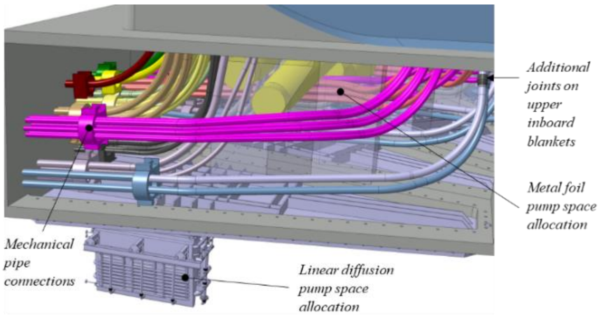


Figure 5-3: Lower port installation isometric view

The challenges for the port design were to enable integration of enough shielding around the port area, while still integrating the required pipework and vacuum pumps. The maintenance sequence was design driving especially ensuring the outer divertor target segments could be maintained without removing any other in-vessel component.

The WCLL blanket pipe work was selected as the highest risk due to the increased number of pipes and the requirement to have a drain for the lithium lead via the lower ports. Two main configurations were evaluated, one with the pipe cutting/welding tool inserted near the join to the component – enabling tighter packaging of the pipework and one with larger minimum pipe radii enabling the tool to be inserted from outside the port area. The latter solution was selected, as the packaging benefit was minimal. Furthermore, the insertion outside of the port area provided a significant benefit for maintenance duration, as the pipe cutting and welding is no longer reliant on opening the port – enabling greater parallelization of maintenance.

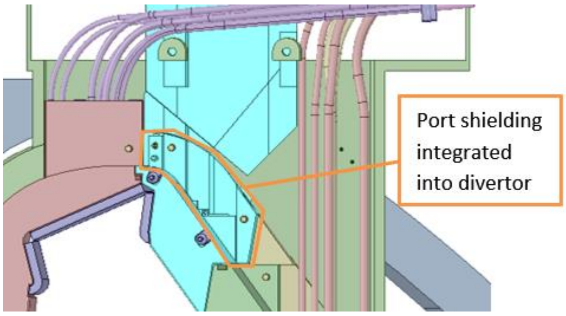


Figure 5-4: Port shielding integration

Radiation shielding has been implemented as features and modifications to other components, rather than dedicated components (see figure 5-4). These features include water shielding manifolds, additional steel and doglegged gaps. The shielding was initially assessed using a simplified ray-tracing model to identify and resolve neutron streaming paths. Further neutronics assessment was then completed using MCNP this showed a reduction in peak nuclear heating on the TF coils of 75%. Unfortunately this was short of the 95%

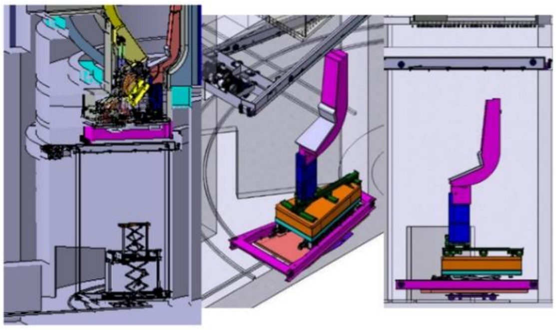
target and further development is required – especially associated with the integration of the vacuum pump, which is reliant on pumping slots providing line of sight to the plasma. The concept included shielding within the pump housing but this area will need further development. With pumps installed in the upper and lower ports it was possible to integrate the equivalent number of metal foil pumps to the existing DEMO baseline design, despite the increased spatial constraints.

5.4. Maintenance

As well as supporting the design development of the port and in-vessel components to meet maintenance requirements a maintenance strategy was developed. This drew from the current DEMO baseline, as well as developing bespoke concepts as necessary. The focus was on the lower port. The strategy made use of a maintenance basement below the machine, featuring a vertical lift that could be repositioned between ports, and became the base for a range of different tools designed to enable installation and extraction of components. This system can be seen in figure 5-5

The maintenance solution demonstrated basic feasibility of the tools and kinematics, with improvements found for many of the blanket segments, however the inboard segments were still challenging. Load assessment of the blanket handling tools found them to be at or above limits, especially including seismic load cases; much of the challenge is driven by the ‘reach’ required to lift the blanket from the port.

Figure 5-5: Lower port remote maintenance system



The increase in numbers of components and pipework was expected to lead to an increase in maintenance duration. The pipe configuration chosen had a significant positive impact, enabling pipe cutting/welding without needing to open or clear the port, taking the cutting and welding operations away from the critical path. Furthermore, with the components being removed from both the upper and lower ports, more activities could be completed concurrently, negating the impact of the increase in component quantity. The assessment gave a full blanket and divertor maintenance duration of 160 hours compared to 180 hours for the existing baseline design, however it was noted that at least 20 hours could be saved in the existing baseline by using equivalent pipe geometry.

6. Evaluation

Based on the initial concept models, the vertical lower port design development and extrapolation from existing data it was possible to evaluate the four main DN options. Evaluation was completed using five individual Measures of Effectiveness (MoEs) [8], from which Measures of Performance (MoPs) were derived that enabled scoring of the designs. The final scores are shown in table 6-1.

The option 32G (horizontal port) and 22D (vertical port) both score well. The key difference between these options is the integration measure. This measure tended to reward designs consistent with the DEMO baseline design. However the 22D design does present a challenge for structural support of the vacuum vessel and magnets while still allowing access for maintenance.

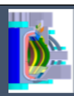
MOEs	Weight %	 Option 1 (32G)	 Option 2 (22D)	 Option 3 (22A)	 Option 4 (36A)
Availability (RAMI)	37.3	124	162	137	174
Handle-ability	13.8	63	77	80	52
Recoverability	6.2	31	37	37	25
Integration (with rest of system) + fit	37.5	263	206	197	216
Manufacturability	5.1	162	162	174	149
		643	**644**	**625**	**616**

Table 6-1: Evaluation scores for DN options

7. Conclusions and further work

Four configurations have been developed that demonstrate basic feasibility of a Double Null design, however there are still areas requiring further development. The maintenance has demonstrated some small improvements resulting from the split in blankets but unfortunately there are still challenges remaining with the inboard blankets. This minor improvement comes with the cost of increasing the number of components and complexity of the port integration. Rescue and recovery has not been considered in this study and will need further study in any future work.

The design studies highlighted that service connections are at limit of feasibility; further segmentation of in-vessel components would require a significant change in design strategy.

The integration of the inner target into the breeding blanket remains a key risk, and alternative designs should be developed to enable independent replacement of the inner target. Furthermore, other risk areas that would need further development include:

- Development of specific DN load cases for in-vessel components
- Design and structural assessment of vessel and magnet supports (especially with respect to the vertical lower port)
- Assessment of vacuum pump design against pumping requirements
- Internal detail of breeding blankets and divertors and assessment of Tritium Breeding Ratio (TBR)
- Vertical stability and plasma control implications for DN design

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 and 2019-2020 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

References

[1] C. Bachmann et al., Key Design Integration Issues addressed in the EU DEMO pre-concept design phase, Fusion Engineering and Design, vol 156, (2020)

[2] G. Federici et. al., Overview of the design approach and prioritization of R&D activities towards an EU DEMO, Fusion Engineering and Design, 109-111, Part B (2016) 1464-1474.

[3] G. Keech et al., Issues of the vertical blanket segment architecture in DEMO: Current progress and resolution strategies, Fusion Engineering and Design, Vol 146, Part B, 2019, Pages 1408-1412

[4] O. Crofts et al., Overview of progress on the European DEMO remote maintenance strategy, Fusion Engineering and Design 109-111 part B (2016) 1392-1398.

[5] R. Albanese et al., Electromagnetic analyses of single and double null configurations in DEMO device, Fusion Engineering and Design, Vol 146, Part B (2019) Pages 1468-1472

[6] J.H You et al., European divertor target concepts for DEMO: Design rationales and high heat flux performance, Nuclear Materials and Energy, Vol 16 (2018), Pages 1-1

[7] G. Federici et al., An overview of the EU breeding blanket design strategy as an integral part of the DEMO design effort, Fusion Engineering and Design, Vol 141 (2019), Pages 30-42

[8] NASA Systems Engineering Handbook, 2017 NASA SP-2015-2016 Rev 2