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Advancement in the development of remote handling tools for the volumetric neutron source blanket

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ABSTRACT

A feasibility study of a new testing facility, i.e., the Volumetric Neutron Source (VNS) in a tokamak configuration, was initiated in 2023 and is now under way to address potential showstoppers. Key outcomes of the engineering activities are presented in [1] and the latest improvements in [2]. The main goal of the VNS is to provide a realistic environment to test the in-vessel components of fusion reactors, in particular the tritium-breeding blanket. Lessons learned during previous years of DEMO development point to the need for thorough nuclear design integration already at the level of the basic machine design; hence, issues related to the maintenance of the in-vessel components have been addressed at a basic level. The work presented here describes the remote maintenance strategy for VNS blanket segments, which is an adaptation of the concept proposed for DEMO in previous years [3]. The work discusses the basic approach for the development of an integrated remote blanket strategy for the VNS blanket. Consistent with the initial requirements of the machine, the remote replacement sequence of the blankets, the potential list of the required tools and transporter, and the conceptual design of some of the main tools are presented and discussed in this article.

1. Introduction

The Volumetric Neutron Source (VNS) is a beam-driven tokamak that has been developed for the purpose of testing in-vessel components of fusion reactors [1,6]. The VNS design draws upon lessons learned from previous development projects, such as ITER and DEMO [1]. The VNS incorporates innovative approaches to reduce construction risks by adopting ITER-like concepts while introducing customized solutions tailored to its unique requirements. The work focuses on development of an integrated remote maintenance strategy for the VNS blanket, starting from previous studies carried out for DEMO [1]. The study is based on the definition of a preliminary remote replacement sequence of the Blanket with the associated potential list of required tools and transporters. The vertical transporter of the VNS blanket segments is under development, results about the extraction sequence and the accessibility to the blanket segments are here discussed. The kinematic model of the transporter has been created and tested in a virtual environment to validate the assumed extraction sequence. This paper provides a comprehensive overview of the most critical remote handling tools, namely the blanket transporter and the cask of the blanket transporter. In addition, it offers an extensive analysis of all the equipment and tools that require further study and development in the future. The authors acknowledge that their paper does not claim to cover all issues related to the development of remote maintenance tools. However, they aim to provide a solid foundation for a structured approach to the problem.

2. Maintenance strategy overview

A tritium Shielding Blanket (SB) is installed inside the vacuum vessel (VV) of VNS, covering most of the plasma-facing surface to absorb neutrons and attenuate secondary gamma radiation resulting from neutron interactions [1]. Due to neutron irradiation over time, the SB materials degrade, necessitating periodic replacement during the VNS operational lifetime. The associated in-vessel maintenance operations must be conducted using remotely operated tools and in a manner that could later be adopted in commercial fusion power plants (FFPs),

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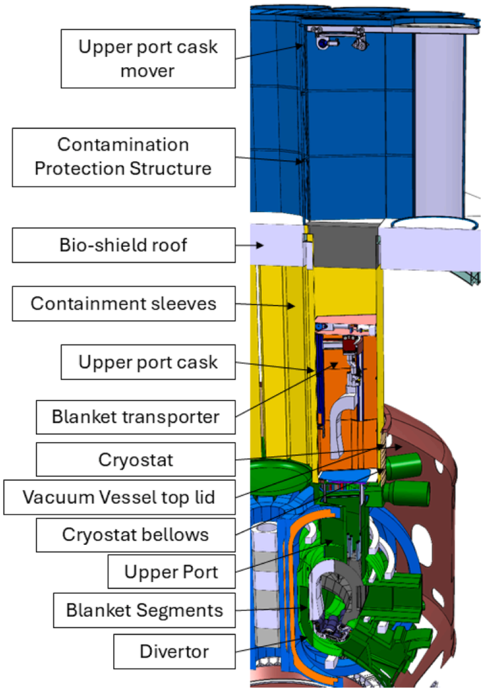

Fig. 1. Overview of Main components of VNS Tokamak during remote maintenance.

ensuring reasonably short downtimes [1]. Segments are extracted from the VV through the upper ports using a vertical transporter, and once removed, are transported to the Active Maintenance Facility (AMF) within casks in a double sealed environment to prevent the spillover of the radioactive dust once the upper port is opened and to prevent the outgassing of the tritium and to reduce the radiation propagation in the tokamak building [7] (Fig. 1). This design uses ITER-like concepts for remote handling, while incorporating innovative solutions to improve reliability and efficiency [1]. The approach here proposed is based on previous studies carried out in the last years on DEMO [3,4,7]. Consequently, the VNS reactor design aims to demonstrate rapid and reliable remote maintenance techniques, ensuring availability levels compatible with the economic requirements of FPPs. The present phase of the VNS remote maintenance project is centred on the development of a robust maintenance strategy taking into account the aspect related to the integration of the RH tools with the machine components. The basic idea of the strategy is to develop methods, tools and procedures that can be applied to all commercial FFPs, ensuring the required machine availability and the economic sustainability of fusion energy. The approach is based on the assumption that the development of the RH scheme of the machine evolves in parallel with the design and integration of the plant. The remote maintenance strategy for Blanket segments in the VNS must meet several critical requirements to ensure efficiency, safety, and compatibility with high plant availability goals. These aspects can be summarized as following [1]:

- **Contamination Protection:** The RH tools must operate within a sealed cask located in a sealed room to prevent the spillover of dust particles and tritium in the tokamak building,
- **Availability**: The swift replacement of SB segments is of crucial importance in order to maintain VNS availability.
- **Manipulation**: The RH system must enable complex kinematics to lift, to extract and to tilt the SB segments by a few degrees, in order to disengage them from their supports during the process of extraction from the VV. *This operation must ensure compatibility with the blanket support scheme and facilitate efficient handling of the blanket itself.*
- **Design Criteria**: The BB cask and transporter must conform to EN 13,001 standards.
- **Decontamination**: The design of the system is predicated on decontamination by minimizing surface complexity, incorporating

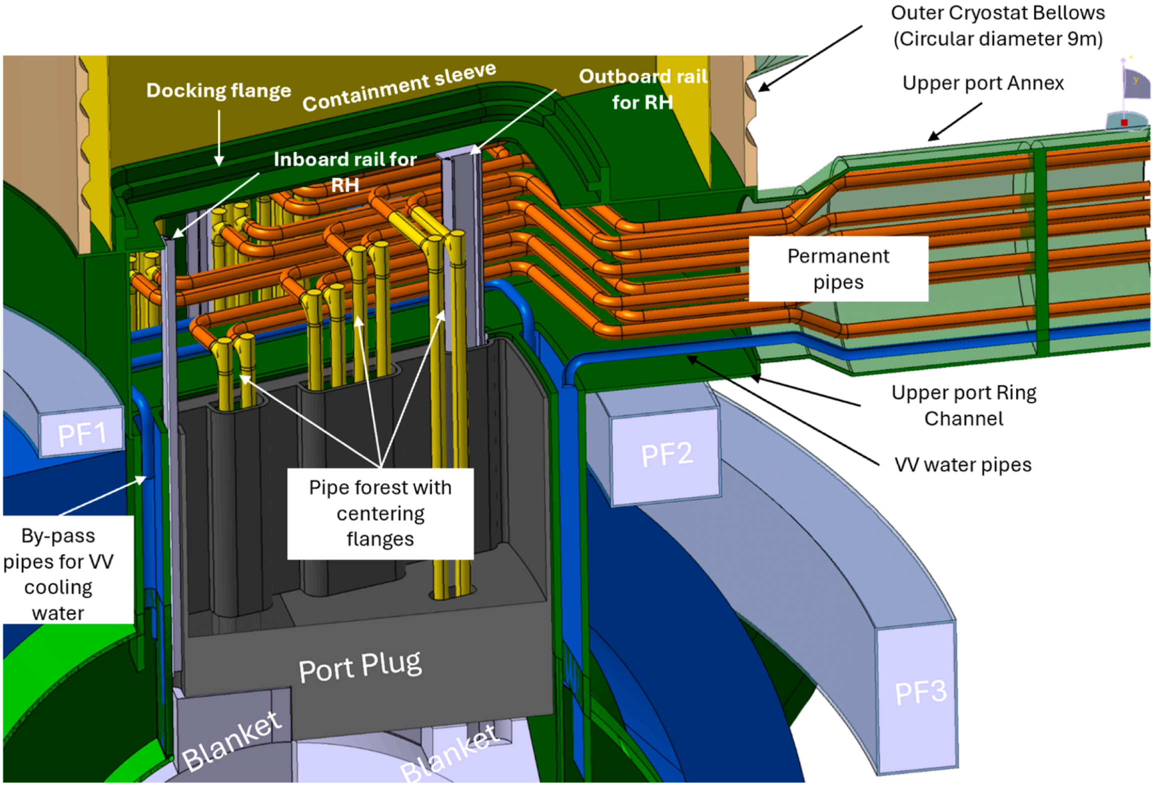

Fig. 2. VNS Upper Port Integration – Section View.

removable panels to isolate complex components, and using materials with low tritium absorption [1].
- **Compatibility with High Radiation Fields**: Remote maintenance tools must be radiation-tolerant, ensuring reliable operation in high-radiation environments.
- **Standardization**: In order to optimize operations and to reduce the cost related, wherever possible, the maintenance tools must be designed with standardized components, thus facilitating repair, replacement, and re-commissioning.

Moreover, since the dimensions of the remote handling equipment must be considered in the first phases of the design, it is assumed that the equipment is stored and maintained in an AMF. This aspect will have a significant impact on the costs of the entire plant and the associated buildings. The RH scheme proposed for the VNS is based on a double-confinement approach. All RH activities are carried out inside a dedicated cask, in which RH tools and components to be transported to AMF are stored and operated. The casks move inside a contamination protection structure and containment sleeve, which act as a second confinement barrier and plug on the docking flange positioned on the upper part of the port. Both the contamination protection structure and the containment sleeve also prevent the adjacent port areas from becoming contaminated in the event of dust particles spilling over. The casks are not connected to any building areas to prevent radioactive particles from spilling over, thereby reducing the surfaces of the building exposed to radiation and the amount of cleaning required inside the building. The contamination protection structures protect building areas located on top of the bio shield roof, while the containment sleeve protects the interspace area between the cryostat and the bio shield. The casks and contamination protection structures are covered by flat surfaces that can be easily cleaned on site and in the AMF (Fig. 1). It was also assumed that the VNS blanket would be replaced via all twelve upper ports to reduce the complexity of the remote handling task and tools. No blanket toroidal mover is used in the current machine configuration [8].

The development of the RH approach for the blanket replacement is driven by the arrangement of the component in the upper port, since prior to the removal and installation of the blanket segments the component obstructing the upper port must be removed and stored in the AMF. The blanket segments are fed via upper port, 18 pipes are routed through the upper port annex and upper port: 4 pipes for each outboard segment (cooling inlet and outlet plus purge gas inlet and outlet), 2 pipes for the cooling of the two inboard segment and 2 pipes for the cooling of the port plug (Fig. 2). The pipes are composed by two legs: the vertical routed through the upper port and the horizontal one placed in the upper port ring channel and in the upper port annex. The vertical legs of the pipes are assumed to be manipulated as a single component during the RH activity, they are keep together by a permanent frame structure that remains in-place during the operation of the reactor [7]. The pipes are also equipped with vertical end stub with caps that will be removed during the pipes disconnection to allow for the insertion of the In-Bore tools as it is proposed in [7] for DEMO. The upper port plug is placed behind the blanket and provide the shielding of the port, it is made of a box steel structure filled by water and bolted to the upper port structure, above the upper port ring channel is placed the docking flange for the casks docking and the upper port closure plate that is sealed with a welded lip seal. The port plug provide also the supporting structure for the blanket segments, once the port is opened, the obstructing component are removed and the blanket disconnected, the removal of the blanket can start by means of the blanket transporter, no other mechanical component are installed between the blanket segments and the vacuum vessel and need to be removed [9]. Moreover the current configuration of the blanket lower supports guarantees that the outboard segments can be removed and installed with the divertor cassettes in place [9,2]. The upper port is also equipped with permanent vertical rails providing supporting structure for the RH tools operated inside the cask. This paper addresses the design of the most critical equipment for the RH of the VNS blanket: the Blanket Transporter and the Typical Service Cask Transporter. The design of all other transporters will be derived from that of the blanket transporter in order to reduce development costs.

3. Blanket replacement sequence and remote handling tool list

The current configuration of VNS assumes that the blanket segments and the component above them inside the upper port (i.e. feeding pipes, port plug, closure plate, etc.) will be replaced via upper port. Parallel to the design integration of the upper port areas the preliminary list of the required tools for the RH activities and the casks needed to store and operate them has been provided, moreover the macro-sequence for removal and installation of the blanket segments has also been developed and summarized in the following Table 1 and Table 2. The tables also define the tools to be used for each remote handling tasks. Prior to the removal of the blanket segments the magnetic coils will be deenergized, the VV will be vented and the In-Vessel cooling system will be drained. The impact of the presence of any diagnostic plug in the upper port has been temporarily neglected, it will be considered once the diagnostics will be better developed. Currently, the table does not include any cleaning or finishing tools for pipes or mechanical components (e.g. bolts and seals). The port plug and closure plates are fixed to the vacuum vessel structure using twist locks or bolting systems that remain connected to the component during the removal.

The divertor cassettes must be removed prior the task n.10 in Table 1, vice versa it must be installed after the task n.1 in Table 2.

After the task n. 6 the pipes remain positioned in situ welded at level of the horizontal legs. In task n.10 Table 2 it is assumed a lip seal as system for VV sealing, the leak check of the lip seal of all the ports will be conducted inflating helium inside the vacuum vessel. The upper port closure plate is assumed as fixed to the vacuum vessel through twist locks and wedges avoiding bolts and welded leap seal for the port sealing.

There are eleven different types of cask in total. Some of these can be duplicated or reused to optimise remote handling activities and reduce time.

In order to address the feasibility of the proposed approach, the conceptual design of the Contamination Protection Structure, the typical Service Cask and the Blanket Transporter has been carried out, since the dimensions of these tools and structures have a huge impact on the overall building structure and, consequently, the costs of the entire plant. This design will be described in the next sections.

4. Loads

The remote handling tools and the structures are dimensioned according to EN13001, two different load combination have been considered:

- **Load combination A** covering regular loads under normal operation, i.e. hoisting load plus mass of the transporter itself
- **Load combinations C** covering a selection of regular loads combined with occasional and exceptional load, i.e. regular loads, hoisting load plus mass of the Blanket Transporter combined with exceptional load due to external excitation of crane supports, i.e. seismic event of level 1 – SL1, assuming the following acceleration values:

$$\text{Horizontal} = \pm 0.8\mathrm{m}/\mathrm{s}^2$$

$$\text{Vertical} = \pm 3\ \mathrm{m}/\ \mathrm{s}^2$$

Table 1
Overview of the blanket removal sequence, list of Casks and RH tools required.

ID TASK	Task Description	Tool	Contamination Control
1	Concrete shielding plugs removal	Lifting and manipulating tool for concrete plug of bio shield roof	N/A - the component are inside the Contamination Protection Structure
2	Cask Transfer from AMF to the Upper Port Contamination Protection Structure and then docked on the Upper port flange	Rails and tools for cask transfer and lifting installed on contamination protection structure	N/A - the component are inside the Contamination Protection Structure
3	Upper Port Closure plate removal	Tools for unbolting and unsealing of the Closure Plate Tool for port closure plate manipulation and positioning	Cask #1: ➢ Storage and operation of closure plate unsealing and unbolting tools ➢ Storage of the Closure Plate ➢ Storage and operation of the tool for closure plate manipulation and positioning
4	Blanket feeding pipes removal – *Phase 1*: Removal of Top Caps of pipes vertical legs	Tools for Pipes caps cutting Tools for deployment of the caps cutting tool Tools for manipulation of the pipes caps	Cask#2: ➢ Storage of the pipes caps ➢ Storage and operation of caps cutting tools ➢ Storage and operation of the tool for cutting tools deployment
5	Blanket feeding pipes removal *Phase 2*: In Bore- cutting at level of the blanket chimney	Tool for In-bore cutting tool deployment In-bore cutting tools	Cask#3: ➢ Storage and operation of the In-bore cutting tools ➢ Storage and operation of the In-Bore cutting tools manipulator
6	Blanket feeding pipes disconnection – *Phase 3*: Ex-bore cutting at level of horizontal legs of the pipes and pipe forest removal	Tools for ex-bore pipes cutting Tool for ex-bore cutting tools deployment Tool for pipe forest manipulation	Cask #4: ➢ Storage of the pipes forest ➢ Storage and operation of pipes forest manipulating tool ➢ Storage and operation of the tool for ex-bore cutting tools deployment
7	Upper Port Plug Removal	Tool for Port Plug Unbolting Tool for port plug manipulation	Cask #5: ➢ Storage and operation of port plug manipulator ➢ Storage and operation of the port plug unbolting tool ➢ Storage of the port plug
8	Removal of the Central Outboard Segment	Blanket Transporter	Cask#6: ➢ Storage of the blanket segment ➢ Storage and operation of the blanket transporter
9	Removal of Left/Right Outboard Blanket		
10	Removal of Left/Right Inboard Blanket		

These values has been estimated for DEMO in [10] and they quite aligned with the ITER ones [12,13]. Same as the ITER, the RH tools are designed for seismic loads of category II (Class A/B, i.e. SL-1) but are not designed for seismic loads of category III/IV (Class C/D, i.e. SL-2) [11, 12] . For the latter, the overall plant safety and the recoverability must be demonstrated. The values of the acceleration must be confirmed once the site for the construction of VNS will be defined.

Blanket transporter is preliminary assumed as crane with enhanced risk, for this reason a risk class II component is considered.

The Blanket Transporter has a payload capacity of seven tons, which corresponds to the dead weight of the outboard blanket segment. The cask elevator system has a payload of around 10 tonnes, while the contamination protection structure and cask lifting system are designed for a payload of around 20 tonnes.

5. Active maintenance facility

The Active Maintenance Facility (AMF) is a nuclear building at the VNS plant in which activated and contaminated machine parts are prepared for disposal elsewhere. The AMF is intended for use as a building for radioactive waste interim storage, the testing of activated components and refurbishment for a period of up to 30 years. It is important to note that clean components are not stored in the AMF; rather, it serves as a route to the tokamak machine and for transferring components to installation containers or tools. It is assumed that clean spare components can be stored during operation in the Assembly Building and transported by truck to the AMF for installation. The main in-vessel components that must be treated within the AMF, either due to expiry of the service life or failure, are: Blanket, Divertor, Neutral Beam Injector, port plugs and component for vacuum tests before installation after repair or refurbishment.

The AMF is located in the 12 o'clock position on the site in relation to the Tokamak building (Fig. 3). The Tokamak building and the AMF share a common basement. The AMF is also a nuclear building and must therefore meet all requirements arising from this classification. The transfer connections between tokamak building and AMF are located on different levels to transport components to and from the AMF.

According to the present status of the VNS, a preliminary estimation of the AMF building dimensions has been conducted, resulting in a bounding box of approximately 75 × 50 × 30 m The AMF comprises six levels, two subterranean and four above ground. Each floor is connected to the corresponding tokamak building. On each floor, corridors equipped with rails and turntables ensure the transportation of components in double-sealed containment from the tokamak building to the AMF and vice versa (Fig. 4).

6. Contamination protection structure

The Contamination protection structure is a semi-permanent steel structure placed above the bio shield roof, equipped with lifting systems and turn tables. Its main function is to provide a double confinement of the area impacted by the remote handling activities, it covers the entire path from the Upper Port up to the Active Maintenance Facility. The basic design of the contamination protection structure aims at providing individual and independent access for upper port casks to the 12 upper ports. During docking the upper port casks must be within a sealed room with minimized volume to reduce the load of the detritiation system. The adopted solution therefore implements 12 discrete trapezoidal cask containment cells in the maintenance hall above the upper ports. These can be isolated (sealed) from the transfer corridors by the revolving

Table 2
Overview of the blanket installation sequence, list of Casks and RH tools required.

ID TASK	Tasks Description	Tools	Contamination Control
1	Installation of Left/Right Inboard Blanket .	Blanket Transporter	Cask#6: ➢ Storage of the blanket segments ➢ Storage and operation of the Blanket transporter
2	Installation of Left/Right Outboard Blanket		
3	Installation of Central Outboard Segment		
4	Installation of Upper Port Plug	Tool for Port Plug bolting Tool for port plug manipulation	Cask #5: ➢ Storage and operation of the tool for port plug manipulation ➢ Storage and operation of the port plug bolting tool ➢ Storage of the port plug
5	Installation of Blanket feeding pipes *Phase 1*: Positioning of the pipes forest, Ex-bore welding at level of horizontal legs of the pipes and pipe forest installation	Tools for ex-bore pipes welding Tool for ex-bore welding tools deployment Tool for pipes forest manipulation	Cask #7: ➢ Storage and operation of the pipe welding tools ➢ Storage of pipes forest manipulating tools ➢ Storage and operation of the ex-bore welding tools deployment ➢ Storage of the pipes forest to be installed
6	Blanket feeding pipes installation *Phase 2*: In Bore - welding at level of the blanket chimney	Tool for In-bore welding tool deployment In-bore welding tools	Cask#8: ➢ Storage and operation of In-bore welding tools ➢ Storage operation of the tool for deployment of the In-Bore welding tools
7	Blanket feeding pipes installation – *Phase 3*: Installation of pipes Top Caps	Tools for Pipes caps welding Tools for deployment of the caps welding tool Tools for manipulation of the pipes caps	Cask#9: ➢ Storage of pipes caps ➢ Storage and operation of tool for caps manipulation ➢ Storage and operation of tools for caps welding ➢ Storage and operation of the tool for welding tools deployment
8	Blanket feeding pipes installation – *Phase 4*: Welds helium leak check	Machine for pipes helium leak checking Tools for deployment of helium leak checking machines	Cask#10: ➢ Storage and operation of machines for leak checking ➢ Storage and operation of the tool for deployment of the helium leak checking machines
9	Upper Port Closure plate installation	Tools for bolting and sealing of the Closure Plate Tool for port closure plate manipulation and positioning Tool for lip seal manipulation	Cask #11: ➢ Storage and operation of the tools for sealing and bolting of the closure plate ➢ Storage of the Closure Plate ➢ Storage and operation of tool for closure plate manipulation and positioning
10	Cask Transfer from the Upper Port through the Contamination Protection Structure to the AMF	Rails and tools for cask transfer and lifting installed on contamination protection structure	N/A but the component are inside the Contamination Protection Structure
11	Concrete shielding plugs installation.	Lifting and moving tool for concrete bio shield roof concrete plug	N/A but the component are inside the Contamination Protection Structure

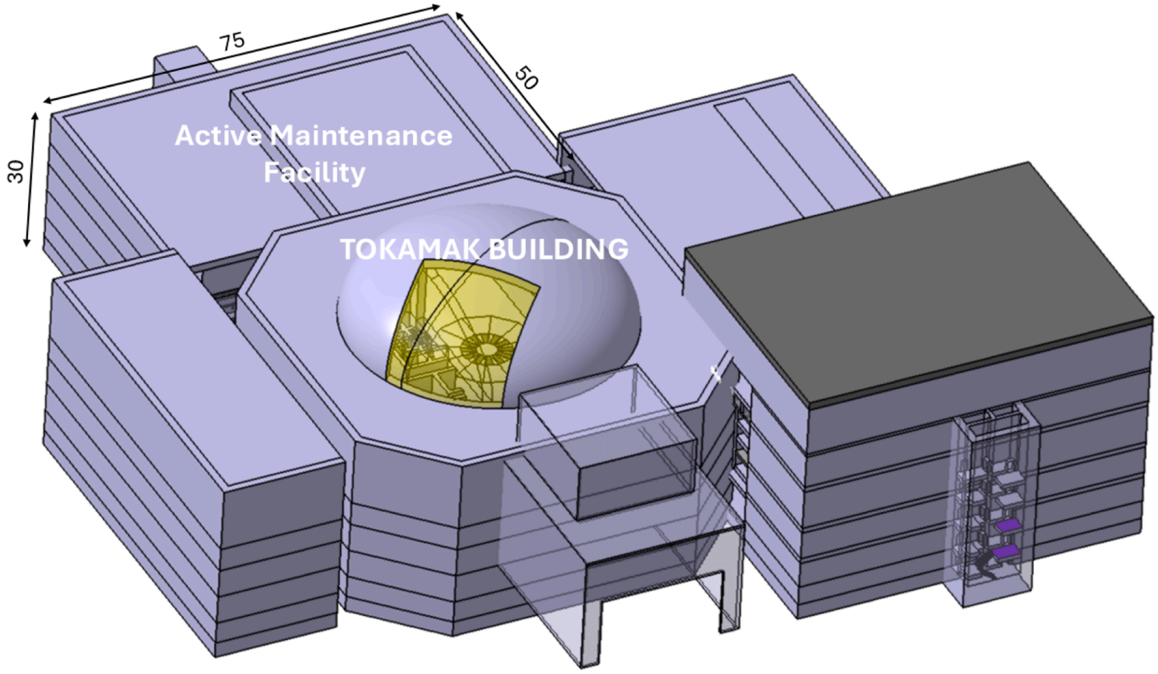

Fig. 3. VNS Site Layout - dimensions are in meters.

doors of turntables. The turntables can isolate different parts of the contamination protection structure from one another. In addition they allow the change of the travel direction of the upper cask transporter on the spot, which minimizes the space required for its movements. The circumference of the external ring channel in the upper maintenance hall fits the 12 turntables, whose diameter is defined by the size of the upper port cask. 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.

The contamination protection structure is a semi-permanent installation to be installed prior to the nuclear operation phase of VNS. In the unexpected case of large-scale repair of the tokamak, e.g. to replace the central solenoid, the part in the upper maintenance hall can be either transported as a whole or be disassembled into 3 or 4 parts for transport to the assembly hall by the main overhead crane. On separation points contamination protection structures will be installed to prevent the spread of contamination into the torus hall or into the assembly hall (Fig. 5).

It was chosen to transport the BB segments in vertical rather than horizontal configuration, although this requires the upper port cask transporter to be supported at its top against toppling and therefore carrying about two-thirds of its overall weight from above rather than

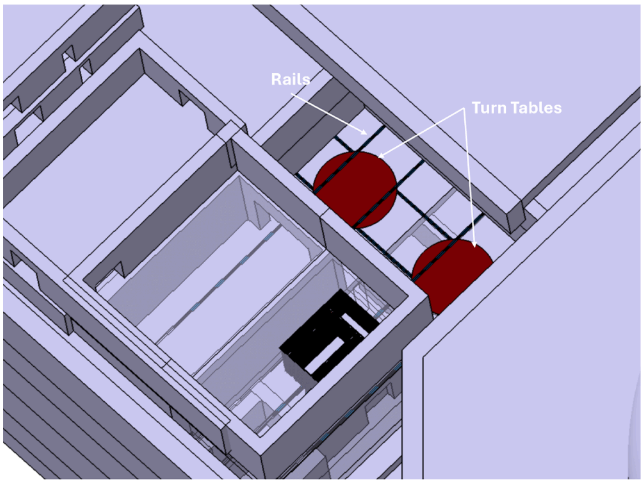

Fig. 4. Detail of rails and turn tables for casks transfer.

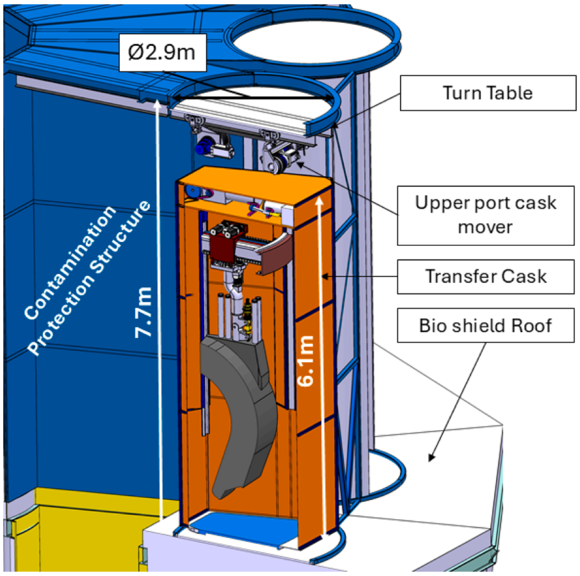

Fig. 5. Contamination protection structure and cask.

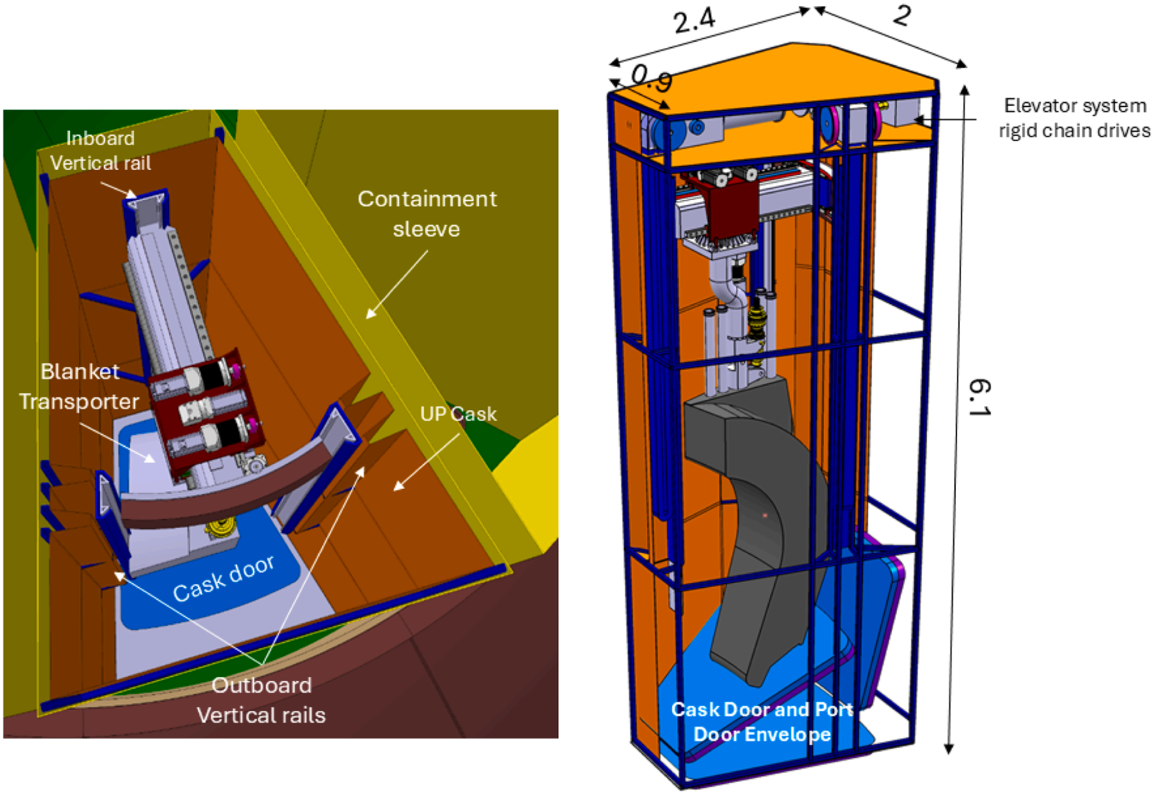

Fig. 6. Left: Top isometric view of cask with blanket transporter. Right: Overview of the transfer cask, cask transporter, envelope of the port door and cask door, cask elevator system with main dimensions in meters – cask liner is cut to show the components inside. The Cask door and port door opening mechanism is not shown.

below.

This choice has the following rationale:

- The BB segments are removed from the VV and delivered to the AMF hot cells in vertical configuration. Hence the transportation in vertical configuration avoids the need for transitions from vertical into horizontal configuration and reverse.
- The transport of the long blanket segments in horizontal configuration would require large spaces at turning points and a very complex tool to perform the 90° turn considering also the weight and the long and thin shape of the blanket segments.
- Since the upper port cask must be lowered onto the docking flanges on the VV or the corresponding flange in the AMF hot cells, a crane (Fig. 5) is required above the cask. It has been designed with the sum of the dead weights of the blanket transporter, the cask and the cask lifting system as the payload.

7. Service transfer cask

The service cask is a sealed, unshielded container for transferring the blanket segments, the other components to be removed from the upper port (i.e. upper port plug, pipe forest, pipe top caps) and related remote handling tools between the docking stations on the VV and the AMF. The main functions of the cask are: (i) Storage of components to be transferred to the AMF, (ii) Storage of remote handling tools needed for disconnection and manipulation, (iii) Operation of remote handling tools (see Table 1 and Table 2). 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 Contamination Control Door (CCD) as well as RH tools as required to remove and install blanket segments and to carry out inspections. The cask weighs is about 12 tons. It has a height of ~6.1 m and a trapezoidal cross-section enveloping that of the upper port (Fig. 6). 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.

The lower part of the cask — the part that docks with the VV docking flange — is equipped with two folding doors. The first is the cask door, which remains installed during the transfer of components to the AMF. The second is the port door, which provides a temporary closure of the port once the cask is disconnected from the VV and transferred to the AMF. This system assures that the contaminated volumes (i.e. the one the VV and the other inside cask) are closed during the remote handling activities. Upon extraction of each BB segment the VV and the cask are closed by the double-lidded CCD while the cask transports the blanket segment to the AMF. Indeed, 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 (Fig. 6). In the top of the cask an elevator system is implemented that allows lowering the blanket transporter and the others remote handling tools [7] 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 transporters and the tools operating inside the cask are attached to these skids. Rigid chains are used rather than ropes in order to react upward lifting forces that occur due to the large moments that may act on the transporters. The rigid chains have been dimensioned considering a maximum tension load of about 200 kN and a compression load of about 20 kN, these correspond to the worst case once the left outboard segment is lifted. 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 (Fig. 1). 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

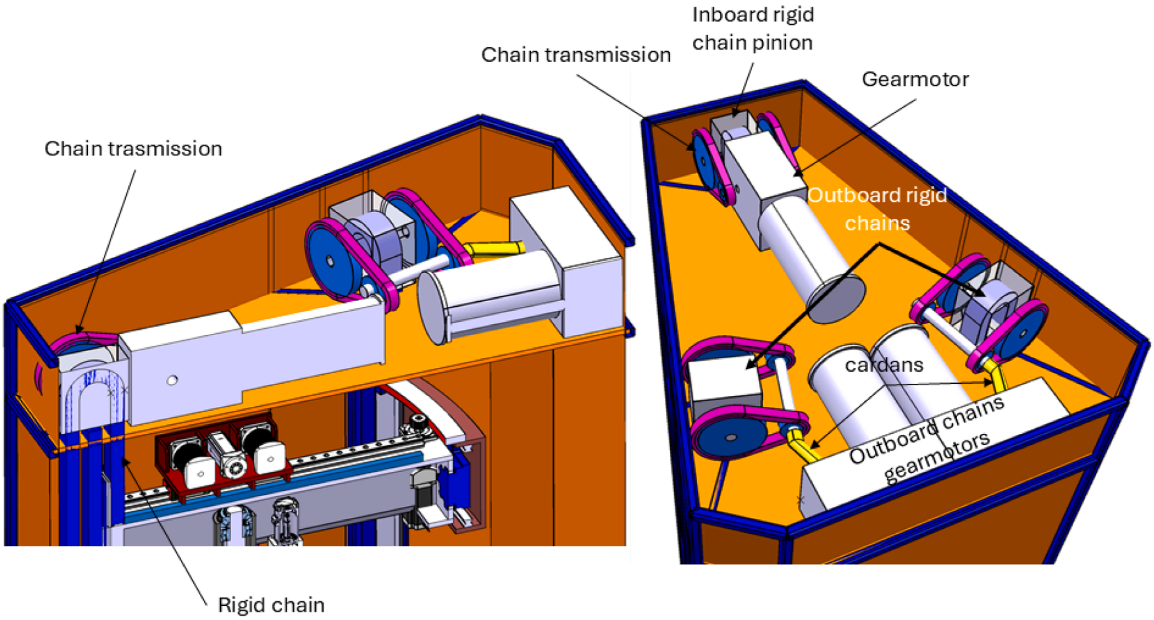

Fig. 7. Detail of cask elevator system.

provide space for the CCD garage-door-like movement. Three gearmotors placed on the top of the cask structure actuates the three rigid chains by means of the chain transmission system with ratio 1 to 3. The three gearmotors assure a nominal torque on the output shaft of about 3 kNm and maximum holding torque of about 6kNm in case of seismic event. The motors are equipped with an anti run-back device, while allowing rotation in the direction required, this device operates instantaneously in case of a power failure, preventing the shaft from running back. Since the axes of the gearmotors and the chain transmissions are not aligned (Fig. 7), the two gearmotors actuating the outboard rigid chains are joined to the chain transmission and then to the rigid chain pinion by means of a cardan joint. As the remote handling tools will not operate in a vacuum, it is assumed that all rotating and sliding parts (bearings, pinions, wheels, etc.) are lubricated and double-sealed to prevent lubricant spreading. The design of all upper port casks is based on those developed for the blanket transporter, with the objective being to reduce the impact of the development cost of remote handling tools. The focus of the work was on the cask with the most demanding performance specifications, i.e. the cask of the blanket transporter.

8. Blanket transporter

The blanket transporter is a seven degrees of freedom crane manipulator with a kinked rigid arm. It is joined to the three rigid chains of the cask transfer through three skids that slide inside the cask rails. The outboard two are joined to the toroidal beam while the other at the

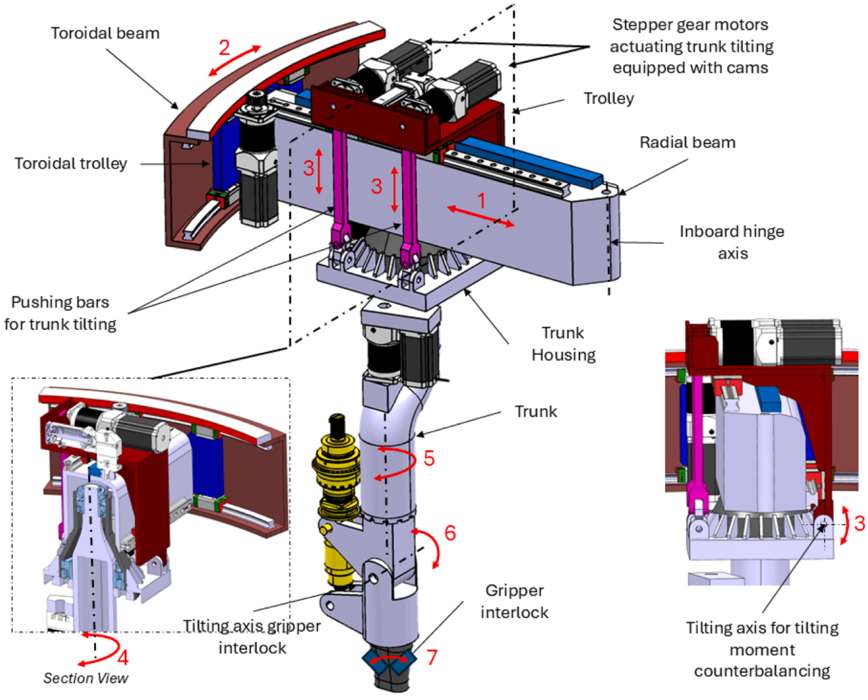

Fig. 8. Blanket transporter.

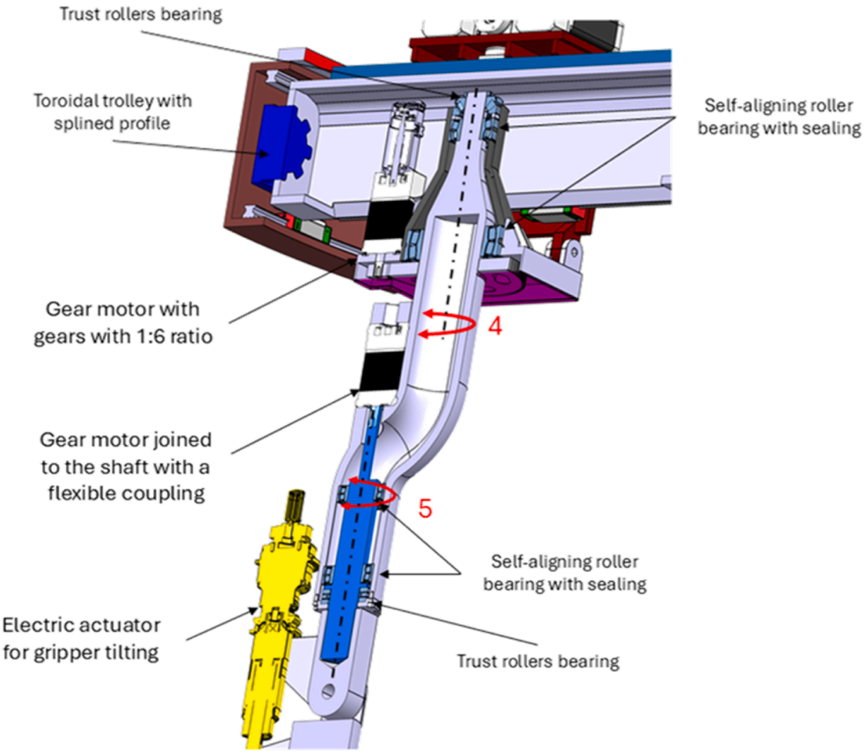

Fig. 9. Blanket transporter trunk section.

inboard is connected to the radial beam through a hinge that allow the toroidal rotation of the radial beams. The rigid chains provide the lifting of the whole system transporter plus blanket.

Its main structure comprises a C-shaped toroidal beam equipped with linear ball bearing rails for load transfer and a rack-and-pinion system actuated by an electric gear motor to drive the toroidal movement (*axis n°2* labelled in Fig. 8). A radial beam with an open box section is joined to the toroidal beam via a toroidal trolley equipped with linear ball bearings and a splined profile to support and drive the radial movement of the trolley and trunk (*axis n°1* labelled in Fig. 8). The loads are

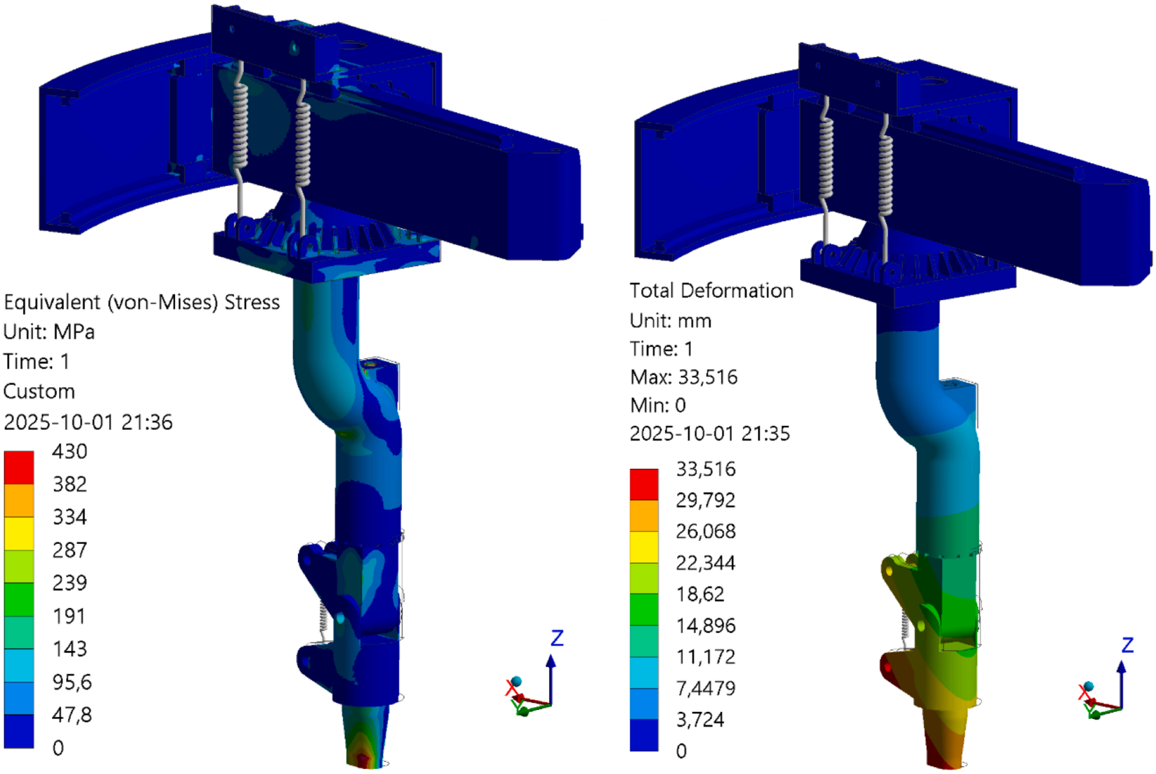

Fig. 10. Results of FEM analysis of the Blanket Transporter.

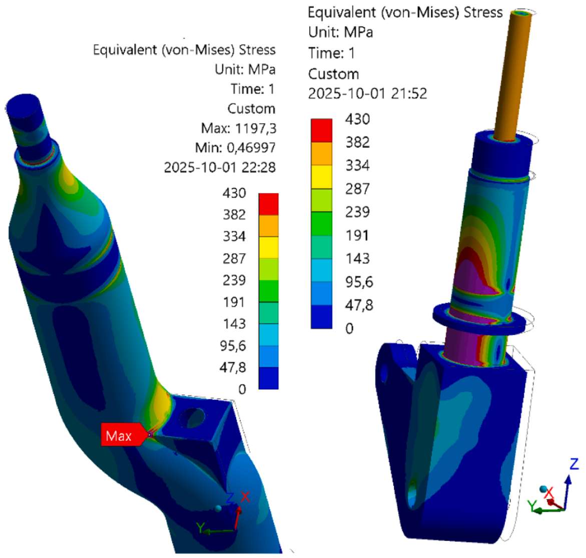

Fig. 11. Von mises stress distribution in the most stressed components: Trunk on the left, Gripper shaft on the right.

transferred from the trolley to the radial beam through a couple of linear ball bearings, placed on the top and on the sidewall of radial beam and actuated by a rack and pinion system mounted on the top of the radial beam assuring the radial movement about the axis n°1. The trolley is connected to the trunk housing and hence to the trunk by a rotational hinge and a couple of pushing bars connected through a couple of the cams with an eccentricity of about 5 mm mounted on two shafts actuated by a couple of synchronized gear motors placed above the trolley (*axis n°3* labelled in Fig. 8).

These systems assure the tilting of the blanket segment to counterbalance the tilting moment generated by the off-centred position of the blanket centre of gravity, an angle of about 1° is needed to counterbalance the tilting moment. The trunk rotates inside the trunk housing about its main axis, it is supported by a couple of self-aligning roller bearing with integrated seal and relubrication facilities to withstand the tilting moment and a thrust bearing to be sealed for the vertical loads (*axis n°4* – labelled in Fig. 8). The axis n° 4 is actuated by a gearmotor with a gear transmission in a sealed box with ratio 6:1 (labelled in Fig. 9). A second rotational axis (*axis n°5* labelled in Fig. 8 and Fig. 9) is mounted on the lower part of the trunk to have a better accessibility to the blanket segments, this axis is actuated by a gearmotor joined to the gripper shaft through a flexible coupling to compensate any misalignment between the axes of the gearmotor and of the griper shaft. Another tilting axis is mounted on the lower part of the trunk to disengage the blanket segments (*axis n° 6* labelled in Fig. 8) this part is joined to the gripper interlock that engage in the corresponding slot on each blanket segments. The gripper interlock engages with two braces in the slot to lift and manipulate the blanket segment, the design of this part is similar to the one developed for DEMO in [4,14,17,18]. The two braces are actuated by electric motor (*axis n°7* labelled in Fig. 8).

All the mechanical components and the supporting structure of the transporter have been dimensioned and checked according to the EN13001. The rotating and moving parts (linear ball bearing, bearings, gears and gearboxes) are assumed lubricated and double sealed since the transporter will not work in a vacuum environment. Structural FEM analyses have been carried out to check the structural integrity of the transported under the assumed loads. In Fig. 10 the maximum Von Mises Stress and the global displacements in case of a seismic event of level 1 are shown. .

Due to the tilting moments the most stressed parts are the trunk and the gripper shaft, for these component high strength steel is assumed (Fig. 10).

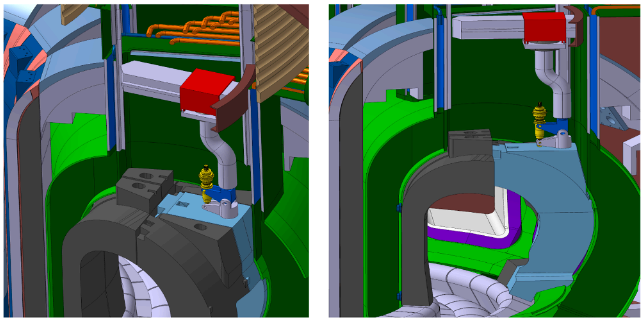

Fig. 12. Left: Blanket segment gripping; Right: Triangular support unlock.

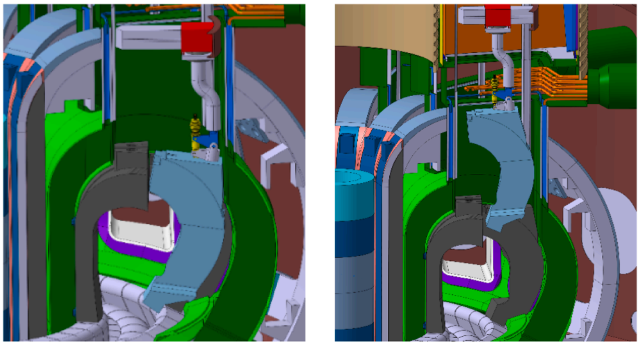

Fig. 13. Left: Blanket segment tilting and extraction; Right: Blanket segment lifting.

Table 3
First of a kind scalability - FOAK.

RH Handling Component	VNS (7t segments)	FOAK Scaling Path
Transporter	Vertical lift + tilt (7t)	Much Capacity via parallel kinematics
Cask Interface	Upper port docking flange	Identical docking, larger envelope
Tooling	In-bore cutters, ex-bore grippers	Modular heads for larger pipes
Sequence Logic	12-port parallel replacement	Identical, ports scaled toroidally

The gear motors and actuators are off-the-shelf components, since the requirement for rad-hard resistance of such components has been neglected for the time being. Kinematic simulations in virtual environment have also been carried out to check the accessibility and the extraction path of each blanket segment, the simulations proved the possibility of the remote extraction and manipulation of the VNS blanket segments as it is shown in the following figures. The kinematic simulation also incorporated the blanket support system, as delineated in [15,16]. In detail the adopted scheme involves ferritic materials embedded in the blanket segments. These are drawn towards the centre of the machine due to the toroidal field gradient, which exerts pressure on the inboard segments against the vacuum vessel (VV) and the outboard segments against the dedicated support structure. This solution eliminates the need for mechanical fixation by bolts. Additionally, the upper port shield plug secures all five segments of one sector vertically after installation. The concept of the attachment is that each segment is equipped with toroidal shear keys to withstand the significant radial moments generated during plasma disruptions Figs. 11-13.

9. Conclusions

The remote handling approach for the blanket replacement of VNS has been developed. The following has been provided as preliminary step in addressing the overall feasibility of the proposed approach: a list of the necessary remote handling tools, the sequence of remote handling tasks, the design of a standard service cask, the design of the contamination protection structure, and the design of the blanket transporter. The transporter's control system can be developed based on previous studies that addressed similar aspects for DEMO [19,20]. Tools for removing and installing the pipe forest still need to be developed, but will be based on the approach already proposed for DEMO in references [7,21–23]. The status of the VNS blanket design suggests the development of a dedicated test facility in which critical design aspects can be tested: (i) the functionality of the cams, and then the tilting mechanism to counterbalance the significant moments caused by the off-centred position of the blanket segments' centre of gravity; and (ii) the functionality of the gripper interlock, based on previous studies carried out for DEMO [18]. The cask design proposed here will be used for all the other casks needed for the remote handling of blankets, as listed in Table 1 and Table 2 in order to increase standardisation of remote handling tools and reduce costs.

While the baseline remote handling (RH) sequence demonstrates feasibility for nominal blanket replacement, failure scenarios—such as transporter jams at turntables, cask docking faults, or tool seizures—require dedicated mitigation to ensure high plant availability (>70%). The contamination protection structure incorporates 20% excess envelope in cask containment cells and transfer corridors, enabling parallel parking of redundant tooling without disrupting adjacent ports.

Key redundancy features include:

- **Backup tooling deployment**: Duplicate casks (e.g., Cask 6 for blanket transporter) pre-staged at AMF rail sidings, interchangeable via standardized interfaces; in-bore cutters and grippers stored in adjacent service casks (Casks 2–5).
- **Recovery bypass paths**: Turntables equipped with manual override levers and rail sidings allowing cask rerouting around failed units; reversible kinematics validated in virtual environment (e.g., trunk tilt limited to 1° for self-clearance).
- **Manual intervention access**: Sealed hatches in contamination protection structure for teleoperated arm insertion (radiation-shielded, <10 m^3 volume per cell), minimizing detritiation needs.

These provisions, informed by ITER/DEMO experience [5], will be refined via mock-up testing of critical paths (gripper interlock, rigid chain hoists). Moreover, the VNS blanket transporter and cask designs use modular kinematics (EN 13,001-compliant crane architecture) and standardized interfaces that scale with payload capacity and with bigger machines, as demonstrated in prior DEMO studies [3] and adapted here (Table 3).

While larger devices (~2x radial build) will require port enlargement and longer travel distances, the core RH philosophy (double confinement, vertical extraction, rail-based cask transit) remains directly transferable. Other aspects must be investigated in depth in future studies. These studies should focus on the overall tooling system, the Failure Mode and Effects Analysis, the radiation tolerance of the mechanical component, the overall logistics form and the AMF.

CRediT authorship contribution statement

Rocco Mozzillo: Writing – review & editing, Conceptualization. **Vincenzo Claps:** Conceptualization. **Curt Gliss:** Methodology. **Piotr Marek:** Formal analysis. **Guenter Janeschitz:** Supervision. **Christian Bachmann:** Supervision.

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.

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Data availability

Data will be made available on request.

References

[1] C. Bachmann, M. Siccinio, E. Acampora, G. Aiello, J. Bajari, J. Boscary, I. Zammuto, Engineering concept of the VNS-a beam-driven tokamak for component testing, Fusion Eng. Des. 211 (2025) 114796.

[2] C. Bachmann, M. Aiello, R. Ambrosino, J. Bajari, J. Boscary, S. Wiesen, Progress in the concept development of the VNS–A beam-driven tokamak for component testing, Nucle. Fusion. (2026), https://doi.org/10.1088/1741-4326/ae4e46.

[3] C. Bachmann, C. Gliss, G. Janeschitz, T. Steinbacher, R. Mozzillo, Conceptual study of the remote maintenance of the DEMO breeding blanket, Fusion Eng. Des. 177 (2022) 113077.

[4] C. Bachmann, G. Janeschitz, P. Fanelli, C. Gliss, P. Mollicone, M. Muscat, R. Mozzillo, Progress in the development of the in-vessel transporter and the upper port cask for the remote replacement of the DEMO breeding blanket, Fusion Eng. Des. 194 (2023) 113715.

[5] I. Ribeiro, et al., The remote handling systems for ITER, Fusion Eng. Des. 86 (2011) 471–477.

[6] G. Federici, Testing needs for the development and qualification of a breeding blanket for DEMO, Nuclear Fusion 63 (12) (2023) 125002.

[7] R. Mozzillo, C. Bachmann, G. Janeschitz, V. Claps, O.C. Garrido, H. Pan, D. Sorgente, Replacement strategy of the EU-DEMO and CFETR breeding blanket pipes, Fusion Eng. Des. 202 (2024) 114311.

[8] V. Claps, C. Bachmann, G. Janeschitz, R. Mozzillo, T. Steinbacher, Conceptual design of DEMO breeding blanket in-vessel toroidal transporter, Fusion Eng. Des. 202 (2024) 114389.

[9] R. Mozzillo, V. Claps, N. Calzone, G. Janeschitz, C. Gliss, C. Bachmann, Remote maintenance strategy of the volumetric neutron source shielding blanket, Fusion Eng. Des. 218 (2025) 115226.

[10] M. Forni, C. Tripepi, A. Poggianti, Global DEMO Seismic Analysis - Part II Eurofusion IDM EFDA_D_2NLTHT (Private Communication).

[11] J. Palmer, M. Shute, System Requirement Document Divertor Remote Handling System ITER IDM ITER_D_2823C3 v5.7 (Private Communication).

[12] J. Palmer, M. Shute, System Requirement Document Blanket Remote Handling System SRD ITER_D_28B6W8 v4.3 (Private Communication).

[13] G. Mazzone, G. Sannazzaro, T. Schioler, V. Sorin, Seismic design of the ITER main Tokamak components, Fusion Eng. Des. 86 (9–11) (2011) 1984–1988.

[14] D. Combescure, J. Ayneto, F. Rueda, L. Maqueda, X. Zhang, G. Sannazzaro, L. Patisson, Seismic analysis of the tokamak complex building of iter fusion facility, in: Transactions SMiRT-24, BEXCO, Busan, Korea, 2017, pp. 20–25.

[15] R. Mozzillo, V. Claps, N. Calzone, G. Janeschitz, C. Gliss, C. Bachmann, Remote maintenance strategy of the volumetric neutron source shielding blanket, Fusion Eng. Des. 218 (2025) 115226.

[16] C. Bachmann, C. Gliss, T. Härtl, F. Hernandez, I. Maione, T. Steinbacher, Z. Vizvary, Mechanical support concept of the DEMO breeding blanket, Fusion Eng. Des. 173 (2021) 112840.

[17] R. Mozzillo, C. Bachmann, P. Fanelli, G. Janeschitz, T. Steinbacher, Structural assessment of the gripper interlock of the DEMO breeding blanket transporter, Heliyon. 9 (8) (2023) e18926, 1–8.

[18] T. Steinbacher, C. Bachmann, C. Gliss, G. Janeschitz, R. Mozzillo, Design of the gripper interlock that engages with the DEMO breeding blanket during remote maintenance, Fusion Eng. Des. 193 (2023) 113641.

[19] H. Durocher, C. Bachmann, R. Mozzillo, G. Janeschitz, X. Zhang, A spatial five-bar linkage as a tilting joint of the breeding blanket transporter for the remote maintenance of EU DEMO, Machines 13 (5) (2025) 371.

[20] H. Durocher, C. Bachmann, R. Mozzillo, G. Janeschitz, X. Zhang, Motion planning with inverse kinematics and statics of a breeding blanket transporter for robotic remote maintenance of the EU DEMO tokamak, res.squ. (2025), https://doi.org/10.21203/rs.3.rs-6346176/v1.

[21] D. Sorgente, R. Salvato, C. Bachmann, C. Gliss, G. Janeschitz, H. Pan, R. Mozzillo, Overview of in-bore pipe cutting and welding tools for the maintenance of CFETR and EU-DEMO, Fusion Eng. Des. 203 (2024) 114478.

[22] V. Claps, A. Di Giacomo, C. Bachmann, D. Sorgente, R. Salvato, R. Mozzillo, Development of an In-bore welding tool prototype for DEMO's in-vessel pipes, Fusion Eng. Des. 217 (2025) 115166.

[23] D. Sorgente, R. Salvato, V. Claps, C. Bachmann, G. Janeschitz, R. Mozzillo, Advancements of testing activities for development of in-bore welding tool for large feeding pipes of in-vessel components, Fusion Eng. Des. 220 (2025) 115367.