Fusion Engineering and Design 202 (2024) 114389

Contents lists available at ScienceDirect

Fusion Engineering and Design

journal homepage: www.elsevier.com/locate/fusengdes

Conceptual design of DEMO breeding blanket in-vessel toroidal transporter

Vincenzo Claps [a,*], Christian Bachmann [b], Günter Janeschitz [c], Rocco Mozzillo [a], Thomas Steinbacher [c]

[a] CREATE, Engineering School of Basilicata University, Campus Macchia Romana (PZ), 85100, Italy
[b] EUROfusion, Boltzmannstr. 2, Garching 85748, Germany
[c] Max-Planck-Institut für Plasmaphysik, Garching 85748, Germany

ARTICLE INFO

Keywords:
DEMO
Remote maintenance
Breeding blanket
CAD
FEM

ABSTRACT

The development of a viable maintenance strategy for the replacement of the Breeding Blanket (BB) segments of DEMO is a key aspect in the way for fusion energy. Previous work concerned the development of a BB vertical transporter to lift, tilt and handle the BB segment inside the remote handling (RH) ports. A potential solution for the replacement of the BB segments could consist in lifting all BB segments from four RH ports, by mean of BB vertical transporter coupled with a BB toroidal in-vessel transporter avoiding the opening of the remaining ports during maintenance. In this way, the activities concerning the removal and re-installation of the auxiliary components (BB feeding pipes, permanent structure for pipes handling, closure plate, port plug, etc.) inside the non-remote handling ports will be avoided, having a strong impact on the reduction of the remote maintenance times and hence on the overall availability of the machine. To assure the feasibility of the proposed strategy a dedicated tool, capable to move toroidally the huge BB segments, shall be developed. The main function of the tool will consist in lifting and toroidal translation of the BB segments that have to be aligned to the RH port, where they will be grabbed and lifted by the BB vertical transporter. The work here presented focuses on the conceptual design of a toroidal transporter to lift and toroidally translate the BB segments inside the Vacuum Vessel. The conceptual design of the BB Toroidal Transporter (BBTT) was developed to handle both the inboard and the outboard segments; a foldable lower foot, equipped with toroidal trucks and suspension system, has been designed to withstand the assumed loads and seismic loads. Preliminary FEM analysis has been carried out to check the structural integrity of the proposed design.

1. Introduction

DEMO is a device that will follow ITER and has the main goals to demonstrate the production of few hundred megawatts 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 the neutron irradiation, requires replacing it during the lifetime of DEMO [1]. The associated in-vessel maintenance operations must be carried out by remotely operated tools and in a manner that could later be adopted in commercial fusion power plants within a reasonably short downtime. For this, the BB is divided into large vertical BB segments which needs to be carried out in a manner that could later be adopted also in fusion power plants as considered in the European power plant conceptual studies [2].

The extraction of the BB segments from the VV is performed through the upper ports and the use of a toroidal Transporter combined with a vertical one [3] is assumed. Once the BB has been extracted from the VV, its transport to the active maintenance facility (AMF) is carried out within a cask.

2. Maintenance strategy

The commercial viability of a future fusion power plant (FPP) is heavily dependant on high availability [4]. The EU DEMO reactor design must demonstrate rapid and reliable remote maintenance techniques, and a reasonable availability, compatible with the economic performance of a FPP. The aim of the current phase of the European DEMO remote maintenance project is to develop a maintenance strategy based on sound remote handling practice and technologies, relevant for a range of in-vessel component design options. The maintenance strategy

* Corresponding author.
E-mail address: vincenzo.claps@consorziocreate.it (V. Claps).

https://doi.org/10.1016/j.fusengdes.2024.114389
Received 13 October 2023; Received in revised form 20 March 2024; Accepted 22 March 2024
Available online 29 March 2024

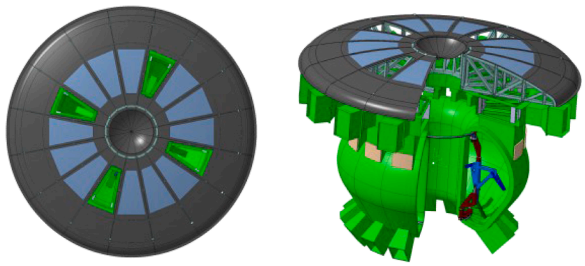

Fig. 1. Left: Top view of Vacuum Vessel with upper port RH opened. Right: Isometric view of Vacuum Vessel with BBTT and upper structure of Cryostat.

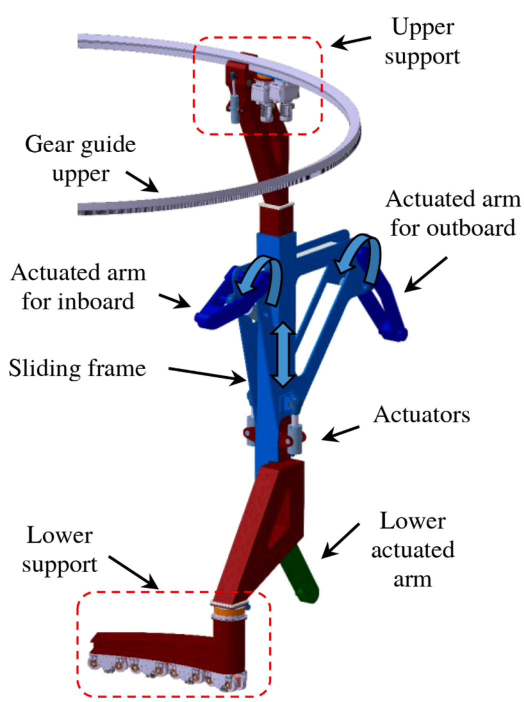

Fig. 2. New design of Breeding Blanket Toroidal Transporter.

is being developed in parallel to ensure that the developing plant designs can take into account the maintenance requirements [5,6]. Indeed, in the present day, there is strategy capable for remote maintenance of the most critical in-vessel components of the machine but there is a lack of solutions and applications tools capable of implementing it; therefore the following report aims to contribute to the development of technologies required to implement fusion power.

Specifically, the work focuses on the development of equipment and methodologies to replace the BB segments.

2.1. Overview of breeding blanket remote maintenance

The remote maintenance strategy of Breeding Blanket segments must meet several requirements [6]:

Contamination Protection: Due to radioactivity from tritium-related phenomena, BB segments are remotely removed using Remote Handling (RH) tools. The tools operate from within a sealed cask located in a sealed room, as implemented in ITER [7].

Availability: Swift replacement of BB segments is crucial for DEMO's availability and goals. DEMO has 16 upper ports, each with three outboard and two inboard BB segments, overall 80 segments. Maintenance is assumed to be simultaneous in ~4 upper ports to minimize downtime and the number of removed components.

BB Extraction Sequence: A BB vertical transporter operates in the Vacuum Vessel (VV) upper port of one sector, sequentially removing three outboard and two inboard BB segments. Using a BB Toroidal Transporter within the VV to move segments from adjacent sectors, minimizing the number of open upper ports, is considered.

Manipulation: The RH upper port requires complex kinematics for tilting the BB segments by a few degrees to disengage them from supports during removal from the VV.

Design Criteria: The BB cask and transporter adhere to EN 13,001–3 standards. Considering the significant duration of operation under load, equipment is designed for seismic event SL-1 [8].

Decontamination: Facilitating decontamination is a priority. Design guidelines include surface reduction, use of removable panels to isolate components with complex surfaces, and the use of materials with low tritium absorption, like metallic walls, concrete walls with a metallic liner, or special paint.

Compatibility with a high radiation field: remote maintenance tools must also take into account the radiation field present.

2.2. RH strategy requirements

The BB RH strategy aims at the high plant availability through efficient maintenance operations. For that purpose, several rules have been adopted [6], which include:

- 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 for the design of maintenance tools is imposed.

3. Overview of DEMO BB Toroidal Transporter

To apply the BB remote maintenance strategy described above, it is necessary to design equipment to move the BB segments toroidally and align them below the RH ports opened. The designed tool is named Breeding Blanket Toroidal Transporter (BBTT).

The BBTT is assumed, once the five segments below the RH port opened are removed from the VV, the tool will be inserted inside the VV for removal of the segments from adjacent VV sectors. The BBTT is able to disengage the BB segments from the support and move them toroidally below the centre of the RH upper port opened, Fig. 1. From this location another tool operating within the upper port will lift the BB segment into the cask [3]. The machine configuration used is DEMO 2017 [9].

3.1. Main functions of BBTT and requirements

The following aspects were considered to design the BBTT:

- Overall dimensions of BBTT consistent with the upper port footprint;
- The BBTT shall handle both type of Breeding Blanket segments: Inboard and Outboard;
- The BBTT shall withstand the assumed loads (seismic and dead weight of segments).
- EN 13,001–2, EN 13,001–3 and EUROCODE 3 have been considered as design criteria [10–12]
- For the design of the BBTT, it was considered that the rails (upper and lower) are already in the VV and the divertors have been removed;
- Maintenance time as short as possible to maximize the machine availability;
- Minimize surfaces exposed to contamination;
- Use off-the-shelf component.

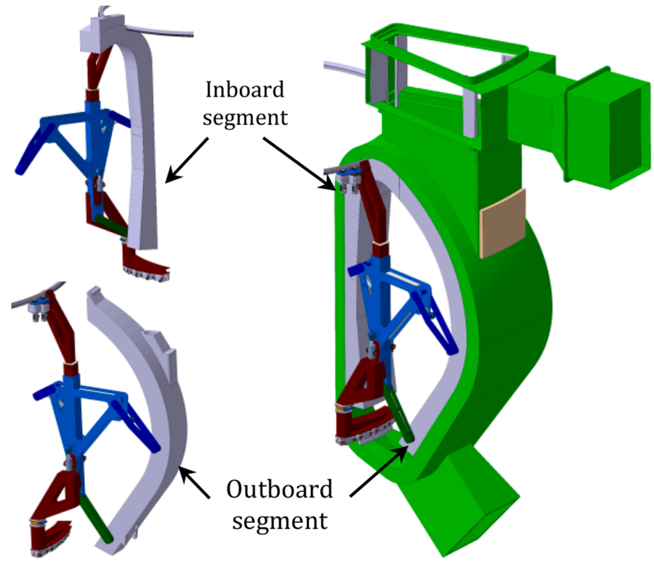

Fig. 3. BBTT inside the Vacuum Vessel is able to handle both types of Breeding Blanket.

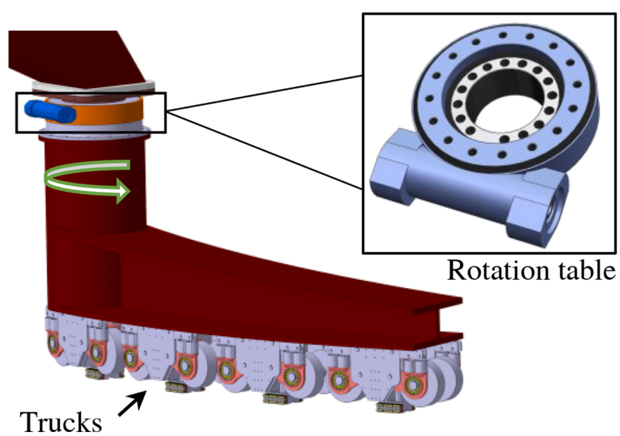

Fig. 4. Lower support. Right: Detail of Rotation table.

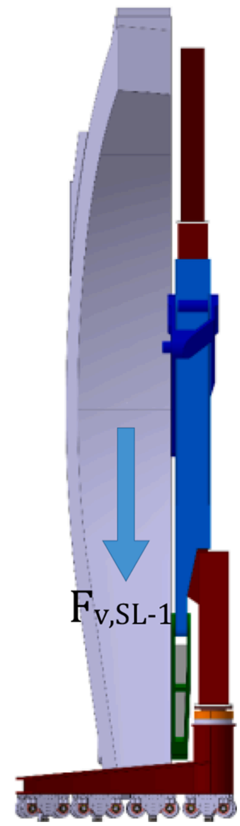

Fig. 5. Breeding Blanket Toroidal Transporter with BB.

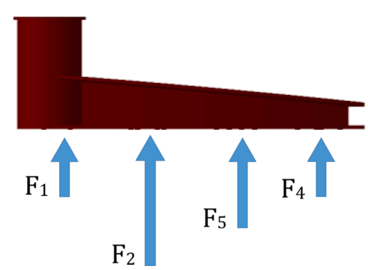

Fig. 6. Assumed forces distribution.

4. Description of breeding blanket toroidal transporter concept

The conceptual design was developed taking into account all aspects described in chapter 3.1 and the current RH strategy.

The BBTT can slide in toroidal direction on the gear guide on the top and on the toroidal rail on the bottom, which is not shown. The Transporter is composed of the following components, see Fig. 2:

- Main structure and sliding frame;
- Actuated arms for inboard and outboard segments;
- Lower actuated arm;
- Upper support;
- Lower support;
- Supply cables, still missing.

4.1. Main structure and sliding frame

The sliding frame is actuated by actuators placed on the sidewall, this vertical movement is necessary to disengage the BB segments from the support. At this time, the type of actuators to be used has not been defined, but it is probable that electric/water hydraulic actuators will be used, which, although bigger than hydraulic actuators, avoid contaminating the VV with oil residue, like in ITER [13]. To handle both types of BB segments (inboard and outboard), it was necessary to add an actuated arm on the inboard side. On the bottom of the sliding frame it was necessary to add a lower actuated arm that allows to balance the BB segments during handling. The actuated arms allow the BB segments to be rotated by a few degrees in order to disengage them from the support, see Fig 3.

4.2. Lower support

The structure of the lower support, Fig. 4, is designed to:

- Reduce the footprint of BBTT, hence to fold and unfold the foot during the insertion of the transporter inside the Vacuum Vessel, proper rotation table, Fig. 4, has been dimensioned and integrated in BBTT design.
- Transmit the massive forces due to the masses to be moved;
- Move the BBTT toroidally.

Table 1
Values of the forces considered on the lower support.

Forces	Assumption	Value
F_1	20% $F_{v,SL-1}$	0.38 MN
F_2	30% $F_{v,SL-1}$	0.57 MN
F_3	25% $F_{v,SL-1}$	0.475 MN
F_4	15% $F_{v,SL-1}$	0.285 MN

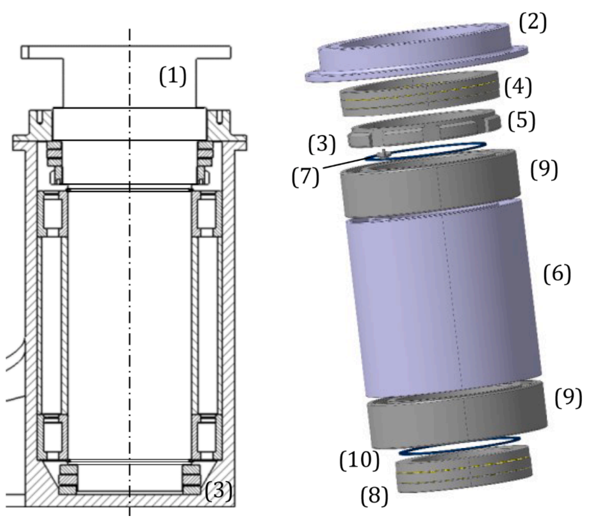

Fig. 7. Bearings assembly drawings. Right: Exploded view bearings assembly.

Table 2
Descriptions of the components used.

N.	Description	N.	Description
1	Shaft	6	Spacer
2	Flange	7	Lock nuts and locking device SKF MS3092–88
3	Lower support	8	Axial bearing SKF 81,268 M
4	Axial bearing SKF 81,188 M	9	Cylindrical roller bearing SKF NCF 3088 CV
5	Threaded ring SKF HME 3088	10	Seeger ring DIN 471

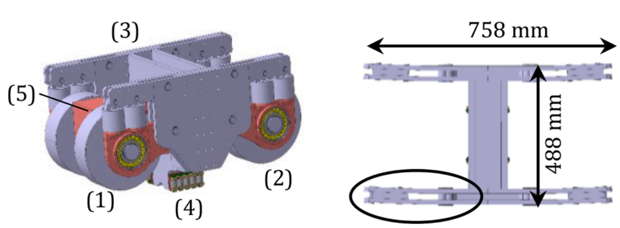

Fig. 8. Left: Truck used to move the lower support. Right: Frame design detail, top view.

4.2.1. Assumed forces distribution

In Fig. 5 we can see the BBTT in the toroidal translation phase of one of the BB segments. It can be seen that the distribution of forces on the bottom support will not be uniform. In particular, the most stressed area will be the one on which the vertical force exerted by the breeding blanket is applied.

The assumed distribution is shown in Fig. 6:

This force schematization is a useful assumption to achieve more accurate pre-dimensioning of the trucks; more precise information on force distribution will require global finite element analysis to take into account the stiffnesses of individual components to transfer loads to the lower structure. The values of the forces are shown in Table 1:

4.2.2. Bearings configuration

To have correct alignment and to guarantee correct force transfer between the main frame and the lower support, the following bearings configuration was used, Fig. 7:

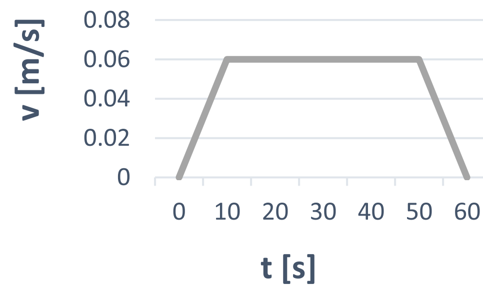

Fig. 9. Speed handling characteristic.

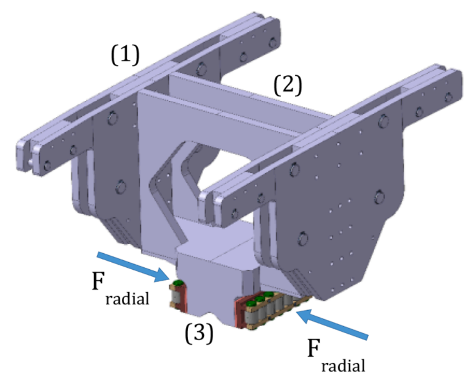

Fig. 10. The frame and the radial guide.

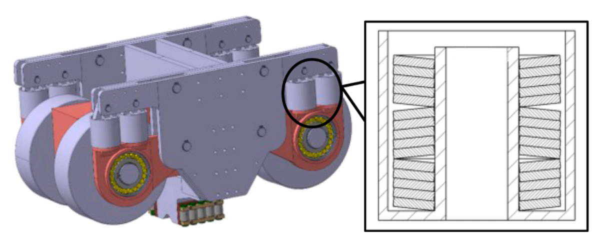

Fig. 11. Suspension detail.

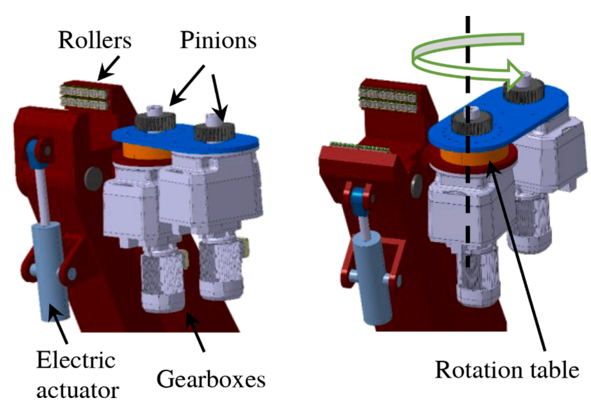

Fig. 12. Left: Upper support in working position. Right: Upper support in pull-out position.

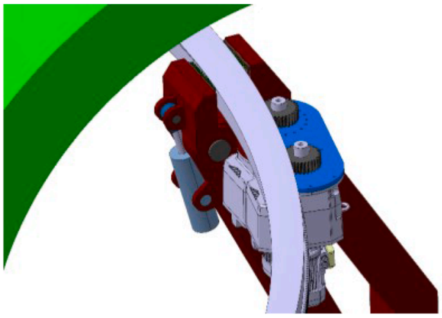

Fig. 13. BBTT engaged on the top gear guide.

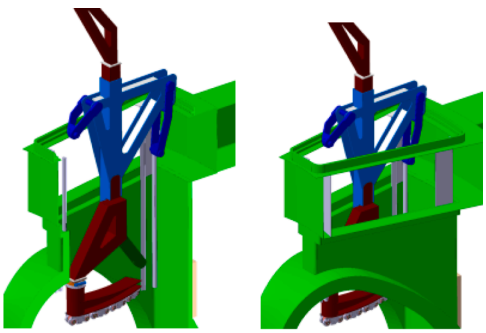

Fig. 14. BBTT during insertion/extraction from upper port.

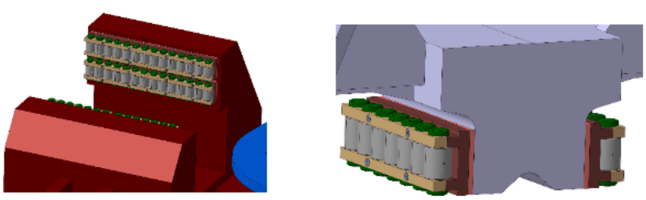

Fig. 15. Left: Rollers details on upper support. Right: Rollers details on truck.

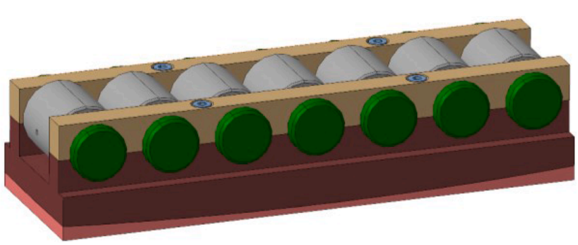

Fig. 16. Rollers configuration detail.

Table 3
Load case.

Load cases	F_{radial} [MN]	F_{tor_top} [MN]	F_{tor_bottom} [MN]	F_{vert} [MN]
Dead Weight	0	+0.20	−0.20	1.8
SL-1 event with toroidal acceleration 1.5 m/s^2	0	+0.20 + 0.27	−0.20 −0.27	2.1

Table 2 shows the descriptions of the components used:

4.2.3. Truck

Trucks are used to ensure the movement of the BBTT and unload the forces on the rail through the lower support. Four trucks are mounted on

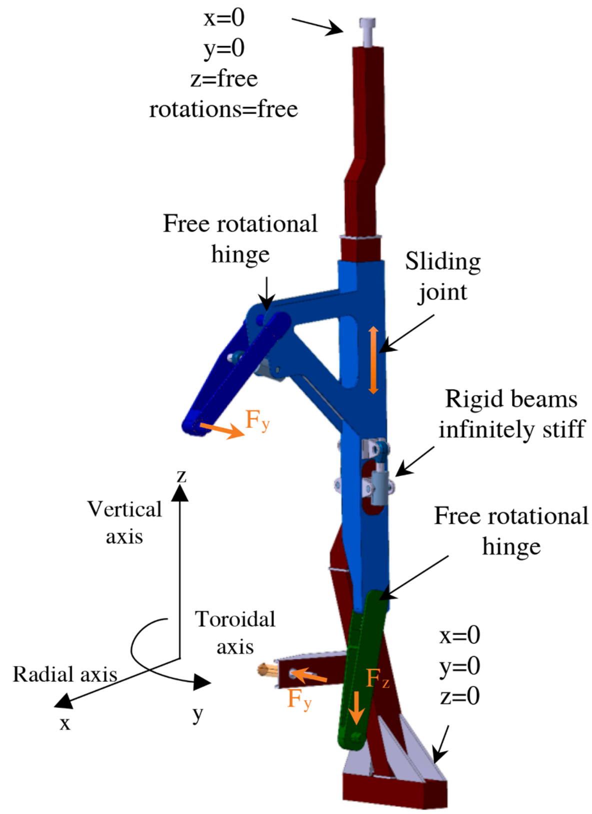

Fig. 17. Boundary condition FEM.

the lower support. Each truck consists of the following parts, Fig 8: front axle (1); back axle (2); frame (3); radial guide (4); gearbox (5).

To ensure proper contact between the trucks and the bottom rail, the following arrangements have been adopted:

- The ends of the truck frame are bent a few degrees;
- Self-aligning bearings are used to connect the axles to the trucks frame.

Assuming that the handling speed of the BBTT is 0.06 m/s, the BBTT is able to run 3 m in 60 s, see Fig 9.

4.2.4. The frame and the radial guide

The frame, Fig. 10, consists of two side plates (1) connected by bolts. The two side plates are welded to an orthogonal frame (2) which has a cavity, where the gearmotor will be located. On the lower part of the frame we have the radial guide (3) which is in contact with the tracks and will have the function of transmitting the radial forces and defining the BBTT's trajectory. A series of rollers are mounted on the radial guide to minimise friction and transmit the radial forces.

4.2.5. Suspension

A very important role is played by the suspension, which acts as a link between the axle and the truck frame, Fig 11. The presence of the suspensions is crucial, in order to ensure that all wheels are in contact with the surface of the rails, they allow any gap due to the construction tolerances of the wheels and rails to be covered. It is assumed that for tracks and wheels the tolerance is ±0.5 mm.

In addition, the presence of the suspensions, also ensures a better distribution of loads. The flexible suspension much reduce the impact loads due dynamic loads e.g. seismic loads or travel on uneven rails. This prevents components from breaking.

As the required stiffness was very high disc springs are adopted [14], which provide more stiffness for the same footprint with helical springs.

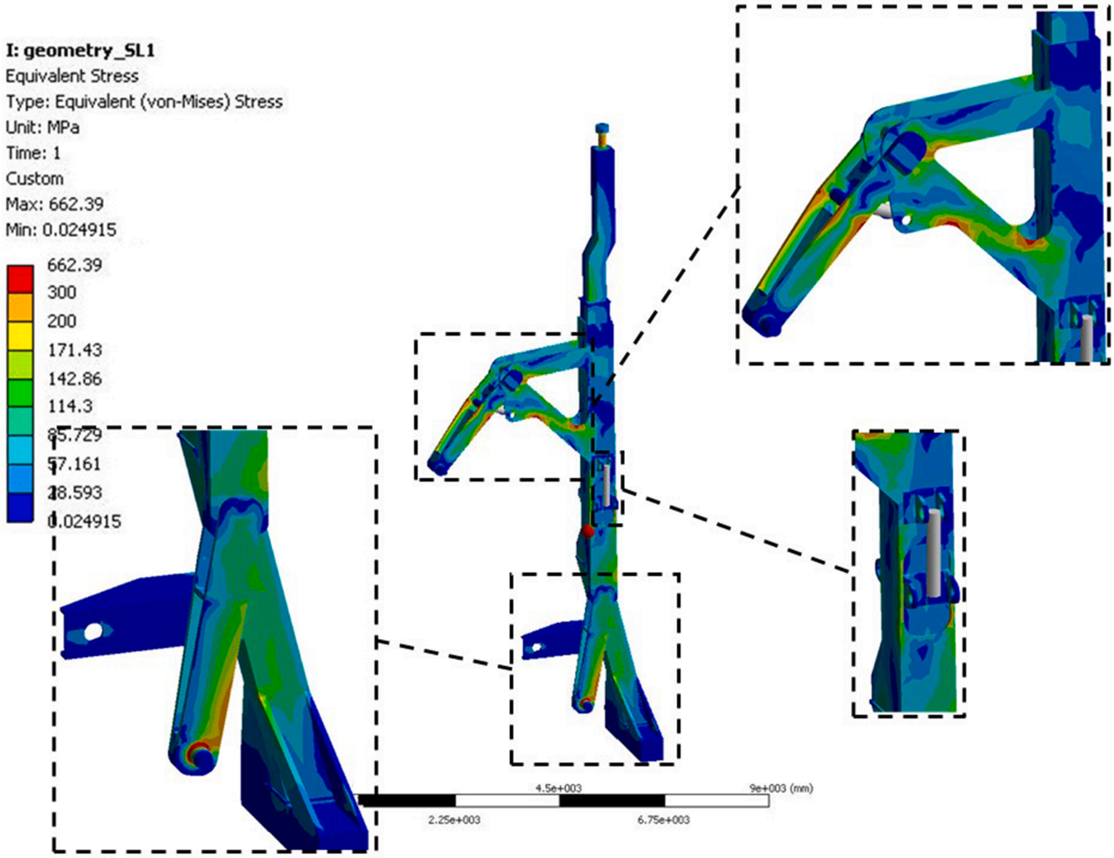

Fig. 18. Equivalent Von Mises Stress Dead Weight + SL1.

The lower suspension system of the BBTT is designed for payloads up to 80 tons. An effort to reinforce the current design is required to enable handling BB segments of up to 180 tons as foreseen in [6].

4.3. Upper support

The structure of the upper support, Fig 12, is designed to:

- Reduce the footprint of BBTT, hence to fold and unfold the second gearbox during the insertion of the transporter inside the Vacuum Vessel, proper rotation table, Fig 12, has been dimensioned and integrated in BBTT design.
- Transmit the massive forces due to the masses to be moved;
- Move the BBTT toroidally.

BBTT movement is provided by the pinions driven by the gearmotors which have an output torque 2100 Nm and output power 7.5 KW. The selected gearmotors are not specific to work in nuclear environments. Currently all the components are designed for a payload up to 80 tons. An effort to reinforce the current design is required to enable handling BB segments of up to 180 tons as foreseen in [6].

A gripper system actuated by a piston was designed to engage the BBTT on the upper gear guide, Fig 13.

4.4. Inserting and extracting the BBTT inside the vacuum vessel

The BBTT is inserted and then removed from the Vacuum Vessel through the upper port as required by the current maintenance strategy.

While designing the BBTT, the maximum extension of the tool was take into account. The dimensions of the BBTT must be comparable with those of the upper port as illustrated in Fig 14. In order to have a BBTT footprint comparable to that of the upper port, it was necessary for the upper and lower supports to be foldable, as described in the previous paragraphs

4.5. Rollers

The transmission of forces from the BBTT to the upper gear guide is ensured by the presence of a roller pattern, Fig 15. This solution was adopted also on the radial guide of the lower support, Fig 15.

The size of each roller has been defined assuming a maximum force to be transferred of 0.62 MN for the lower support and 0.72 MN for the upper support. To achieve this load bearing capabilities the following configuration were used:

- In the lower support, 7 × 1 needle bearings (SKF HK2030) are assembled for each truck into a housing with external dimensions of 190 mm x 60 mm.
- In the upper support, 14 × 2 needle bearings (SKF HK2030) are assembled into a housing with external dimensions of 380 mm x 125 mm.

The roller housing is assembled with a contact plate via a spherical surface. The spherical contact surface allows the roller to align to the surface of the rail, hence ensures a uniform distribution of the contact force across all needle bearings. The intention is to install a cage with bearing balls in between the two spherical surfaces to reduce friction, Fig 16. During assembly of the trolley with the radial rail the gap will need to be adjusted at each roller. This mechanical adjustment is foreseen to be done by shims. Since the rollers and their assembly require customized design solutions, a consultation with an industrial partner should be sought.

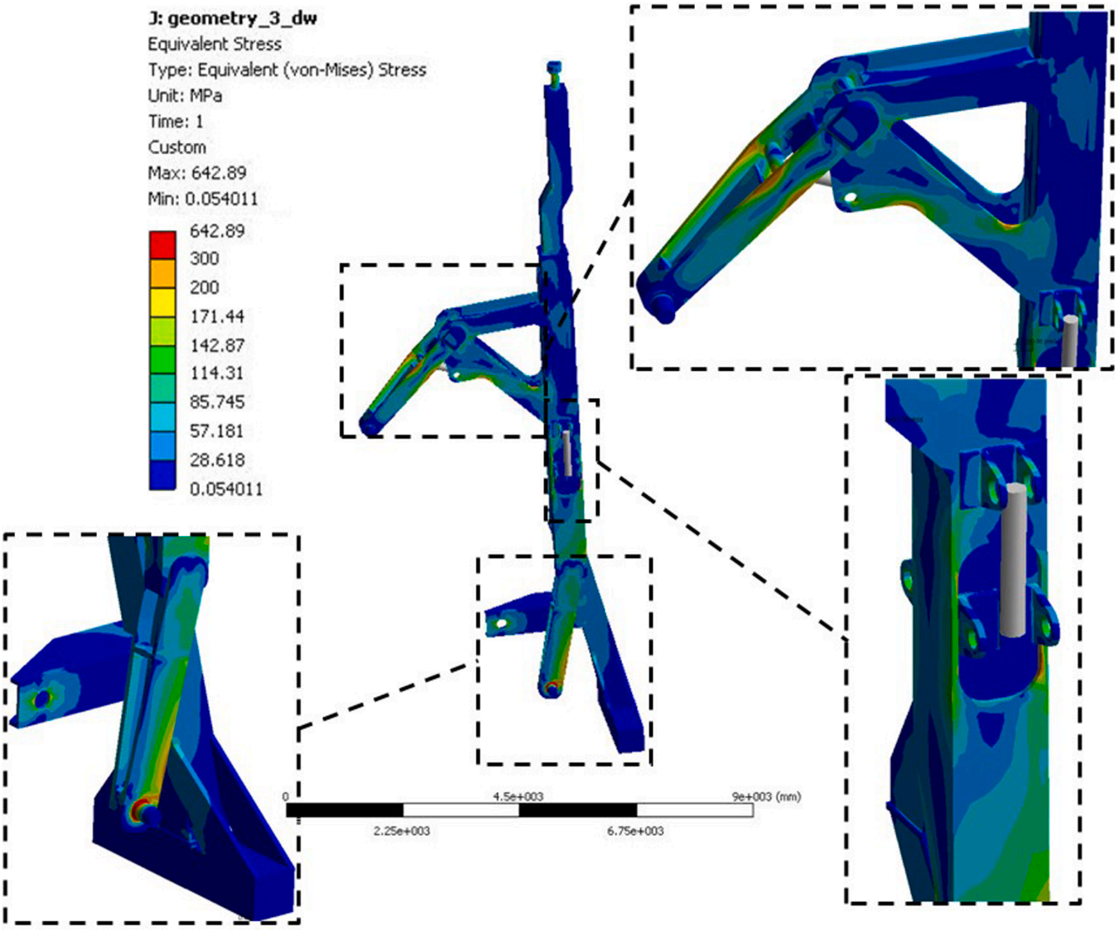

Fig. 19. Equivalent Von Mises Stress Dead Weight.

5. Structural analysis of the BBTT vertical frame

The feasibility of the BBTT was verified from a structural point of view with respect to the critical load condition. The results of the FEM analysis conducted are presented in the following chapter. FEM analyses were currently carried out on a simplified main frame structure and on the sliding frame to obtain initial feedback on the central structure of the BBTT tool.

5.1. Load and boundary conditions

In Table 3 the load conditions about the load case are listed, in the first only the dead weight of the BB segment (180 tons) is assumed as load, in the second the structure has been checked against a seismic event SL-1, event in which the masses are accelerated with 1.5 m/s^2 [15] in toroidal direction.

The BB transporter is locked in the lift position, the BBTT is directed into the VV by rails that interface with the lower and upper support. The presence of the upper support and the lower support ensure that the radial (x-axis) and toroidal (y-axis) movement of the BBTT is zero when the BBTT is locked. The BBTT is placed between the two rails therefore the movement along the z-axis is zero on the lower support while on the upper support there is a small clearance. Rotations are assumed free as such the vertical displacement. The vertical frame and the sliding frame are linked by sliding joint that allow for relative vertical movement of the sliding frame with respect to the vertical frame Fig 17. The upper arm is connected to the sliding frame by means of a rotational hinge. The actuator has been simulated as rigid beam infinitely stiff (the stiffness adopted for the two beams is two orders of magnitude higher than the one of the other components).

The software used for the analysis id ANSYS Workbench R15.0 and the used element are SOLID 186. The analysis method is the elastic one and provisionally, stainless steel AISI 316L(N) [16] has been chosen as reference material.

5.2. Results

The results show the design feasibility from the structural point of view in both load cases. The structure shall be reinforced in some areas as it is shown in the Figs. 18 and 19. Proper attachment point for the BB segments shall be designed.

6. Conclusion & outlook

The development of the BBTT is essential to be able to implement the maintenance strategy described. The current configuration of the BBTT allows:

- Insert and extract the BBTT through the upper port;
- The BBTT handles both types of Breeding Blanket segments: inboard and outboard;
- At present, the BBTT allows the movement of BB segments of the HCPB type which have a mass of 80 tons [6]. The BBTT's main frame is capable of supporting a load of 180 tons, but the BBTT's lower suspension system is designed for payloads up to 80 tons. An effort to reinforce the current design is required to enable handling BB segments of up to 180 tons as foreseen in [6].

To complete the design of the BBTT it will also be necessary to study: Design of engagement pins with BB segments; Design of cables/supply lines; Design of actuators of actuated arms; Global FE structural analysis; Reinforcement for higher payloads; Compatibility with a high radiation field; Validation in test mock-up.

The design of the BBTT was performed according to the European standards for lifting devices [10–12] and considering possible loads related to an earthquake (SL-1). The type of BB that will be used has not yet been defined, but performance limitations in the design of a suitable lifting system (e.g. reduced performance in terms of manageable weight) may result in additional requirements that have to be imposed on the BB design.

Another aspect to be emphasised is the importance of carrying out tests on the assumed equipment/concept in order to bring out any issues.

CRediT authorship contribution statement

Vincenzo Claps: Writing – review & editing, Writing – original draft, Visualization, Investigation, Conceptualization. **Christian Bachmann:** Visualization, Validation, Supervision, Methodology, Conceptualization. **Günter Janeschitz:** Visualization, Validation, Supervision, Project administration, Methodology. **Rocco Mozzillo:** Visualization, Validation, Supervision, Formal analysis, Data curation, Conceptualization. **Thomas Steinbacher:** Visualization, Validation, Supervision, Conceptualization.

Declaration of competing interest

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

Data availability

Data will be made available on request.

Acknowledgments

This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 - EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.

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