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Progress in the development of the in-vessel transporter and the upper port cask for the remote replacement of the DEMO breeding blanket

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ABSTRACT

The breeding blanket (BB) segments are by far the largest in-vessel components of DEMO. For their remote replacement through the upper vertical ports of the vacuum vessel (VV) recently a new concept has been developed, [1]. The concept minimizes the spread of contamination as all in-vessel operations are carried out from within a cask that is sealed to the VV and located within a sealed room providing a second confinement barrier inside the nuclear building. The removal of the BB segments from the VV is carried out by a BB transporter that is operated on the elevator system of the >20m higher cask. The limited available space makes the compact design solutions that have been developed critical to the overall concept. The BB transporter is designed according to nuclear design codes and for high payloads since the BB segments may weigh up to 180 tons. Due to the eccentric engagement points on the backside of the BB segments and due to seismic accelerations, that need to be considered, too, the BB transporter resists also to bending moments. It can carry out translational as well as tilting movements as required to disengage the BB segments from their supports and to remove them through the upper VV port. The main requirements regarding integration, BB manipulation and structural integrity have been verified. Next development steps need to include further design improvements, integration of in-vessel position survey, definition and control of motion actuations, supply cable routing, the development of rescue and recovery scenarios as well as the validation in relevant test facilities. This article describes the design of the BB lifting tools including several modifications following a set of analyses that were recently performed.

1. Introduction

DEMO is the step between ITER and a commercial fusion power plant. It shall deliver few hundred MWs of net electricity into the grid and operate with a closed tritium fuel cycle. Hence tritium is bred in a breeding blanket (BB) covering the internal wall of the vacuum vessel (VV). The degradation of the BB materials requires regular replacement [2], which must be done in DEMO in a manner that could later be adopted also in a fusion power plant. The replacement of the BB was identified as a key issue of the EU DEMO [3]. A concept for the replacement of the hot BB by remote controlled tools from above the tokamak has been presented recently [1]. This adopts, as in ITER, the *sealed environment concept* [4],[5], whereby all in-vessel operations (IVCs) are carried out from within a cask that is sealed to the VV.

The BB is maintained from within a containment cell on top of the bioshield roof through the upper ports of the VV. Separate containment cells above each upper port mean that in-vessel operations can be carried out in all upper ports independently. Direct vertical lifting of the BB segments is not possible since the magnetic coils outside the VV limit the size of the access ports [6]. Furthermore, also tilting movements are required to disengage the BB segments from their supports and to move them through the upper port clear of the in-situ BB segments that

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partially obstruct the upper port [7]. The *BB transporter* carries out horizontal translational and tilting articulations of the BB segments while vertical translations are performed by the elevator system that is operated inside the *upper port cask*.

The large mass of the BB segments (up to 180 tons) means the BB transporter must be designed for high payloads. A further challenge are the high bending moments that must be reacted due to the off-centered location of the lifting points on the BB segments. Additional bending moments occur due to accelerations during seismic events. The design of the BB transporter and of the cask that is described in this article is therefore critical to the feasibility of the BB maintenance concept.

2. Overview

2.1. BB maintenance operations

BB maintenance preparation: Prior to the removal of the BB the following operations are carried out: (i) venting the VV and de-energizing the magnetic coils, (ii) draining the in-vessel component cooling systems, (iii) removal of the divertor, (iv) removal of upper port closure plate, (v) removal of components installed inside the upper port, i.e. piping, shield plugs, and upper limiter [7]. These operations are not described in this article.

In-vessel access from the top: The DEMO VV has one upper port in-between each pair of TF coils. Corresponding trapezoidal openings are implemented in the cryostat top lid and the bioshield roof [8]. The latter is closed during plasma operation by a bioshield plug. Currently, we assume all upper ports are used to extract the BB, i.e., DEMO has 16 upper RH ports. Through each upper port five segments can be removed sequentially. This is in line with the approach defined in [6] and does not require RH tools to operate in the high gamma radiation environment inside the plasma chamber [9]. To reduce the number of upper ports that need to be opened for the complete replacement of the BB, a toroidal mover might be considered in the future that would operate inside the VV to move BB segments from adjacent sectors to a RH port.

BB segment removal: Due to the space constraints inside the upper port the lifted BB segment cannot be removed by means of translational movements alone. Tilting the segments by few degrees is needed to disengage them from their supports and move them clear of residual BB segments, which partially obstruct the port, see Fig. 1. Furthermore, the removal of the inboard segments requires the prior removal of the divertor cassettes through the lower port [10]. In addition, before lifting a BB segment the BB transporter applies a counter-moment to the gripper to counteract the moment that occurs due to the off-centered lifting point, see section 4.3. A tilting mechanism about the second horizontal axis is therefore also required.

2.2. Design criteria and loads

Design criteria: The BB cask and the BB transporter are designed in accordance with EN 13001-3 [11]. For the cask another design code may be applicable. However, the basic rules for structural integrity considered so far, are not expected to differ significantly.

Dead weight: The dead weight (DW) of the blanket transporter is approximately 33 tons. The DW of the lifted blanket depends on the BB concept being considered, either the water-cooled lithium lead (WCLL) [12] or the helium-cooled pebble bed (HCPB) [13]. In the design of the BB transporter and the cask the mass of the heavier (undrained) WCLL BB is considered, i.e., 125 tons for the inboard and 180 tons for the outboard segment, respectively. There will be no liquids inside the BB segment since the cooling water will be removed prior to maintenance.

Remanentmagnetization: The residual magnetic field generated by the magnetized BB segments has been estimated to be approximately 0.04 T. The consequent net toroidal force acting on a single BB segment in its assembled position is ~5 kN.

Seismic loads: Seismic loads are considered in the design of the BB transporter and the cask. The different levels of seismic events to be considered in the design of DEMO are associated with different damage limits [14]. The design loads, which the structures need to resist without any damage requiring repair, are the loads that occur in an SL-1 event. In the structural integrity assessment, the following partial safety factors are considered according to EN 13001-3: 1.41·DW + 1.1·SL-1.

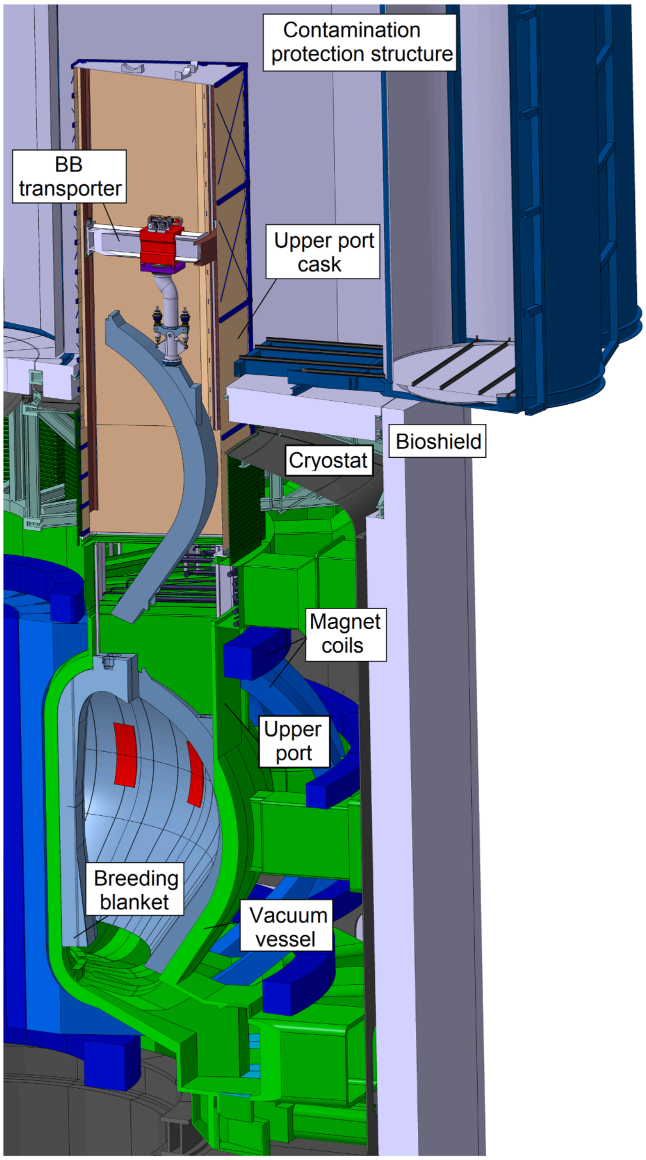

Fig. 1. View of the DEMO tokamak during BB maintenance with BB transporter operating within the upper port cask that is docked to the upper port.

The seismic loads for an SL-1 were derived conservatively as in ITER as one third of those calculated for the more severe SL-2 event, [15]. Since the DEMO site has not yet been selected, the design ground spectrum defined for the ITER site at Cadarache [16] has been postulated and seismic isolators were considered below the building. Several ground motion records from relevant European databases, e.g., the European Strong-motion Database, were considered and three-directional acceleration time histories were calculated for the cask support location on the VV upper port and the bioshield roof.

A preliminary seismic analysis was carried out and the results were used for the preliminary structural integrity assessment presented in this article. A more recent seismic assessment considering several minor design modifications has determined seismic loads that are higher by ~20 - 40%. Consequently, the design loads of the BB transporter and the cask need to be increased by ~10-15% since seismic loads contribute approximately one third of the total loads. It is expected that minor design adaptations of the BB transporter will be required.

Seismic accelerations increase the vertical load and in particular cause the BB segments to swing horizontally like a pendulum. The equivalent horizontal acceleration causes a bending moment that needs to be sustained by the BB transporter. Fortunately, the excitation of the lowest natural frequency of the lifted BB segment (~0.35 Hz) is moderate since it is below the natural frequency of the building (~0.5 Hz).

The most challenging loading scenario occurs when a seismic event would occur during the initial lifting of the inboard segment. Since the upper port narrows towards the inboard side the BB transporter cannot reach a location above the inboard wall. The consequent large offset between the gripping point and the centre of gravity of the inboard segment causes a large bending moment about the toroidal axis at the location of the gripper. The horizontal seismic acceleration further increases the acting moment to ~4.4 MNm. The acting forces and moments are transferred through the BB transporter to the three skids that are operated by the cask elevator system, see below. On single skids vertical forces occur up to ~2.3 MN (downwards) and up to ~0.35 MN (upwards).

3. Upper port transfer cask

3.1. Overview

Function: The upper port transfer cask is used for the transfer of in-vessel components between the VV and the active maintenance facility (AMF). It is a sealed container that prevents contamination to spread from the VV or from hot components inside the cask into the building. For this purpose, the cask docks to the docking flange of the upper port before opening both VV and cask. Before leaving the docking flange a double-lidded contamination control door (CCD) is divided into the port door that seals the VV and the cask door that seals the cask. The cask has a confinement function and therefore is a safety-important class component.

Cask types: Different types of upper port casks use a range of tool sets to perform different functions inside the upper port, e.g., servicing of the upper port pipes, installation / removal of the vacuum closure plate, of the shield plugs [7], and of one BB segment at a time. While the internal tools are different, the basic design of the upper port cask with the docking flange, the double-lidded door, and the internal elevator system are equivalent.

Transport and support: The upper port transfer cask is a passive container that is moved by the cask transporter. The cask transporter is a remotely operated vehicle that travels on a rail system on the upper floor of the AMF and on the bioshield roof level [1]. Its crane system can engage to features on the roof of the upper port transfer cask (not yet designed). Guides on both lateral sides of the cask engage with support structures on the cask transporter during the uplift to provide horizontal support during transport. When the cask is lowered onto the docking flange these guides engage with structures of the transfer corridors to ensure the >20m high cask will not topple during seismic events. An assessment whether the hot BB segment requires active cooling during transfer is on-going. Such a system would require an on-board battery. During transfer all tools are in break mode fixing their positions, which is not difficult considering the high gear ratios in the gear boxes used. We assume that the negative pressure that is generated inside the cask during and prior to undocking can be maintained during cask transfer without any active system.

3.2. Design

Basic design and material: The upper port transfer cask weighs ~90 tons, it has a height of ~22m and a trapezoidal cross-section that overlaps that of the VV upper port (radial length: ~7.1m, width: up to ~4.5m). Its structural design is based on steel girders with diagonal tensioners much like a steel building. This is sheathed on the inside by a thin steel liner to facilitate decontamination operations. For the structural members the conventional steel 1.4462 with a yield stress of 450 MPa was selected. The structural integrity assessment of the upper port cask is presented in [18].

Automatic connectors: Several automatic connectors are installed on the outside of the cask. These have not been designed yet. When the cask is lowered on a docking port these connectors will engage and provide the electrical, fiber optic, and – if necessary – water hydraulic connections as required to control and operate the tools and the cask systems.

Port door mechanism: When the cask has docked to the VV the cask door is joined to the port door. The double door weighs approximately 8 tons and is then opened into the cask like a garage door bringing it from its horizontal into a vertical position on the outboard side of the cask. The opening method requires - like in a conventional garage - a minimum amount of space.

3.3. Elevator system

Inside the cask an elevator system allows the vertical translation of whatever tool is used. The tool is mounted to three skids that are moved on the inboard and the lateral sides of the cask along vertical rails. The elevator system is designed for the weight BB transporter that lifts one heavy BB segment and to support it against seismic loads. To also react the consequent upward forces each skid is attached to a rigid chain rather than a rope. While the tensile force is reacted by Ø32mm shear pins connecting the chain elements, the upward force is transferred on compression pedestals from one chain element to another.

The elevator system allows lowering the skids beneath the cask docking flange into the VV upper port. The skids are therefore aligned with the inner periphery of the upper port. The vertical rails do not span across the full height of the cask since in the lower part they would clash

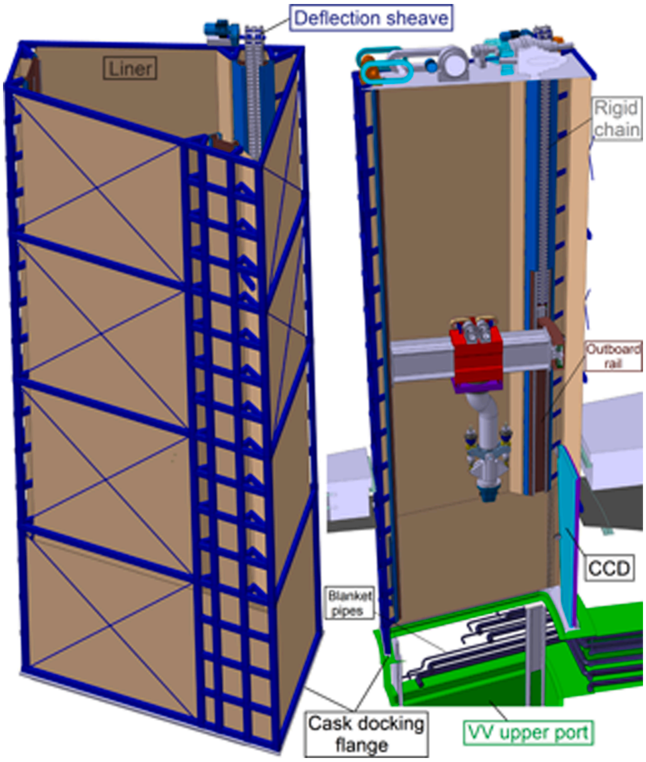

Fig. 2. Left: BB transfer cask with external frame structure (blue) and internal liner (light brown), roof not shown. Right: Vertical rails (dark brown) inside the cask and BB transporter lifted by rigid chains. CCD (cyan and purple) stored in vertical configuration.

with the opening kinematics of the CCD, see Fig. 2. When the CCD is open and stored in the outboard side of the cask, the rails are lowered (the inboard rail by ~1.0m, the outboard rails by 5.1 m) and engage with matching rails that are integrated inside the VV upper port.

Since the rigid chains must remain inside the confinement of the cask a recess was introduced in the liner to also envelop the loose end of the chain. The space for this recess is limited to ~450mm and corresponds to the diameter of the deflection sheave, which drives the chain. The footprint of the cask consequently overlaps that of the upper port. The length of a single chain element (150 mm) cannot be larger than one third of the deflection sheave diameter. Consequently, each rigid chain is made-up of ~200 elements over its length of ~30m. To prevent the rigid chains from buckling when loaded in compression they are guided and supported against out-of-plane forces by the rails.

4. BB transporter

4.1. Overview

The BB transporter as shown in Fig. 3 weighs ~33 tons, its radial and toroidal size matches that of the VV upper port (~6 × 3m) and is approximately 6.5m high. Its parts are made of conventional types of steel as listed in Table 1. The BB transporter is operated inside the BB transfer cask and can be lowered into the VV upper port. It grips one of the five BB segments located below one upper port and manipulates it to disengage it from its supports [17] and maneuver it out of the VV.

The BB transporter is an automatic lifting device that is controlled remotely. All its components are designed for high reliability and are compatible for the operation inside the clean vacuum vessel, i.e., lubrication is avoided where possible, otherwise lubricated components are sealed. Failure of drivetrain components will generally cause the stop of the RH equipment rather than uncontrolled accelerated movements. The BB transporter is supplied with electric power and signal cables in the interior of the cask. These supply lines still need to be added to the design. Complex electronics with microprocessors are avoided as their function may be impaired in the radioactive environment. In principle, the BB transporter can operate in the well-known geometry of the VV based on the feedback from the absolute encoders that measure the positions of each of its joints. For additional operation monitoring it might be considered in the future to install visual cameras with light sources or laser viewing systems, e.g., in the upper part of the port where gamma radiation levels are lower.

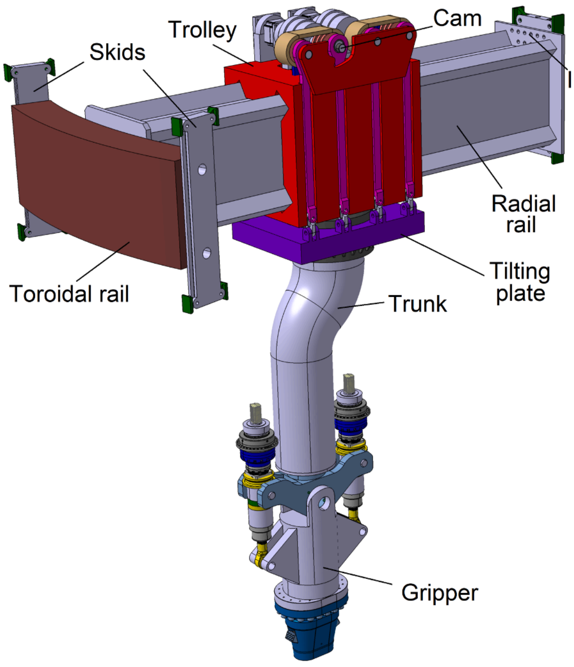

Fig. 3. BB transporter attached to skids.

Table 1
Steel grades foreseen for the structural parts of the BB transporter.

Part	Material grade	Yield stress (20°C)
Parts requiring welding	1.4462	450 MPa
Parts not requiring welding	1.4410 or 42CrMo4	550 MPa
Gripper interlock	S890QL1 (EN 10025-6)	830 MPa
Bolts	12.9 14.9	1080 MPa 1260 MPa

4.2. Configuration and basic design

The supports of the BB transporter, i.e., the three skids, are positioned on the periphery of the upper port. This enables the efficient transfer of in-plane forces into the walls of the port and those of the cask. At the same time due to the compact design of the skids and the rigid chains almost the entire space within the upper port remains clear for the BB transporter to manoeuvre the BB segments. Using rails for horizontal support with simple flat surfaces interfacing to the BB transporter allows extending these into the upper port and establishing, with alignment pins, a suitable transition between cask and port rails. The continuous rails make a vertical translation of the BB transporter possible from the top of the cask down to its operational position during disengagement of the BB segments and vice versa. Hence no transfer of the BB segment to a 2nd tool dedicated to the >20m lift is necessary. Consequently, a common interface is integrated in all BB segments for the gripper to engage with.

The movements within the port footprint are implemented as *horizontal* translations to avoid any components to accelerate “downhill” in case of a drivetrain failure. Consequently, the BB transporter was devised with a *trolley*, that travels radially along a rail and that integrates the gripper. For toroidal translation towards the port sidewalls the radial rail can pivot about a hinge on the inboard side, see also [1]. On the outboard side the radial rail is fixed to a skid that runs inside a curved toroidal rail, which is integrated in-between the outboard skids.

Large bending moments and a large vertical force due to the payload need to be transferred from the gripper through the BB transporter to the skids. Consequently, all components are made of massive steel parts and load capacity has been the main driver in the definition of the revolute joints. Structural analyses have been carried out to verify most of the BB transporter components, see paragraph 4.6. Particularly critical is the transfer of the bending moments at the gripper and from the trolley to the radial rail. The size of both components is limited by space constraints. A large trolley would be bulky and too constrained to manoeuvre within the upper port close to the centre of gravity of the BB segments, which would increase again the bending moments. The most compact design of the trolley that was identified (and implemented) is a massive housing embracing the radial rail with interfaces in all four corners via rollers. Its radial/toroidal dimensions could be reduced to 1.56 m × 1.2 m. Nonetheless, the geometrical centre of the trolley cannot be moved directly above the attachment points of the inboard and the lateral outboard segments, which are located very close to the port sidewalls. Consequently, the gripper must be shifted within the footprint of the trolley (by ~0.4m). A large vertical pipe with a kink, the *trunk*, is therefore integrated below the trolley via a rotational joint, see Fig. 4. The rotation of the kinked trunk about the vertical axis provides the additional horizontal translation required for the gripper to be moved in proximity of the port walls. As a result, a 2nd lower rotational joint is implemented at the bottom of the trunk to restore the orientation of the gripper. The trunk, being a large pipe, is well-suited to transfer the large bending moments and horizontal forces from the gripper to the trunk. It has a variable diameter, 730 mm on the top and 630 mm on the bottom.

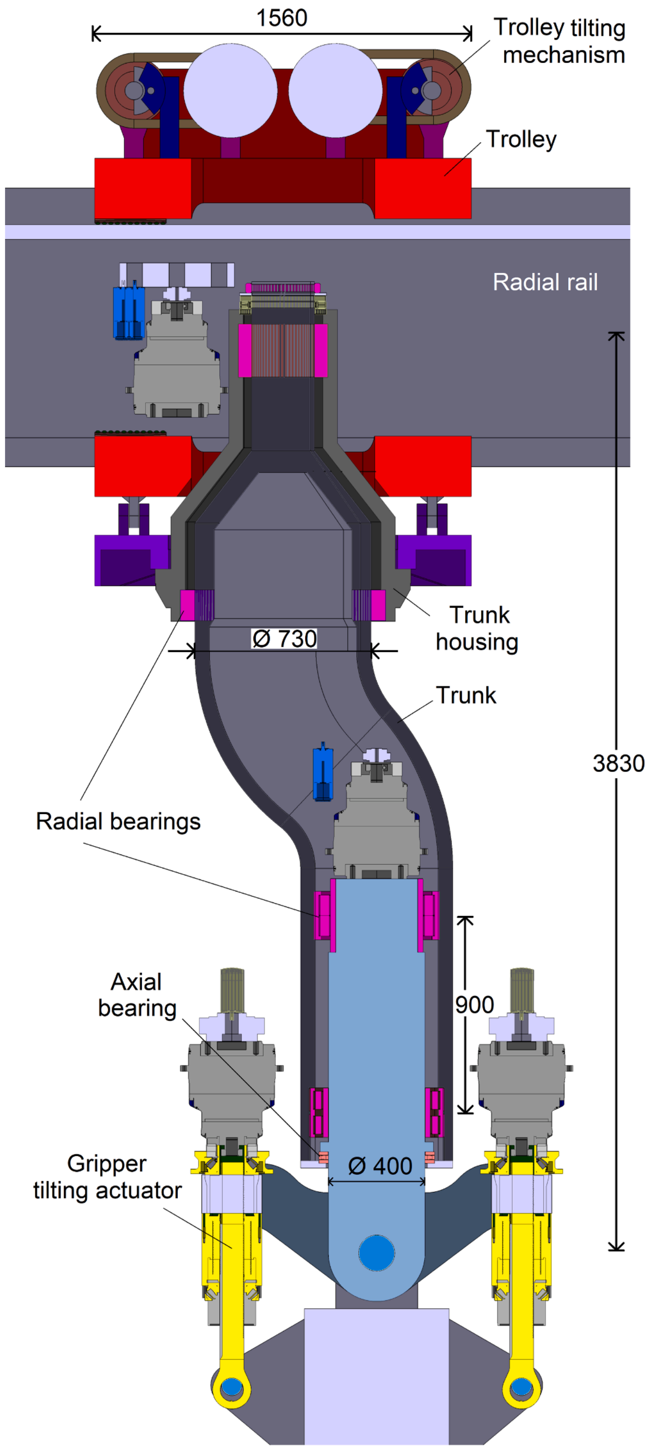

Fig. 4. Vertical section of the trunk with radial and axial bearings (pink) of two rotational joints: to the gripper on the bottom and to the trunk housing at the top (interface to BB (blue) indicatively), dimensions in [mm].

It is worth noting that an important aim in the design of the BB transporter (and in its future optimization) is the minimization of its overall vertical size. Since the BB transporter must be accommodated inside the cask above the BB segment, its size increases the height of the cask and consequently the height of the contamination protection structure and the AMF upper floor, which have large cost associated. For this reason, it was e.g., chosen to integrate the trunk inside the radial rail rather than below.

4.3. *Counterbalance of moments*

When the BB segment is lifted the BB transporter and the BB segment itself deflect horizontally due to the off-centered gripping point. Without counterbalance the acting bending moments would be partially reacted during the initial lifting phase by horizontal forces on the bottom support of the BB segment. Towards the end of the disengagement, when this contact is lost, a sudden horizontal movement of the lifted BB segment and a damage to the support structure could potentially occur. To avoid these issues two moments about both horizontal axes that counteract the off-centered moments are applied to the BB segment before lifting. One of these moments can be applied by the tilting mechanism of the gripper, see section 4.5. The moment about the second horizontal axis can be applied by the tilting mechanism of the trolley, which uses four cams with an eccentricity of 20 mm to tilt the plate below the trolley, which the trunk is attached to, see Fig. 3.

4.4. *Joints*

Design: The design of the different joints of the BB transporter is critical due to the limited available space and due to the large bending moments, that need to be resisted. To reduce the difficulties each joint provides flexibility along one degree of freedom only. E.g., the two joints of the trunk that allow for rotation about the vertical axis have the same design principle: The bending moments are reacted by two radial bearings that are 0.9m apart, the vertical force is reacted by a separate axial bearing.

Drivetrain: To minimize resistance in the movements of the BB transporter components sliding joints were avoided. Instead, rollers with sealed bearings are used. Off-the-shelf components with sufficient load bearing capacity were identified for the leadscrews providing linear actuation (Ewellix [19]), the gearboxes (e.g. Wittenstein [20]), and the bearings (SKF [21]) in order to confirm their fitting within the available space.

Actuators: Initially, water hydraulic actuators as used in the ITER divertor handler [22] had been considered [1]. They were excluded in favor of electric engines which could be packaged within the available space. Both technologies can similarly tolerate the high gamma radiation environment. Electric solutions however eliminate the need to handle hydraulic lines, the risks associated with hydraulic leaks in the high-vacuum area and the need to integrate hydraulic connections at the automatic connectors of the cask. At the same time hydraulic actuators might be re-considered in the future given their higher force density and the possibility to relax a joint by releasing the hydraulic pressure. This might be beneficial, e.g., for guided engagement of the gripper interlock.

4.5. *Gripper*

The gripper engages with the BB segment and can tilt it about the toroidal axis by ±8°. The gripper consists for this reason of two parts that are joined by a large central pivot pin. Two large leadscrew linear actuators provide sufficient force to tilt the heavy segment. The upper part of the gripper has a shaft that is mounted into the trunk and can be rotated about the vertical axis, see Fig. 4. The lower part has a flange, which the gripper interlock is mounted to.

The gripper interlock engages with the BB segments. It is the highest loaded part of the BB transporter. Its design is therefore particularly critical, and it has been developed to a higher level of detail as compared to other parts of the BB transporter [23]. The corresponding structural assessment is presented in [24]. The main challenge of its design is to enable the transfer of the large bending moments across the relatively small accessible surface on the backside of the BB segment. This is particularly narrow in case of the lateral outboard segments. A rectangular shape with rounded corners was chosen that fits well the accessible surface. The longer radial and shorter toroidal dimensions (625 × 425 mm), see Fig. 5, also match the dominant moment acting about the

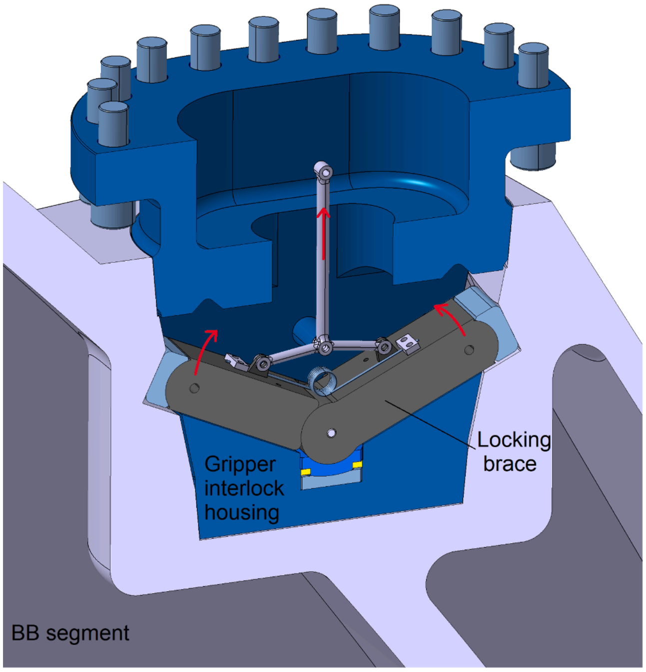

Fig. 5. Gripper interlock engaged with BB segment with locking braces and indication of unlocking movement (actuator drivetrain not shown).

toroidal axis.

The gripper interlock is made of high strength steel, see Table 1. It consists of a massive housing that is inserted about 450mm deep into a countersunk hole in the chimney of the BB segment. To enable guided engagement the main contact surfaces, have a conical shape. Upon insertion of the interlock into the countersunk hole, the locking mechanism unfolds two inclined braces that protrude through cut-outs in the housing. When the BB segment is lifted, they are pushed against contact surfaces on the BB segment. The gripper interlock can be disengaged only once the segment has been put down, preventing an accidental release.

Since a single point of failure of the gripper or its locking mechanism could lead to a load drop, these components are foreseen to be designed as per section 4.3 of the KTA 3902 [24] with increased requirements for acceptance testing and in-service inspection according to KTA 3903. In this case a load drop needs not to be considered for design-basis incidents or accidents.

4.6. *Structural integrity verification*

The structural integrity of the BB transporter and the cask has been assessed using several different finite element models and following the rules defined in EN 13001. Following the assessments, the design of several parts has been improved, e.g., the rigid chains of the cask elevator system, the trolley and the trunk were somewhat increased in size. A re-iteration of all structural assessments fully consistent with all design modifications has not yet been carried out.

The analyses carried out so far have verified the load bearing capability of the most important structural components and have identified the acting forces and moments at the joints of the BB transporter. The stress level in the highly loaded trunk is shown in Fig. 6. The structural verification of the gripper is presented in [28]. The radial and toroidal rails instead were found to be over-designed and some of their dimensions could be reduced in the future.

4.6. *Discarded alternative concepts*

In the early 1990s a handling device for vertical blanket segments had been devised for NET [25],[26]. It included a trolley that could be translated in both horizontal directions. Consequently, the lifting device was operated inside a large rectangular ex-vessel support structure. We had previously considered a similar concept that is shown in [27] as “end-effector mounted on a telescopic mast”. The fact that parts of the trolley could be moved over the center of gravity of the BB segments was found to be a significant advantage of this concept. We discarded the concept since the implementation of a second confinement barrier inside the building seemed not possible. The rectangular frame structure was significantly larger than one single upper port, spanning across 3 upper ports. Hence a sub-division of the maintenance hall on top of the bioshield into individual containment cells that can be sealed from each other, see [1], is not possible.

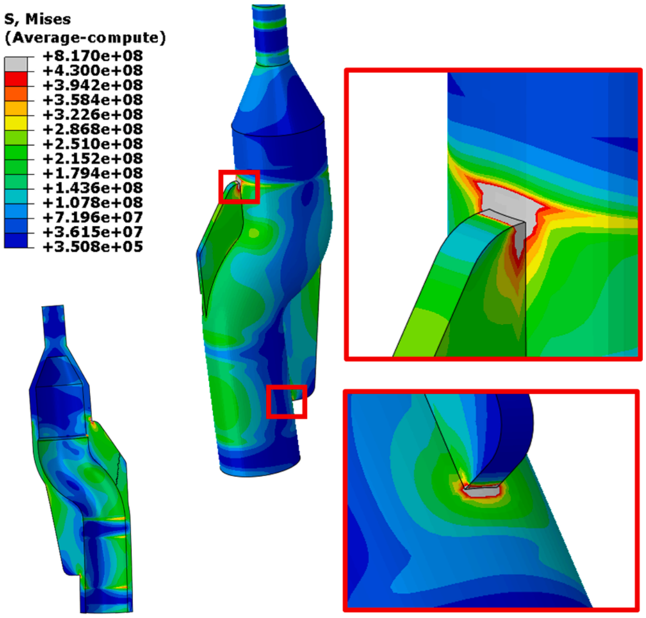

Fig. 6. Stress level in the trunk for the most severe loading condition during lifting of the inboard BB segment [MPa], red contour manually defined as 430 MPa.

5. Summary

The design of the BB transporter operated within the upper port cask is critical to the feasibility of the maintenance concept for large vertical BB segments that has recently been presented [1]. The design of both BB transporter and upper port cask was further developed and is verified in this article to meet the principal requirements, i.e. (i) to withstand all loads that occur during the lifting of the large payloads, (ii) to be capable of performing the required manipulations of the BB segments, and (iii) to fit within the available space.

To further mature the design described here further verification and validation is required, incl.:

- Development of a control system, dynamic simulation, and assessment of positional accuracy during blanket handling.
- Further development of the design of the BB transporter and BB cask including e.g. the routing and connectors of the supply cables.
- Detailed structural integrity assessment.
- Development of rescue scenarios.
- Construction and operation of a test facility.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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References

[1] C. Bachmann, et al., Conceptual study of the remote maintenance of the DEMO breeding blanket, Fusion Engineering and Design 177 (2022), 113077.
[2] G. Federici, et al., Overview of the DEMO staged design approach in Europe, Nuclear Fusion 59 (6) (2019), 066013.
[3] C. Bachmann, et al., Key design integration issues addressed in the EU DEMO pre-concept design phase, Fusion Engineering and Design 156 (2020), 111595.
[4] Isabel Ribeiro, et al., The remote handling systems for ITER, Fusion Engineering and Design 86 (6-8) (2011) 471–477.
[5] S. Beloglazov, et al., Configuration and operation of detritiation systems for ITER Tokamak Complex, Fusion engineering and design 85 (7-9) (2010) 1670–1674.
[6] Ch Bachmann, et al., Issues and strategies for DEMO in-vessel component integration, Fusion Engineering and Design 112 (2016) 527–534.
[7] Christian Vorpahl, et al., Initial configuration studies of the upper vertical port of the European DEMO, Fusion Engineering and Design 146 (2019) 2469–2473.
[8] C. Bachmann, et al., Containment structures and port configurations, Fusion Engineering and Design 174 (2022), 112966.
[9] D. Leichtle, et al., Global shutdown dose rate maps for a DEMO conceptual design, Fusion Engineering and Design 98 (2015) 1524–1527.
[10] Curt Gliss, et al., Initial integration concept of the DEMO lower horizontal port, Fusion Engineering and Design 146 (2019) 2667–2670.
[11] EN 13001-3-1:2012+A2, Cranes - General Design - Part 3-1: Limit States and proof competence of steel structure, 2018.
[12] A. Del Nevo, et al., Recent progress in developing a feasible and integrated conceptual design of the WCLL BB in EUROfusion project, Fusion Engineering and Design 146 (2019) 1805–1809.
[13] Francisco A. Hernandez, et al., An enhanced, near-term HCPB design as driver blanket for the EU DEMO, Fusion Engineering and Design 146 (2019) 1186–1191.
[14] Christian Bachmann, et al., Initial definition of structural load conditions in DEMO, Fusion Engineering and Design 124 (2017) 633–637.
[15] J.-M. Martinez, et al., Structural analysis of the ITER vacuum vessel regarding2012 ITER project-level loads, Fusion Eng. Des. 89 (7–8) (2014) 1836–1842.
[16] G. Mazzone, et al., Seismic design of the ITER main Tokamak components, Fusion engineering and design 86 (9-11) (2011) 1984–1988.
[17] Christian Bachmann, et al., Mechanical support concept of the DEMO breeding blanket, Fusion Engineering and Design 173 (2021), 112840.
[18] P. Mollicone, et al., Preliminary structural design verification of the DEMO breeding blanket transporter and transfer cask", this conference, Fusion Eng. Des. (2023).
[19] https://www.ewellix.com/en/products/ball-and-roller-screws/roller-screws/planetary-roller-screws.
[20] https://alpha.wittenstein.de/en-en/products/servo-gearboxes/low-backlash-planetary-gearboxes/tp-planetary-gearbox/.
[21] https://www.skf.com/at/products/rolling-bearings/roller-bearings/cylindrical-roller-bearings.
[22] Mikko Siuko, et al., Water hydraulic actuators for ITER maintenance devices, Fusion engineering and design 69 (1-4) (2003) 141–145.
[23] T. Steinbacher, et al., Design of the gripper interlock that engages with the DEMO breeding blanket during remote maintenance, Fus. Eng. Des. 193 (2023) 113641.
[24] Safety Standards of the Nuclear Safety Standards Commission (KTA), KTA 3902 – Design of Lifting Equipment in Nuclear Power Plants.
[25] D. Maisonnier, et al., Remote handling of the blanket segments: testing of 1/3 scale mock-ups at the Robertino facility, Fusion engineering and design 29 (1995) 298–308.
[26] F. Andritsos, et al., Simulation and experimental validation of first wall/ blanket assembly and maintenance for the next step fusion reactor, Fusion engineering and design 42 (1-4) (1998) 473–484.
[27] Oliver Crofts, et al., EU DEMO Remote Maintenance System development during the Pre-Concept Design Phase, Fusion Engineering and Design 179 (2022), 113121.
[28] R. Mozzillo, et al., Structural assessment of the gripper interlock of the DEMO breeding blanket transporter", this conference, Heliyon (2023).