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Initial Configuration Studies of the Upper Vertical Port of the European DEMO

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In the current pre-concept phase of the European DEMO, integration studies of the systems in the Upper Port area are being carried out. In DEMO, the Upper Port of the Vacuum Vessel is extraordinarily large to allow for the vertical extraction of the Breeding Blanket segments. This requires a number of components inside and outside the port to be integrated with tight space constraints: The Upper Port structure and its annexes, the adjacent Toroidal and Poloidal Field Coils, the Thermal Shields, the piping connection to the Vacuum Vessel Pressure Suppression System, the Shield Plug and its inserts, the feeding pipework of the in-vessel components and part of the Breeding Blanket supporting structures.

Apart from functional aspects, the design of these components is driven by considerations of structural integrity, maintainability and irradiation shielding, which are mutually competing in many areas. Several studies were conducted on the design of the Upper Port and the required configuration of the components within. The present article describes the development approach, the studied options and the respective results, the identified issues as well as the proposed engineering solutions, in particular with respect to the mechanical design of the Upper Port and the integrated Shield Plug.

Keywords: DEMO, Upper Port, Integration, Vacuum Vessel, CAD

1. Introduction

The European effort to develop a demonstration fusion power plant (DEMO) aims at producing hundreds of MW of electric power with a closed fuel cycle where the tritium fuel is bred self-sufficiently inside the machine [1]. This requires dedicated components, called Breeding Blankets (BBs), to cover a significant volume in high neutron flux, ergo in-vessel. In the pre-conceptual design phase of DEMO until 2020, different BB configurations are being explored [2] of which the so-called *full-segment vertical architecture,* cf. , is the current baseline [3,4].

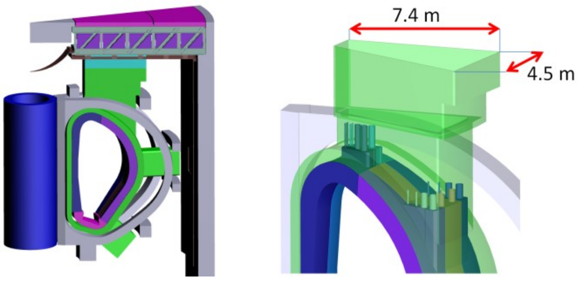

*Fig. **1** DEMO Tokamak baseline design 2017: One-sector (22.5°) cutaway view (left) and Upper Port detail (right).*

Remote maintenance of this configuration foresees to replace the 5 BB segments per vacuum vessel (VV) sector at least once during the lifetime of DEMO through the large, vertical ports of the machine. Blanket handling in this environment is challenging and the large outboard segments with a height of 12 m weigh 55 t. One port per vessel segment, in total 16, allows access to all blankets without significant toroidal travel and enables parallel operations reducing maintenance time (thus maximizing plant availability). Maintenance tools operate only inside the ports, avoiding the harsh in-vessel environment.

The **Upper Port (UP) Configuration,** as defined by the DEMO design approach, is shown in Fig. 2 and table 1: The port structure itself, which is an extension of the VV, together with the main internal components. The port design as of the baseline 2017 was driven by engineering experience without being systematically justified. Therefore, a strategy to ensure traceability and thus, progress in the design was developed. Based on consecutive stages of design and verification by analysis, it aims at developing a sound Port Configuration, satisfying all requirements, to be used as reference design, e.g. for integrating tenant systems.

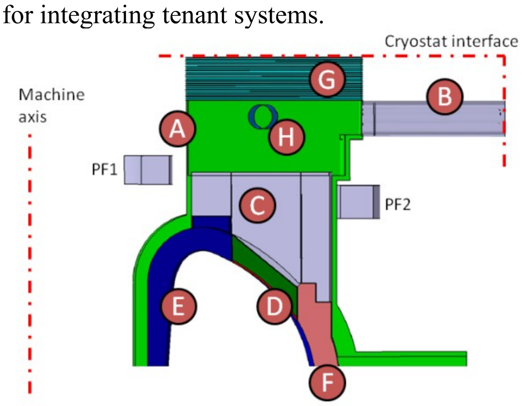

Fig. 2 UP main components: Port structure (A), Port Annex (B), Shield Plugs (C), Limiter (D), in- & outboard Blanket segments (E,F), Cryostat bellows (G), VVPSS ring-manifold (H). Also shown: PF coils 1 & 2.

This paper describes the general approach as well as the first results of this effort. The main design-driving requirements, choices and assumptions are defined. Subsequently, the status of work on the UP configuration, including a description of several design options under study, is presented, followed by an outlook.

2. Development approach

Various studies on DEMO UPs were conducted in the past [5-7], whose findings, where relevant, are included in this study. As an example of directly usable design input, it was demonstrated that an upper neutron shield, similar in composition and thickness to the VV, meets the shielding

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requirement in the toroidal field (TF) coils [8], with marginal impact only of the port wall and gap configuration. Experience transfer from ITER is ongoing and will be intensified for areas such as port manufacture and penetration & sealing concepts, although significant size and other differences between ITER and DEMO lead to limited applicability in some fields, e.g. the upper bellows.

The development strategy of DEMO's Port Configuration is based on an increase in the number of components[1] and their level of detail over time. The configuration will undergo at least two series of analysis, the first to identify design flaws and to understand interactions, i.e. produce feed-back for design modifications. The last one shall validate the final, modified design. These analyses include neutronics, EM and thermo-structural studies of different design options, where simple options are preferred, but complexity is increased when requirements are not met. For reasonably limiting the effort, not *all* options will be used as input for *all* analyses, but only few relevant variations per type of analysis[2] are derived from the *basic design* as of Fig. 2. This 'modest' systems engineering approach allows quantifying specific aspects of the configuration.

The initial design presented here started from the baseline CAD, implementing input from the main interfaces and additional components identified as essential, in particular an upper limiter [9]. It represents the starting point for the first set of analyses.

3. Results: Capture of main requirements

As outlined in the following, the specific[3] requirements on the port design are either related to maintenance or functional and interface aspects, which are much interlinked. In addition, all vessel-specific requirements apply equally to the ports, necessitating shielding capabilities similar to the VV and a barrier function for torus vacuum and 1st confinement. Table 1 lists the main functional requirements of all port components as introduced in Fig. 2.

The UP and its components have physical interfaces with various systems[4]. The available space is limited radially by the PF1 & 2 coils and in toroidal direction by the adjacent TF coils, see *Fig. 1 & 2*. Significant neutron shielding of these coils can only be provided by the vessel and dedicated in-port components, namely the shield plug. The VV dimensioning is based on the requirement of <50 W/m^3 neutron heating in any coil [4,10] and the same applies for the port design, while realistic assumptions for necessary penetrations and gaps must be used for verification analyses.

To protect the blanket 1st wall from excessive heat loads during upward VDEs, upper limiters were introduced, acting as protruding high-heat-flux elements. Being potentially sacrificial, they have to be replaceable quickly. Although the *plug insert* may also host other components, integration work is based on the limiter due to its plant-level importance and likely highest demands[5].

Not yet part of the design, nevertheless a major UP tenant, the piping of the Primary Heat Transfer System (PHTS) is routed through the port annex to the BBs. In case of a loss-of-coolant-accident (LOCA), the in-port pressure must not exceed the VV design limit of 2 bars [10,11]. This requires a dedicated piping connection from the ports to an external expansion volume. Although the UPs share the torus vacuum and the VV has a VVPSS connection at equatorial level, the streaming paths (inter-blanket gaps etc.) between ports and main VV volume would be far too small to allow sufficient flow and pressure limitation.

Table 1: UP Configuration - Components and functions

ITEM	MAIN FUNCTIONS / ROLE
Port structure (part of VV)	• Enable in-vessel access & replacement of blankets • Host pipework (mainly BB) and components of tenant systems • Provide space and local support for remote maintenance operations • Vacuum & safety boundary • Support the shield plug
(Neutron) Shield Plug	• Decrease sufficiently the neutron flux, especially on the TF leg near the port but generally everywhere outside (ALARA). • Structural role: Transmit large loads (mere operational radial inboard force is of the order of 4 MN [4,12])
Shield Plug insert	• Host upper limiter or other tenants • Be replaceable quickly • Not impede shielding properties
Port annex	• Host & support piping • Vacuum & safety boundary
VVPSS connection	• VV Pressure Suppression System (VVPSS) to limit pressure to <2 bars

In addition, UP design also has to consider plasma vertical stability to be impacted by the existence, or absence, of plasma-near, continuous conducting structures.

Remote Maintainability

Removing blanket segments requires clearing the path of all obstructing/captivating components, such as PHTS piping and shielding elements. The space needed to access and maneuver the payload, as well as for RM tooling operations significantly drives the minimum UP size.

A large part of current DEMO remote maintenance work aims at developing enabling technologies which are substantiated by prototyping [13]. For the UP, the most

[1] To be added later: In-port piping, closure plate, cryostat bellows, building interface, penetration concept and verified VVPSS components.

[2] For instance, the neutronic analysis quantifies the shielding capabilities of three plug geometries, but the structural analysis considers two options representing a design variation more focused on mechanical properties.

[3] Generic requirements also apply (accommodate thermal expansion, withstand loads, design to codes, inspectability…) but are not listed here due to lower importance at the present stage.

[4] BBs (via the shield plug), Cryostat (port annex outer interface & large upper bellows), vacuum closure plate & systems hosted in the plug insert.

[5] in maintenance, volume, weight and services

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relevant operations are cutting and welding[6] of coolant piping and transportation of the blankets, pipes or pipe modules. Pipe *in-bore tools* are being developed for the former [14], and a dedicated blanket transporter [15] for the latter. It should be noted that for RM tooling development, a static in-port design was used for integration studies, which is naturally different from the evolving one presented here. By respecting the tooling requirements in the ongoing UP design, coherence will be achieved at a later stage by reconsolidating the models.

The considered welding technology uses laser optics for butt-welding a blanket pipe stub to the coolant pipe which has to be positioned on top of it. Good lateral and angular alignment of the pipe ends is crucial to ensure weld quality. Also, the current tool cannot be moved in pipe bends with less than 1.5 m radius and requires a straight pipe length of 0.5 m on both sides of the weld position [14].

It should further be noted that blanket handling and other RM operations need to account for failsafe transportation, rescue and recovery [16], especially with respect to incident and accident load cases.

Optimization criteria & primary trade-offs

The UPs are a main size driver of the entire plant. Minimizing the port height by design offers to reduce the height of the Cryostat and hence the entire Tokamak building, with a significant cost implication.

There is a systematic competition between several requirements. For instance, the thickness of the port side walls, now only single-shelled [17], was significantly decreased to enable and ease BB handling, however increasing the neutron flux on the TF leg behind. The analysis suite to be performed on the present design aims to gain a quantitative understanding of these main interactions to identify a sound design point. The high component density around the port area also necessitates to trade off space taken up by functional elements (e.g. VV and coils) and the conservativeness of assumptions on space reserved for components not yet designed (e.g. the VV thermal shield[7]).

More general tradeoffs are shielding vs weight, gaps sizes & handling vs shielding and complexity vs risk & cost.

4. Results: Current design status

Working assumptions and design choices

To establish an initial design, a number of assumptions are needed, such as realistic estimates of achievable tolerances and gap sizes of large components, e.g. blankets[8].

In addition, reasonable boundaries of the design space should be defined. It was decided to consider size and position of port-adjacent coils as fixed[9]. Revisiting these assumptions at a later stage is however an option.

Early design choices help keeping the number of alternatives low and concentrate efforts, and clearly documenting these allows to trace decisions and revisit if need be, which is a key feature of the development process used herein. Design choices so far include for example to implement a *rectangular* cut-out for the shield plug insert, to be extracted *vertically.* Also, routing the BB PHTS pipes in an additional, horizontal annex instead vertically through the closure plate & upper bioshield plug is a *choice* - with apparent, albeit not yet quantified benefits.

Options considered for design & specific analyses

Both coolant options of the BB, water and helium, will be considered, yielding two slightly different UP designs. The interface definitions (pipe diameters, pressures…) are based on the HCPB and WCLL concepts [18], however only the He-cooled design, considered more challenging for integration, is presented in the following.

To reduce the force needed for alignment of the PHTS piping prior to welding to the blankets, past RM studies have introduced multiple bellows along the pipes, which are supported flexibly in a frame forming a pipe module, see Error: Reference source not found (left).

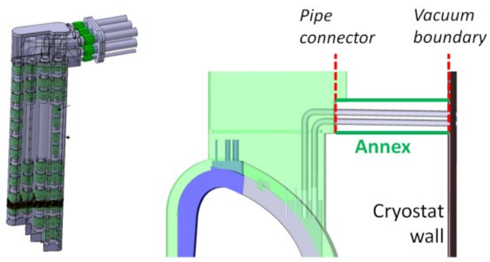

Fig. 3 Pipe module with bellows for flexibility (left, courtesy: CCFE); Alternative: Solid pipe with vacuum feed-through at Cryostat (right), both with connector at transition to horizontal part.

As bellows in the primary cooling loop may pose serious reliability concerns, an alternative design using seamless, solid pipes will be investigated in terms of thermo-structural behavior, as well as possibilities of limiting reaction forces for easier alignment using special pipe supports. To enhance compliance for deflections to be compensated elastically in the pipe itself, the fixed support at the vacuum boundary is relocated to the cryostat outer wall, see Error: Reference source not found (right). For assembly, both options feature a demountable pipe connector at the transition into the annex.

Design evolution

An earlier draft of the limiter foresaw a toroidally narrower insert, protruding through a fork-like section of the blanket, as shown in Fig. 4. This “fork” was however considered prone to structural issues while the remaining

[6] and inspection and possibly inductive heat treatment

[7] Currently assumed space: Distance of 100 mm between UP and TF coils.

[8] Further assumptions: Limiter PFC protrudes by 70 mm w.r.t. BB; VV cooling condition appropriate for shield plug (180°C at 25 bars) & DN80 in-/outlet sufficient for both limiter & plug (one circuit each); VVPSS pipe of 1 m^2 cross section, one el. connector for instrumentation/diagnostics foreseen (space reservation) per plug and BB segment, ~100 pins & ~100 mm outer diameter each.

[9] Instead of using these as parameters to be optimized together with the port design.

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volume on the sides could hardly be used for breeding[10] [19].

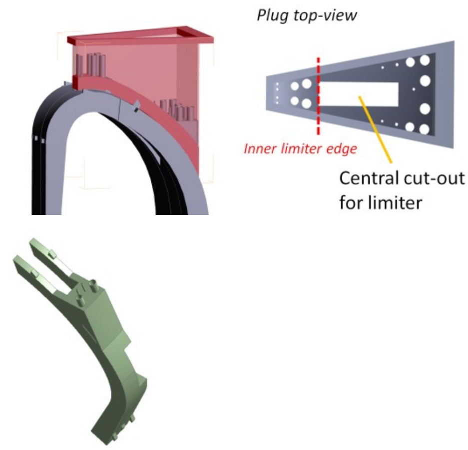


Fig. 4 : Earlier, discarded option: 3D integrated view of plug (red) & BBs (left), singular shield plug top-view (middle) and BB with fork-like cutout on top for limiter (c)

Overview of current design

Therefore, the width of the limiter was increased to equal the BB width in favor of a larger plasma-facing surface, taking up the fork's volume, see Fig. 5.

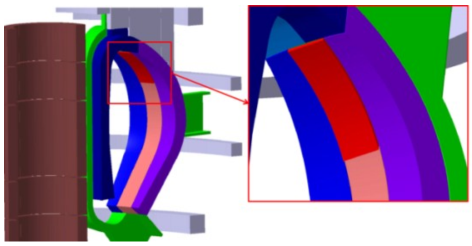


Fig. 5 Limiter configuration (plasma-facing surface in red)

As a consequence however, the remaining structural material of the plug at the inner radial limiter position (see red dashed line in Fig. 4) becomes negligibly small – the plug is basically cut in two poloidal pieces.

Therefore, the load path from out- to inboard was redefined, with a plug featuring a solid, continuous shielding volume, cf. Fig. 6 & Fig. 7 (top), underneath which a limiter sub-component is mounted, instead of having a vertical cutout in the plug for an individually replaceable limiter.

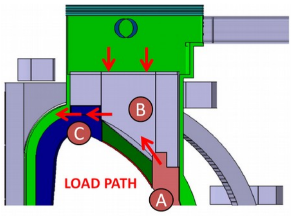


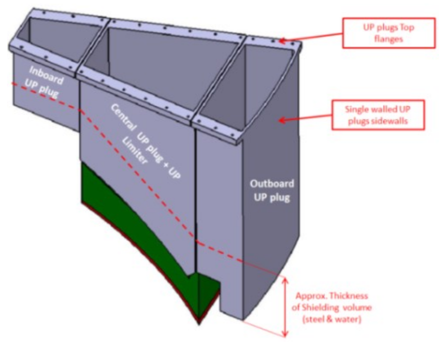
Fig. 6: Load path in current design from outboard BB (A) via central plug (B) to inboard BB (C), then to vessel. Vertical forces on plug transmitted via flange to VV.

Having no cutout requires the plug to be split in three, because a singular plug would be trapped by the BB piping it embraces, whilst the limiter is trapped by the plug. For limiter replacement in the current design, after establishing access to the vessel, the central sub-plug is removed without demounting any other component or pipework except its own supports and supply lines. This increases the plant availability by reducing the maintenance duration. In addition, unlike the usual BB interface, all sidewalls of the plugs are vertical to simplify maintenance.

In this configuration, the in- and outboard BB segments interface via the central shield plug. As sketched in Fig. 6, the mechanical load is transferred in the actual shielding volume of the central plug, a water-cooled steel structure of at least 600 mm thickness. The potentially delicate limiter is force-free thanks to gaps[11].

An overview of the current, box-type plug design is given in Fig. 7. All sub-plugs are attached on top via flanges to the port shoulder, where forces are reacted and also electric currents are transmitted to the VV. This simple design, featuring neither dedicated electrical straps nor complex contact surfaces for force transfer will be assessed and may be subject to change in the next stage of development.

Note also the layout of the VVPSS connection, consisting of a ring-manifold connecting all ports and the radial drain pipe (Fig. 7 bottom).



[10] This would necessitate a complex, locally customized internal BB geometry of cooling channels and breeder volume and is therefore not considered attractive.

[11] Assumption: 20 mm radial distance to both in- & outboard blanket

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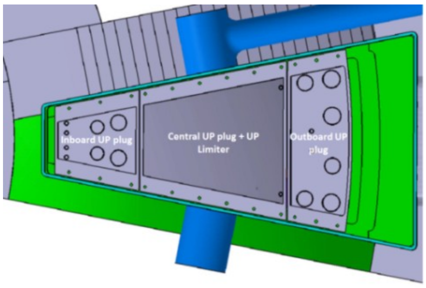

Fig. 7 Three segments of upper shield plug with limiter (green), isometric view (top); Port top-view (bottom) with VVPSS piping (blue) and BB pipe stubs (circles).

5. Conclusions & Outlook

The strategy for developing a justified Upper Port configuration was presented. The specific, design-driving requirements, arising mostly from coil neutron shielding and maintainability considerations were outlined and an overview of the present design status was given.

The next steps include electromagnetic, thermo-structural and pressure evolution analyses[12] as well as neutronic simulations[13]. The results will be fed back into the design to produce the final configuration. In terms of potential design modifications, the next phase will address the blanket transporter interface on top of the BB segments which may be optimized (compacted) to reduce neutron streaming, the BB PHTS collector in the port annex and the implications of using piping without flexible bellows. However, if found to be necessary, the fitness of these bellows for the given environment shall be verified. Also, the possibility of combining the inner and outer shield plugs with the pipe modules they embrace will be investigated.

Acknowledgments

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