

Conceptual study of the remote maintenance of the DEMO breeding blanket

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ARTICLE INFO

Keywords:

Demo
Tokamak
Remote maintenance
Remote handling

ABSTRACT

The development of a remote maintenance concept to replace DEMO in-vessel components after completion of their lifecycle or in case of failure is fundamental to the successful implementation of the EU fusion roadmap. The replacement of the hot breeding blanket (BB), by far the largest in-vessel component, at the end of its lifecycle is particularly important. This includes the removal from the reactor, the transport to the active maintenance facility (AMF) where the BB is decontaminated and prepared for storage as radioactive waste and the preparation and installation of the new BB. Significant effort is made to control and minimize the spread of contamination. All operations are therefore carried out in sealed rooms and corridors.

The high mass of the BB segments requires all remote handling equipment to be capable of handling high payloads of more than 100 tons. It must also operate within tight space and based on impaired feedback from control sensors in the radioactive environment. At the same time, it must be highly reliable in accordance with nuclear requirements and be recoverable in case of failure.

Some concepts of BB lifting devices were investigated in the past [1] (Keep et al., 2017), but were discontinued due to insufficient payload capacity. Thus, the vertical maintenance of the BB was identified as one of DEMO's key design integration issues since failure to develop a feasible concept would potentially require major changes to the tokamak architecture [2] (Bachmann et al., 2020). A new study had been initiated with a focus on structural integrity and efficient load transfer from the BB through the RH equipment to the VV upper port. A concept of the BB transfer cask and the BB transporter resulting from this study is presented in this article together with a conceptual study of the layout of the tokamak building and the AMF. Studies of alternative concepts for in-vessel maintenance are conducted in parallel but will not be described here.

1. Introduction

DEMO is a device that will follow ITER and has the main goals to demonstrate the production of few hundred MWs of net electricity, the operation with a closed tritium fuel cycle, and maintenance systems capable of achieving adequate plant availability. A tritium breeding blanket (BB) is therefore installed inside the vacuum vessel (VV) covering most of the plasma's surface. The degradation of the BB materials due to neutron irradiation requires replacing it during the lifetime of DEMO [3], which needs to be carried out in a manner that could later be adopted also in fusion power plants. For this purpose the BB is divided into large vertical BB segments as considered already in the 1980s for INTOR [4] and NET [5] and later also in the European power plant conceptual studies [6]. Large upper ports are integrated for the heavy BB segments to be lifted by a crane-like device out of the VV and into the

upper maintenance hall above the bioshield for transport to the AMF, Fig. 1.

2. Overview of BB maintenance

2.1. Requirements

Contamination protection: Three phenomena cause the BB segments to be a radioactive hazard: (i) the radioactivity of the BB materials caused by the neutron irradiation, (ii) radioactive particulates on their surfaces, i.e. dust, and (iii) outgassing tritium that permeated into the BB material during plasma operation. Consequently, the removal of the BB segments is carried out by remote handling (RH) tools. As considered in the 1980s in NET [7] and implemented in ITER [8,9] these are operated from within a sealed cask that is located within a sealed room. This *sealed*

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<https://doi.org/10.1016/j.fusengdes.2022.113077>

Received 14 October 2021; Received in revised form 22 December 2021; Accepted 21 February 2022

Available online 28 February 2022

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environment concept with two confinement barriers inside the building is necessary in accordance with the ALARA principle and effectively prevents the spread of contamination from inside the VV and from the transported BB segments into the building. To achieve this goal it is essential to minimize the contaminated surfaces and volumes and regularly clean surfaces inside the cask and inside the secondary confinement to prevent the progressive building-up of contamination levels.

Availability: The requirements for the BB maintenance are derived from the DEMO plant requirements and its operation concept. This foresees in addition to the complete replacement of the BB also the regular removal of single BB segments for the purpose of in-service inspection. The duration of these planned maintenance operations must be short as they impact on the DEMO availability and hence its goal. DEMO currently has 16 upper ports. Below each of them three outboard and two inboard BB segments are installed, respectively. Hence 80 BB segments need to be removed prior to the installation of a new set of BB segments. It is currently assumed that BB maintenance needs to be carried out simultaneously in ~ 4 upper ports in order to reduce the plant downtime to few months. Parallel operations will take place in other upper ports to prepare or conclude the replacement of the BB. It is therefore necessary that upper port maintenance can be carried out in each port independently.

BB extraction sequence: The BB transporter operates in the VV upper port of one VV sector and must remove sequentially the three outboard and two inboard BB segments, see Fig. 2 and [20]. Upon extraction of each BB segment the VV and the cask are closed by a double-lidded contamination control door (CCD) while the cask transports the BB segment to the AMF. It may be considered at a later point in time to use a toroidal mover operating inside the VV and moving BB segments from adjacent sectors underneath the RH port to reduce the number of upper ports that need to be opened. This decision will depend on the available technologies to connect/disconnect the in-vessel pipes, which requires further development work and on the technological feasibility of a toroidal blanket mover.

Manipulation: The upper port is too small to allow direct vertical removal of the BB segments [10]. To remove the BB segments from the VV, kinematics of a certain complexity are required that include tilting the segments by few degrees to disengage them from their supports and to maneuver them clear of residual segments and through the comparably narrow upper port, see Fig. 2. At the same time, a positioning precision is required prior to the last engaging movement that is guided by the wedge-shaped BB mechanical attachments [11], based on the

current design about ± 40 mm.

Design criteria: The BB cask and the BB transporter are designed in accordance with EN 13001-3 [12]. Given the significant duration of the operation under load the BB maintenance equipment is designed also for the SL-1 seismic event [13].

Decontamination: Man-access for maintenance is required to all RH equipment and in all cask transfer areas. At the same time it can be expected that even with a sufficiently low level of airborne tritium, meeting the accumulated DEMO lifetime dose limit to workers [14] will be a challenge. Facilitation of decontamination is therefore important and the following design guidelines were adopted where possible: (i) surface reduction, (ii) use of (removable) panels to separate components with complex surfaces such as cabling from the contaminated volume, (iii) use of surface materials with low tritium absorption, e.g. metallic walls, concrete walls with metallic liner or special paint.

2.2. RH strategy

The BB RH strategy aims at the high plant availability through efficient maintenance operations. Hence the following rules were adopted:

- During plasma operation no RH tools are inside the tokamak complex to allow their maintenance and re-commissioning in the AMF while plasma operation proceeds.
- Wherever practical the use of standardized items is imposed. This includes: one type of cask transporter, the common interfaces to the cask transporter on all upper port casks, components in the cask containment cells supporting the plasma operation are installed on pre-defined containers with accessible service connections.
- Pipes and other components inside the upper port are configured where possible such that the removal path of the blanket segments is not obstructed [13]. In particular, the pipes of the lateral outboard and inboard segments should remain *in-situ* during replacement of the upper limiter or the central outboard segment, see also [20].
- Auxiliary heating and diagnostic systems are designed where possible such that they do not obstruct the removal kinematics of the BB segments, e.g. the mid-steering electron-cyclotron (EC) launcher [15]. In case of the plasma limiters this is not possible [16].

2.3. Loads

The masses of inboard and outboard BB segments postulated here are 88 tons and 126 tons, respectively. This corresponds to 70% of the mass

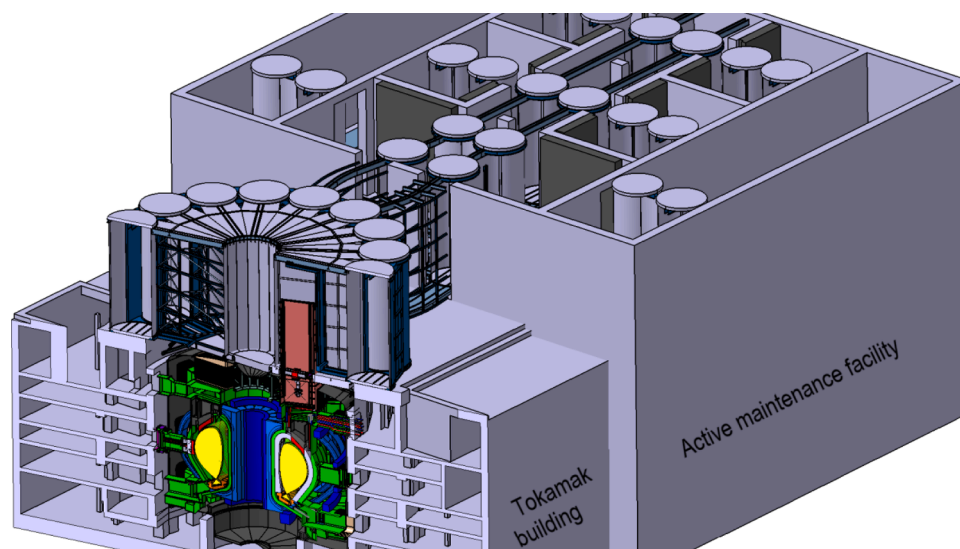


Fig. 1. Section of tokamak complex with conceptual study of AMF and contamination protection structure, VV, BB cask with BB transporter and cask transporter.

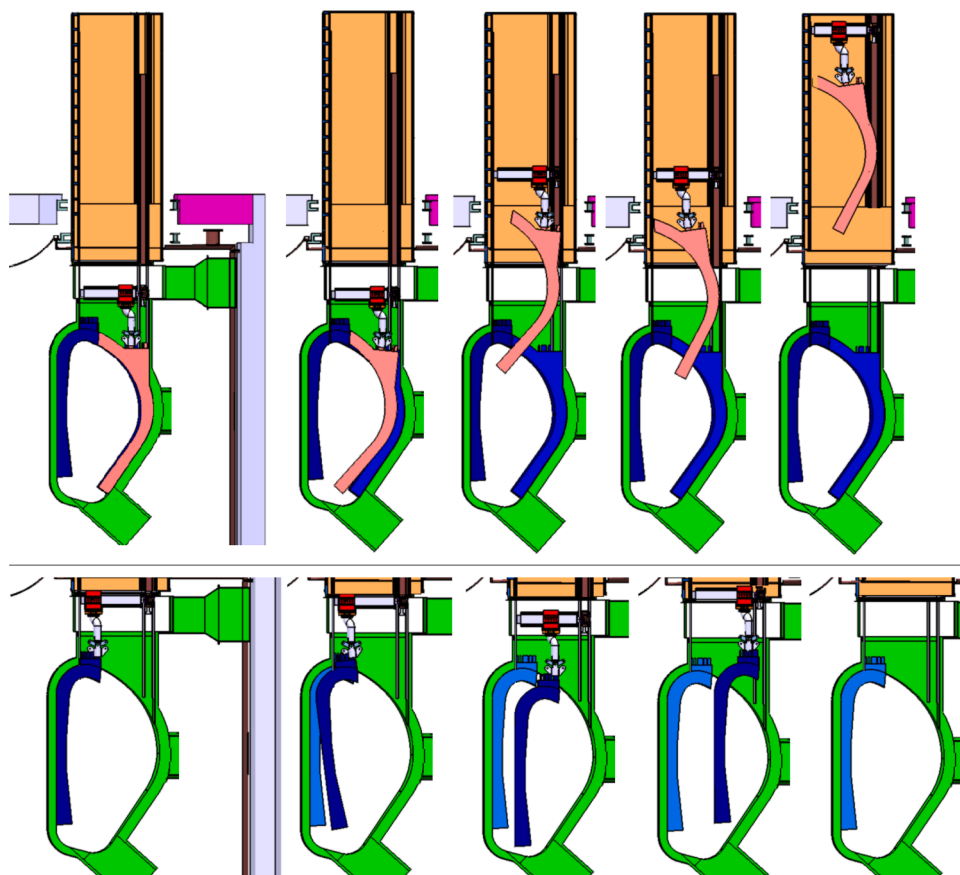


Fig. 2. Removal kinematics of the BB outboard and inboard vertical segments requiring an initial small vertical lift (not shown) followed by a swing about the toroidal axis to free the segments from their bottom supports.

of the (undrained) water-cooled lithium lead (WCLL) BB [17] and about twice the mass of the helium-cooled pebble bed (HCPB) BB [18]. Further studies will aim at improving the bearing capacity of the BB transporter to the full weight of the undrained WCLL segments. Preliminary seismic analyses indicate for an SL-1 event [13] maximum equivalent accelerations of the BB segments of $\sim 0.8 \text{ m/s}^2$ and 2.7 m/s^2 in horizontal and vertical directions, respectively, assuming the natural frequency of the lifted BB segment being in the frequency range of 0.8–6 Hz. These accelerations cause large moments acting on the BB transporter that operates above the BB segments. Additional moments of similar magnitude need to be superimposed due to the load attachment points on the BB segments not being above their center of gravity, see Fig. 3. Considering the partial safety factors defined in EN 13001-3 a design moment of up to $\sim 4 \text{ MNm}$ may occur at the BB load attachment point. At the trolley of the BB transporter the moment is $\sim 30\%$ larger due to its larger distance from the BB segment. The loads carried by the BB transporter are transferred to the three skids operated by the cask elevator system, see below. On single skids vertical forces occur up to $\sim 1.4 \text{ MN}$ (downwards) and $\sim 0.35 \text{ MN}$ (upward).

In particular the seismic loads are yet to be assessed more accurately. These are also subject to change when the DEMO construction site has been selected and site-specific input spectra will replace those defined for the Cadarache site [13] where ITER is being built.

2.4. Tokamak and building configuration

The bioshield roof above the tokamak is a steel structure with radial beams and concrete inserts that can be removed to access the upper ports [19]. A contamination protection structure is mounted onto the bioshield roof and serves as second containment barrier dividing the upper maintenance hall into sectors corresponding to the VV upper

ports, see Fig. 1. This results in segregated volumes that are sealed from each other and are serviced by the detritiation system as needed. The contamination protection structure is extended inside the tokamak complex building to the upper level of the AMF whose floor has several docking stations to hot cells below the floor to unload the active BB segments. The cask is moved along rails within these corridors by the cask transporter.

2.5. Preparation of BB maintenance

Before the removal of a BB segment by the BB cask the vacuum closure plate needs to be removed as well as components installed inside the port such as shield plugs, upper limiter, or piping [20]. This will be carried out by casks with tools specialized for these purposes whose transport and docking use the same infrastructure as the BB cask. The complexity of the tools and operations carried out from within the casks depends on the different purposes. Also the divertor cassettes blocking the BB kinematics need to be removed through the lower port [21].

The BB pipes are routed through the upper port horizontal annex into the upper pipe chase [22]. Consequently, in upper ports where no auxiliary systems such as diagnostics are installed there will be no penetrations of the port closure plate and no ex-vessel components requiring removal from the cask containment cell prior to the arrival of the BB cask (Fig. 4).

3. Contamination protection structure in the upper maintenance hall

3.1. Dome-shaped roof of the upper maintenance hall

The roof of the upper maintenance hall is made of reinforced

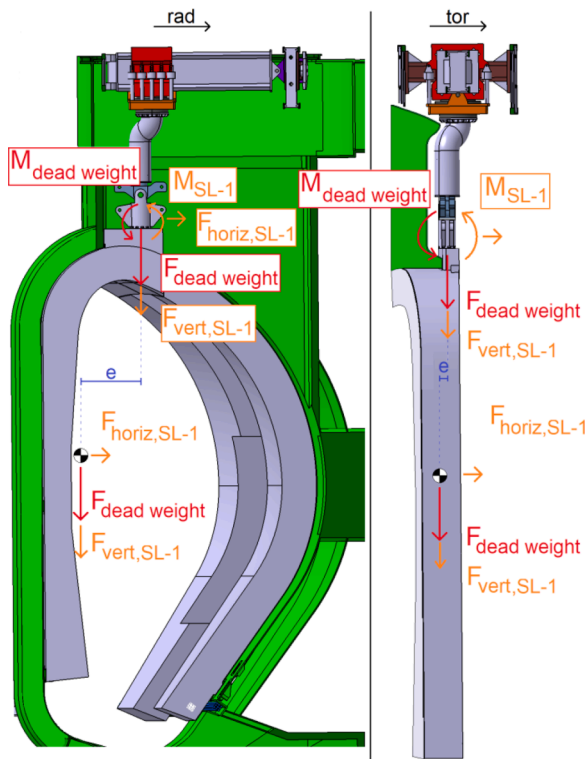


Fig. 3. Forces acting on the inboard BB segment due to gravity and SL-1 and their transformation into equivalent forces and also moments acting on the interface to the BB transporter due to the off-centered attachment point.

concrete and is designed with a dome shape for better membrane strength. With its thickness of 1 m it would be capable of protecting the maintenance zone underneath from the impact of a small airplane [13, 23,24] and at the same time reduces the gamma radiation emitted from the hot BB segments being transported above the tokamak sufficiently to meet the limits at the site boundary [25].

3.2. BB cask docking stations

The BB cask can dock to the VV upper ports and to the AMF docking stations. Sealing is foreseen to be provided through double elastomer seals whose application is possible given the expected moderate gamma radiation level at the upper port docking flange during in-vessel maintenance in the range of ~ 5 Gy/h while the hot BB is in the plasma chamber, and up to ~ 100 Gy/h when it is in proximity of the flange.

3.3. Cask containment cells

The BB cask is located inside a sealed cask containment cell when it is docked to the VV. It is a steel frame structure with walls made of thin steel liners to facilitate decontamination. Although the cask minimizes the spread of contamination outside the cask the cask containment cell is not free from contamination: (i) upon undocking contamination will migrate from small surfaces nearby the cask docking flange, (ii) small amounts of tritium permeate continuously through the cask wall during docking. Both the BB cask and the cask containment cell are connected to the detritiation system that can exchange the air removing tritium to limit permeation through the containment barriers. In addition a pressure cascade is established during in-vessel maintenance between VV, cask containment cell and building areas to limit the spread of contamination in case of leaks.

The 16 cask containment cells are arranged in the upper maintenance hall above the upper ports, see Fig. 5. They can be accessed from an external ring that implements 16 turn tables to allow changing the BB

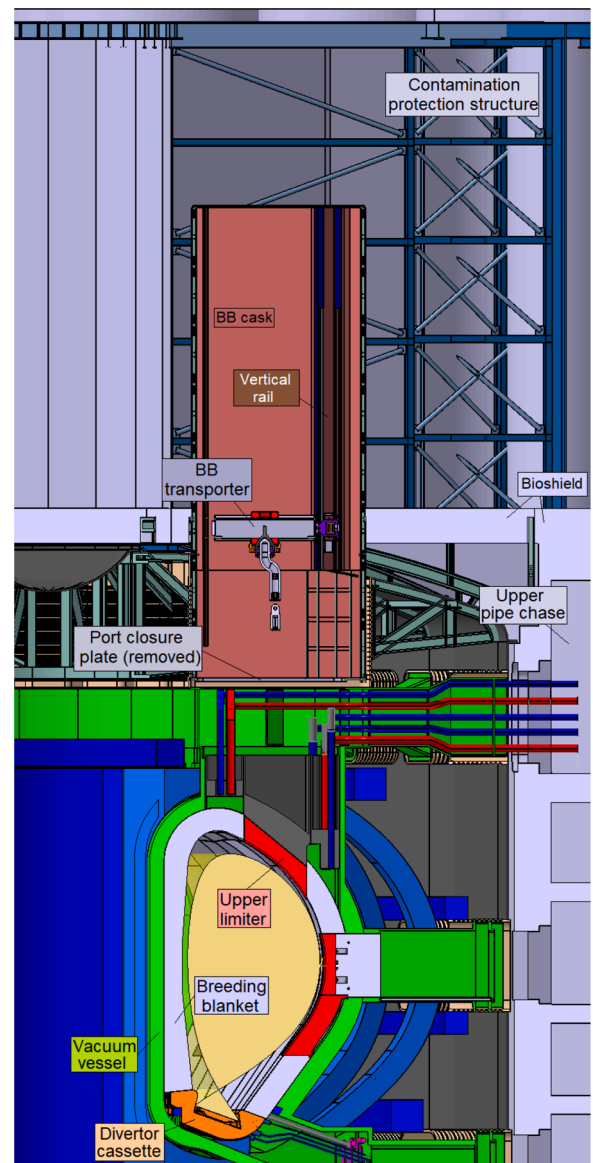


Fig. 4. Section view of the DEMO tokamak with BB cask docked to upper port and all in-port components *in-situ*.

cask orientation on the spot and hence reducing space requirements. Also the ring is a sealed structure. The turn tables use revolving doors that seal the cask containment cells when a cask is docked to the VV allowing other casks to pass and travel to and from other ports. All electrical and hydraulic services will be routed on top of this structure outside the thin metal sheeting. The services needed for the cask transporter are rather simple and can be provided through sliding contacts which allow the motors to go forward and backward. A simple automatic connector for the cask transporter is installed at any cask docking position (tokamak and AMF) to operate the hoists lifting the cask. The services for the tools inside the cask are more complex and will be provided through a series of automatic connectors which engage to the cask during the docking process. These will provide electrical fiber optics and hydraulic connections when the cask is docked to a vessel or AMF port.

All services needed during plasma operation such as pellet injectors, diagnostic, etc. will be provided from within cask-like containers, which can be transported by the cask transporter. These do not dock to the VV port but instead rest on top of the concrete inserts of the bioshield roof. To connect their services automatic connectors will be used where

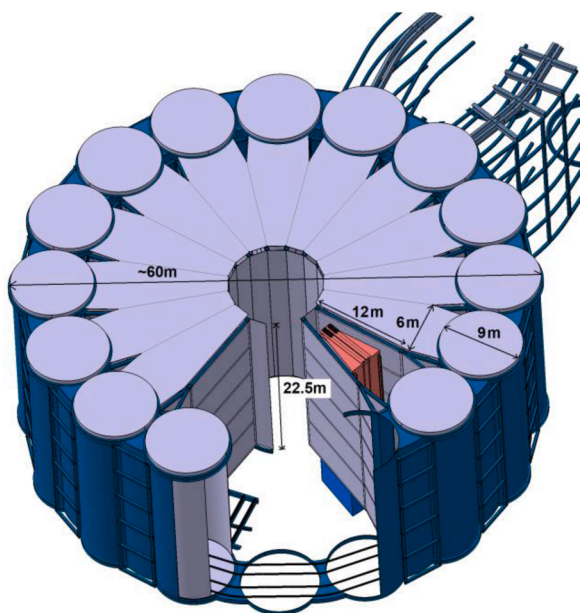


Fig. 5. Contamination protection structure in the upper maintenance hall with 16 cask containment cells and turn tables with revolving doors arranged in an external ring corridor. Also shown: BB transporter delivering a BB cask.

possible. Hands-on operations should be limited as much as possible but are possible for suited personnel with air supply. Also the services for these functions will be routed in the top of the contamination protection structure (e.g. tritium, deuterium gas supplies, cryogenics, pumping, electrical fiber optics, etc.).

3.4. BB cask transporter and rail system

The BB cask is moved and deployed to its docking stations by the cask transporter, which runs on four rails on the floor and four rails on the top that provide stability against toppling in case of a seismic event. 24 large steel wheels (DN300), 8 on the bottom and 16 on the top, bear the loaded weight of the BB cask of up to 300 tons, see Fig. 6. Rails are used to guide the cask transporter, whose control is a simple and robust system without steering mechanism and electronic control units. The large wheels can cope with the small gaps in the rails at the turntables

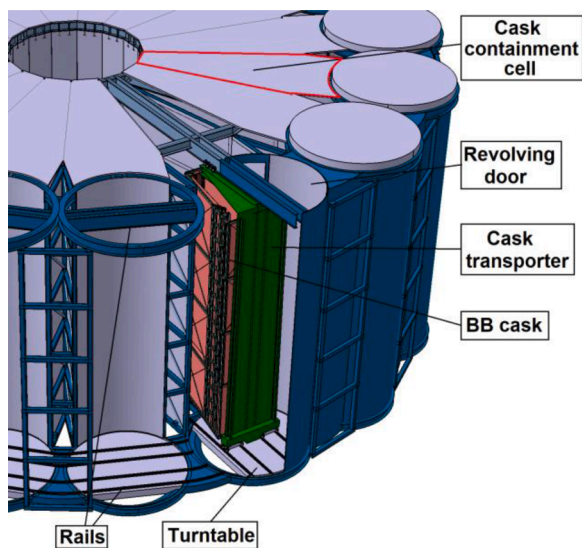


Fig. 6. Cask transporter (green) transferring a BB cask into a cask containment cell.

that are unavoidable.

The cask transporter is an L-shape beam structure with drive wheels and three hoists to lift the BB cask. When the BB cask is lifted from its docking station guiding pins on the outboard side engage in guides on the cask transporter. These pins support the cask horizontally during transport. When the BB cask is lowered through the bioshield roof onto its docking station on the VV port the pins engage with guides on the cask containment cell. The guides facilitate the docking process and provide horizontal support to the high BB cask in case of a seismic event.

4. Active maintenance facility

4.1. Overview

The AMF is a large building adjacent to the tokamak building and opposite of the assembly hall. Repair, refurbishment and testing of hot components removed from the tokamak and to be returned into service is carried out in the AMF. In addition hot components that have reached the end of their lifecycle are prepared to be discarded as rad waste. Hence the AMF is a nuclear building like the tokamak building and is planned to be constructed on a common basemat and sharing the separating wall. Consequently, the corridors where tokamak components are transferred between the two buildings do not require compensation for relative movements.

The rail system inside sealed corridors expands from the upper maintenance hall to the upper floor of the AMF which is leveled with the bioshield roof. Turntables allow the cask transporter to access different areas of the AMF dedicated to the processes linked to the BB maintenance. Each area is sealed by the revolving door of the turntable. It is protected from radiation by a sliding concrete door and has 4–6 docking ports enabling parallel operations of multiple casks. The BB segments can be lowered into maintenance cells in the level beneath, see Fig. 7.

The AMF implements areas dedicated to the following purposes, see also Fig. 8:

- Delivery of hot BB segments
- Loading of new BB segments
- Cask decontamination
- Cask and equipment maintenance and testing
- Cask storage
- Oven for to bake-out the BB segments.

In addition to casks dedicated to blanket handling, casks with different purposes are needed, i.e. pipe handling, bioshield plug and closure plate handling, upper port plug handling, as well as cask-like containers hosting diagnostics and pellet injectors. The latter are located inside the cask containment cells during plasma operation. The total number of casks is expected to be ~50 and large storage areas in the side wings of the AMF are foreseen for these. To prepare the hot BB

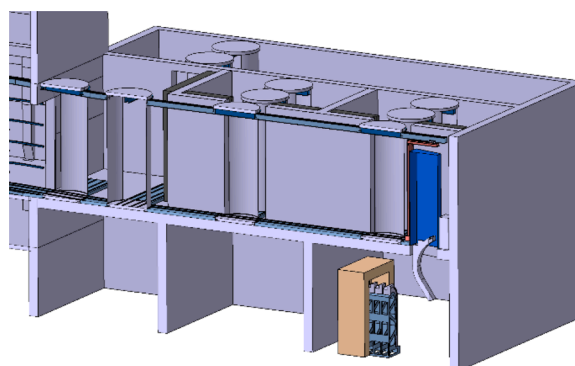


Fig. 7. BB cask on a docking station in the AMF lowering a BB segment into a maintenance cell.

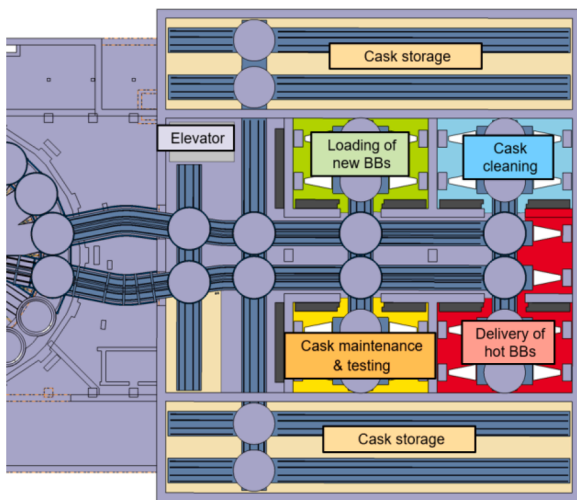


Fig. 8. Floorplan of the AMF with indication of the different purpose areas and the rail system for the cask transfer.

segments for storage as rad waste an oven is integrated below the cask storage area in the right wing with a bake-out temperature of $\sim 800\text{--}1000\text{ }^{\circ}\text{C}$ [26] to ensure the release of tritium permeated into the BB materials. The lower levels of the left wing below the cask storage area, see Fig. 8, will be used as personnel access building, for health physics labs, for suited access to contaminated areas, etc., similar to the ITER personnel access building. The lower areas of the right wing will be used as additional space for the AMF dealing with activated blankets and with general rad waste, such as liquids, filters etc., similar to the ITER rad waste building.

4.2. Contamination control

There are different levels of radiation and contamination in the different areas. Therefore they are sealed and have thick concrete walls for radiation protection.

The ventilation zoning is defined in accordance with ISO 17873 [27] and following the ITER approach [28], classifying the volume inside the VV as C4, the volume inside the contamination protection structure as C3 and the rooms outside the contamination protection structure as C2. Regular cleaning of the internal surfaces of the contamination protection structure will be required to keep the contamination levels sufficiently low to allow the C2 classification of external areas.

4.3. Decontamination

The highest contaminated levels will be inside the casks as they are in direct contact with the vessel and with the used blanket components. The contamination will consist of radioactive dust ($1\text{--}10\text{ }\mu\text{m}$, [28]) and of tritium and its chemical compounds. Regular cleaning of the cask interior and of the used blankets inside the AMF will be performed. The cleaning method will be simple using water and brushes. Water is needed to bind volatile dust but should be used in small quantities as fine spray to limit the amount of accrued contaminated waste water. Cleaning without water is difficult because dust, tritium and its compounds will remain mobilized. Airborne contamination needs to be minimized as it can contaminate even far-away surfaces stronger and can travel through small leaks, which - given the size of the structures - cannot be fully excluded.

The cask cleaning station is therefore an essential part of the BB maintenance process. After delivering a used blanket at an AMF hot cell the cask will dock at a cleaning port, see Fig. 8. There a rotating brush on a robotic arm will reach up into the cask and clean the interior surfaces with minimum water sprays. Then the cask will either return empty to

the machine to pick up another used blanket or will dock at another docking station to pick up a new BB segment for installation in the VV. The regular cleaning of the cask interior will ensure that contamination levels remain constant during the maintenance campaign and hence prevent accumulation of contamination.

The secondary confinement, i.e. the contamination protection structure, do not require cleaning during the maintenance operation. However, cleaning is required upon completion of in-vessel maintenance and before installing the containers that include diagnostics or pellet injectors. The interior surfaces, e.g. walls, ceilings, rails, turn tables and docking stations, are foreseen to be cleaned using small amounts of water and cleaning cloth to remove dust as well as tritium and its compounds. The cleaning operations might be carried out remotely or hands-on (using protective suits) with machines operated hands-on to support the cleaning operations of the large surfaces. This cleaning operation will include all areas in the upper maintenance hall and the AMF upper level including the cask storage areas. The cleaning brushes and the cleaning clothes will be treated as radioactive waste with a special treatment due to their tritium contamination. The moisture trapped in the brushes and clothes will need to be extracted (heat, evaporation, condensation) and together with the used and hence tritiated water be treated as *processing material* in the rad waste building. There the solid dust particles will be removed through filters and the tritiated water will be sent to the tritium plant for tritium recovery.

5. BB transfer cask

5.1. Overview

The BB cask is a sealed, unshielded container for transferring BB segments between the docking stations on the VV and the AMF. The cask performs the primary confinement function of radioactive dust and tritium. It allows operating in its interior the mechanism to open and close the upper port CCD as well as RH tools as required to remove and install BB segments and to carry out inspections. The BB cask weighs ~ 100 tons. It has a height of ~ 20 m and a trapezoidal cross-section enveloping that of the upper port (radial length: ~ 7.5 m, width: up to ~ 4 m).

The cask has an external frame structure to withstand all loads including those acting on the vertical rails. The three rails that are connected by thin steel liners make up much of the inner surface facilitating decontamination processes, e.g. the spraying of water. This inner trapezoidal perimeter corresponds to the inner contour of the upper port, see Fig. 9.

5.2. Port door mechanism

After the cask has docked to the VV the cask door connects to the port door. This double-lidded CCD is moved similar to a garage-door from its horizontal position into a vertical position in the outboard area of the cask by the port door mechanism.

5.3. Elevator system

In the top of the cask an elevator system is implemented that allows lowering the BB transporter into the upper port ring channel and further down into the lower port. For this purpose three skids are hoisted by rigid chains and guided along vertical rails. The BB transporter is attached to these skids. Rigid chains are used rather than ropes in order to react also upward lifting forces that occur due to the large moments that may act on the BB transporter. The vertical rails themselves can be vertically moved by few meters. During in-vessel maintenance they engage with their extensions that are permanently installed inside the upper port. Before the CCD can be moved into its horizontal position to seal both VV and cask, the rails need to be vertically retracted into the cask to provide space for the CCD garage-door-like movement.

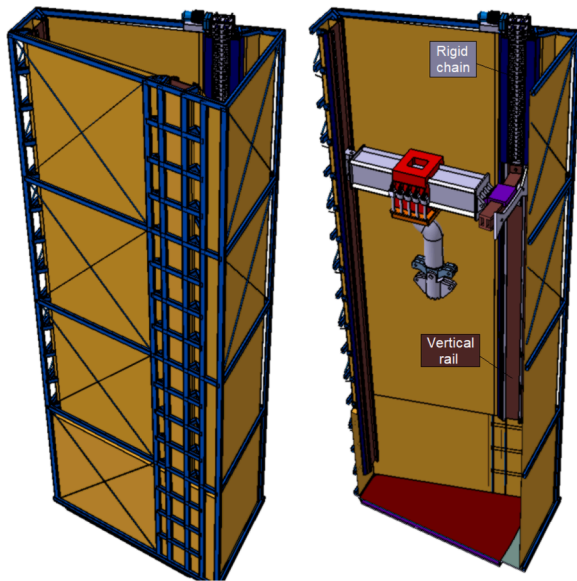


Fig. 9. Left: BB transfer cask with external frame structure (blue) and internal liner (light brown). Right: Vertical rails inside the cask and BB transporter lifted by rigid chains. (CCD mechanism and cask top lid not shown).

6. BB transporter

6.1. Overview

Studies of BB transporter concepts have been conducted in the past [1]. However, these concepts were discarded due to insufficient payload capacity and/or insufficient contamination control. The BB transporter presented here is in an early development state but seems to meet these essential requirements. It can grip any BB segment located below the upper port and perform all required kinematics except vertical translation, which is provided by the cask elevator system. It consists of a radial rail with rectangular cross-section that supports a trolley, which moves radially along the rail. On the inboard side the rail is attached to the inboard skid on a vertical hinge. On the outboard side the rail can run along a curved toroidal rail, which is fixed to the two skids on the outboard lateral walls. This allows the rail to swing toroidally within the port pivoting about the inboard vertical hinge. The trolley implements rollers running along extensions on the four corners of the rail and can move radially. Attached to the trolley is the trunk, a large vertical pipe with a kink that can be rotated. It integrates on the bottom the gripper to connect to the BB load attachment point, see Fig. 10.

All components except special components such as bearings, hinges etc. are made of stainless steel 1.4462 with a yield stress at room temperature of ≥ 450 MPa. The BB transporter as shown in Fig. 11 weighs ~ 33 tons.

6.2. Technologies

To minimize resistance in the movements of the BB transporter components sliding joints are avoided and rollers are used instead. Water hydraulics will be used for actuators and motors. In their sizing an operating pressure of 210 bar has been considered as in ITER [29].

6.3. Trolley

The trolley is a steel housing that implements 2×8 rollers that run along the corner blocks of the radial rail. The rack and pinion linear actuation is integrated on the top of the trolley to facilitate access in case of failure. From below the trolley plate is mounted to the trolley by two pins, see Fig. 11. On the lateral sides of the trolley five actuators at a time

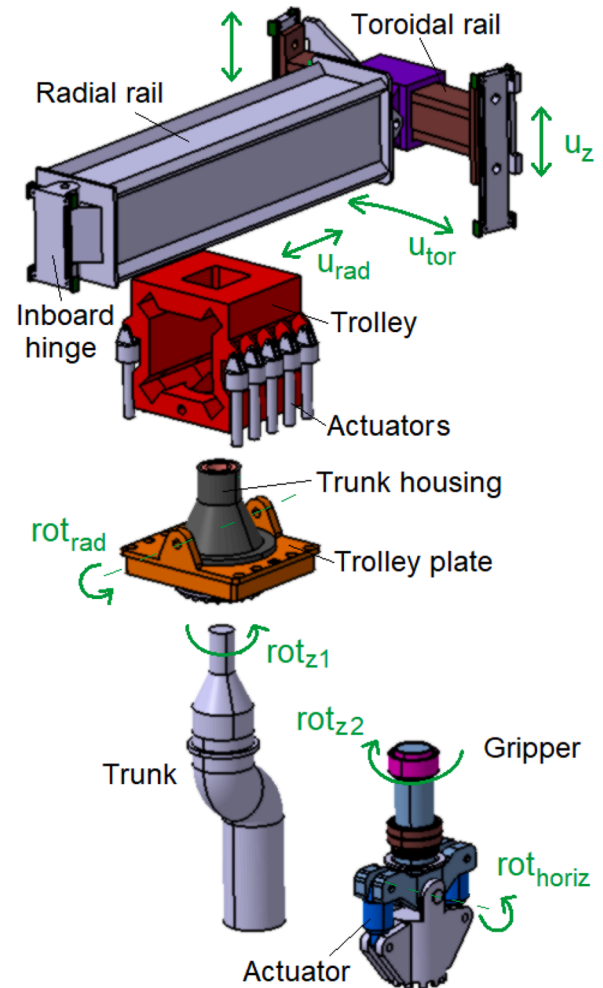


Fig. 10. Exploded view of the BB transporter with indication of degrees of freedom of its joints.

provide the force to tilt the trolley plate by up to $\pm 0.8^\circ$ about the radial axis. This allows compensating deflections of the BB transporter due to off-centered lifting of the BB segments.

6.4. Trunk

The trunk is an S-shaped pipe with outer diameter of 630 mm and 60 mm wall thickness. It has a kink that allows translating the gripper horizontally by 450 mm within the upper port through vertical rotations of the upper rotational joint. The trunk is mounted into the trunk housing which is fixed via a bolted flange to the trolley plate. The trunk housing is partly within the radial rail to reduce the vertical size of the BB transporter and hence that of the BB cask, see Fig. 12.

Two radial bearings in the trunk housing have sufficient capacity to transfer the large moments, an axial bearing withstands the vertical load. The gripper is integrated with the trunk with a second rotational joint that also implements two radial and one axial bearing. This lower rotational joint has the function to compensate the rotation of the upper rotational joint restoring the orientation of the gripper to the radial axis before swinging the BB segment.

The vertical length of the trunk allows the outboard segments being reached while the radial rail of the BB transporter is vertically located above the load attachment pins of the inboard segments. At the same time the trunk is sufficiently long to lower the inboard segments into the divertor area, see Fig. 2.

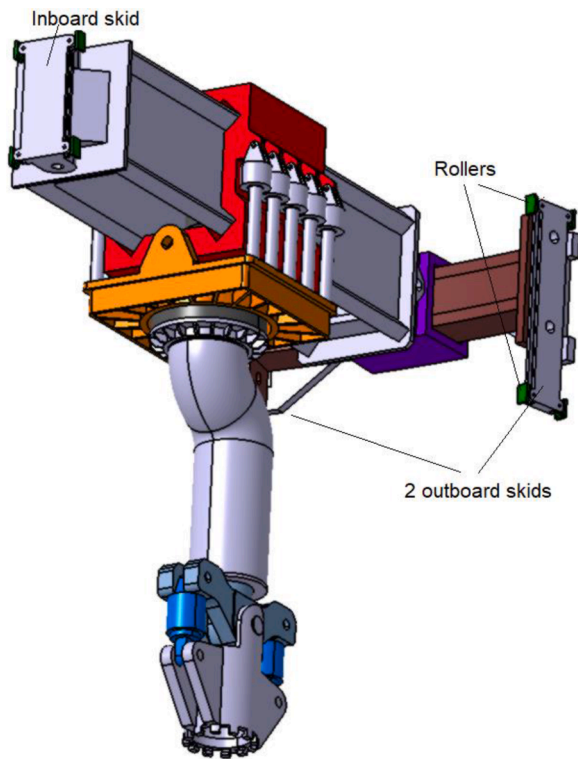


Fig. 11. BB transporter attached to its three skids.

6.5. Gripper and BB load attachment pin

The BB load attachment pin is a solid pin with a diameter of 490 mm and two vertical contact surfaces to transfer the moments by two equal-opposite horizontal forces. The gripper lower cylinder has matching surfaces and is put over the BB load attachment pin. For vertical engagement a Bayonet mount is integrated that engages through a 15° rotation of the gripper.

The gripper (Fig. 13) provides a tilting mechanism that is operated by two hydraulic actuators. It allows tilting the BB segments about the toroidal axis by $\pm 8^\circ$ as required during their removal kinematics, see Fig. 2.

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 [30] 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.

6.6. Structural integrity verification

For a first rough analysis of the load bearing capability a global finite element model including all components of the BB transporter has been used. The stress allowable was considered according to EN 13001 [12] based on the yield stress f_y , i.e. $f_y/(1.1 \times 0.95) = 430$ MPa. Partial safety factors were applied to individual loads, i.e. 1.41 for dead weight and 1.1 for seismic loads. The model was constrained at the skids and had the relevant forces and moments applied to the gripper. The expected transfer of forces is shown by the stress level in the structures, see Fig. 14. The model also shows that trolley and rails are overdesigned and can be optimized in the future. The relatively high stresses that occur in the trunk mean that local reinforcements will likely be required. The interface loads on the rollers and bearings indicate that the bearing capacity of these components is not exceeded.

The structural integrity verification of the individual components of

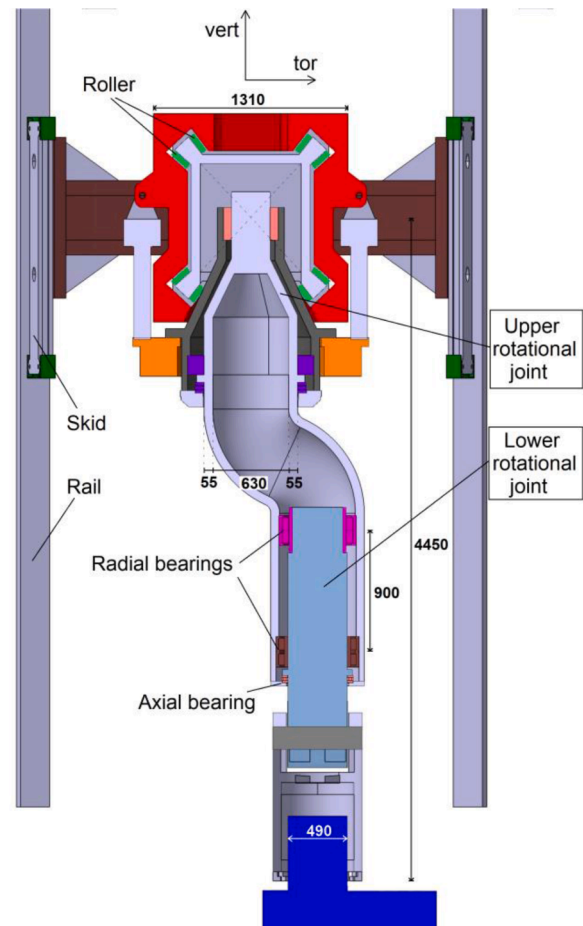


Fig. 12. Vertical section of the trunk with radial and axial bearings (pink) of two rotational joints: to the gripper on the bottom and to the trunk housing at the top (interface to BB (blue) indicatively), dimensions in [mm].

the BB transporter is planned after further design improvements in the future using models with a higher degree of detail.

5. Recovery

Failure of the BB transporter, the cask elevator system or the CCD opening mechanism cannot be excluded and could occur e.g. due to failure of drive units or the occurrence of severe seismic events with low frequency of occurrence, which the components are not designed for. In failure scenarios where a BB segment is lifted by the BB transporter but still located within the VV and partly outside the upper port contour the actuation of the BB transporter must be reinstated to allow the extraction of the BB segment together with the failed transporter. In such scenarios rescue tools and the cask transporter with its ~ 200 ton-crane are moved into the cask containment cell. The cask is opened removing its top lid and/or access hatches on its outboard wall, which causes the spread of contamination into the cask containment cell. The recovery must therefore be carried out by RH tools. The access into the BB cask should allow the recovery tools to access the drive units of the BB transporter, the cask elevator system, the skids, and the opening mechanism of the port door for repair or disconnection and installation of emergency actuation. The failure scenarios and associated recovery plans require in the future a more thorough definition and development. After such an activity the relatively small volume of the affected cell has to be cleaned by RH tools. This applies also to the exterior of the rescued cask and the affected cask transporter. Therefore the rescue tool set will include cleaning tools operated potentially by the upper rail system.

The BB maintenance concept presented in the article aims at

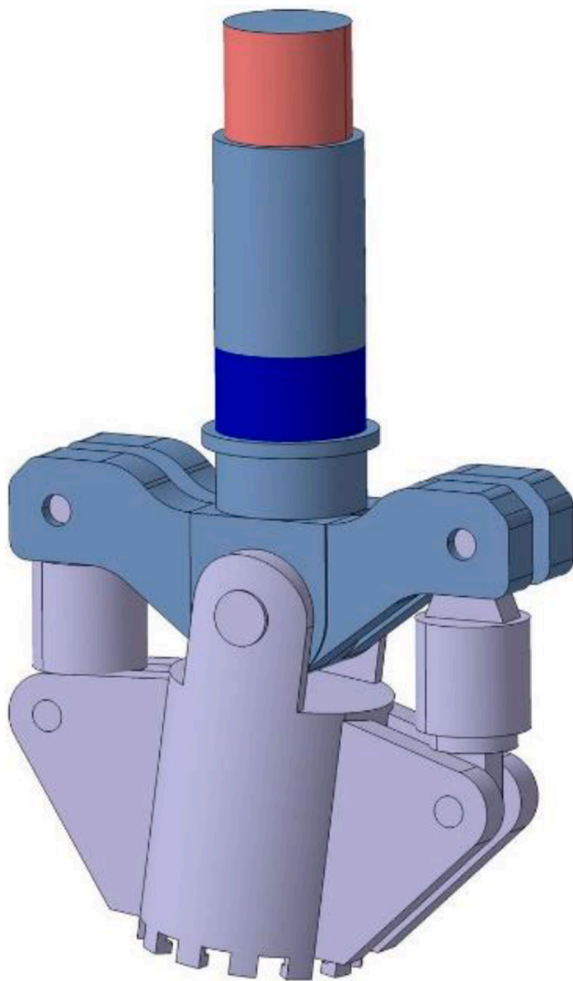


Fig. 13. Gripper in tilted position with connection shaft at the top and indication of locations of radial bearings (red and blue).

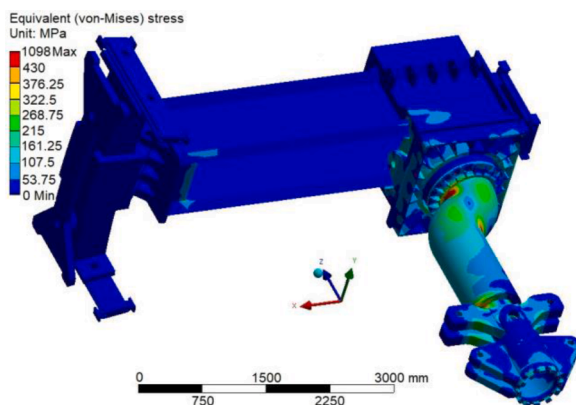


Fig. 14. Stress level in the BB transporter [MPa], orange contour manually defined as 430 MPa.

reducing volumes that are connected to the detritation system and require decontamination. This limits – in general – also the space available for rescue operations, which can be considered a drawback of this concept.

7. Summary

The results of a conceptual study of the remote maintenance of the DEMO breeding blanket have been described including:

- The layout of the active maintenance facility (AMF),
- the transportation of the BB between tokamak and AMF,
- the approach regarding contamination protection based on a sealed container (the cask) operated within a sealed corridor,
- the BB cask, and
- the BB transporter operating inside the cask and the VV upper port and manipulating the BB segments.

The AMF is a large nuclear building with a footprint of approximately 120×110 m adjacent to the tokamak building with areas dedicated to the different processes involved in the BB maintenance, i.e. (i) arrival of hot BB segments, (ii) loading of new BB segments into the cask, (iii) cleaning and decontamination, (iv) maintenance and testing of RH tools, (v) preparation of BB segment for storage as rad waste, (vi) storage of casks, and (vii) personal access. The current layout of the AMF allows the simultaneous maintenance of the BB through four upper ports.

During BB maintenance the BB segments are lifted out of the VV into the BB cask, which is docked to the VV. Prior to un-docking both cask and VV port are temporarily closed by a double-lidded door. The BB cask is then transported by a cask transporter that operates on a rail system inside sealed corridors that are installed on the bioshield roof. The rail system extends to the upper floor of the AMF, which has several docking stations in each of the areas listed above. The BB segments can be lowered into maintenance cells in the level beneath for processing.

After a BB maintenance operation the cask transfer corridors are cleaned by personnel working in protective suits to avoid the accumulation of contamination.

The remotely operated BB transporter operates inside the BB cask and can replace the large DEMO BB segments through the upper vertical ports of the VV. The BB cask has a trapezoidal cross-section, is ~ 20 m high and implements an elevator system. This allows the vertical translation of the BB transporter along three vertical rails that engage with corresponding rails inside the upper port. The BB transporter consists of a trolley that can be horizontally translated within the upper port on a rail system. A gripper engages with a single large pin on the backside of each BB segment. Hinges operated by hydraulic actuators allow performing the tilting movements as required to install the BB segments into their support structures on the VV.

The BB transporter concept has been guided by the rules defined in EN13001 [12] considering in a simplified way also seismic loads as defined for the ITER site (since the DEMO site has not yet been selected). However, full compliance with EN13001 is not yet achieved. It is found capable of lifting inboard and outboard BB segments with masses up to 88 tons and 126 tons, respectively. This corresponds to 70% of the mass of the (undrained) WCLL BB and about twice the mass of the HCPB BB. Further design improvements and reinforcements of critical parts may allow handling higher masses.

For a more complete verification and validation of BB cask and BB transporter the following is required:

- Further development of the design of the BB transporter and BB cask including e.g. actuation or routing/connection of supply lines.
- Detailed structural integrity assessment.
- Development of rescue scenarios.
- Integration the BB attachment pin into the BB.
- Definition of a concept to prevent the accidental drop of the load.
- Construction and operation of a test facility.

An initial review of the BB transporter concept presented here identified in addition a number of hidden complexities which due to the

early stage of design development have yet to be considered. These include the need for greater detail in the blanket transporter design, particularly in packaging drivetrains for actuated joints; detail on the blanket handling control system and identification of requirements to manage dynamic instabilities during blanket maneuvering and ability to achieve the desired positional accuracy; more detailed assessment against the appropriate design codes with thorough seismic assessments; a full assessment of the total duration of the maintenance activities and a more detailed understanding of the sizing of the AMF.

CRedit authorship contribution statement

C. Bachmann: Conceptualization, Methodology, Validation, Supervision, Writing – original draft. **C. Gliss:** Conceptualization. **G. Janeschitz:** Conceptualization, Supervision. **T. Steinbacher:** Conceptualization, Visualization. **R. Mozzillo:** Conceptualization, Visualization.

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.

Acknowledgments

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training program 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.

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