Fusion Engineering and Design 215 (2025) 114980

Contents lists available at ScienceDirect

Fusion Engineering and Design

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

Maintenance plan of the ITER Radial Neutron Camera: Verification and validation by virtual reality simulation

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ARTICLE INFO

Keywords:
ITER
Radial neutron camera
Ex-port radial neutron camera
Virtual reality
VR simulation
Verification and validation

ABSTRACT

The Radial Neutron Camera (RNC) is an ITER diagnostic designed to measure the un-collided 14 MeV and 2.5 MeV neutrons from deuterium-tritium (DT) and deuterium-deuterium (DD) fusion reactions, through an array of detectors covering a poloidal plasma section along collimated Lines Of Sight (LOS).

The Ex-Port RNC is located in the Port Cell (PC) Interspace zone, the first area outside the Vacuum Vessel, and includes several detector units, mounted inside detector boxes. On the base of reliability considerations, the Radial Neutron Camera Maintenance Plan (RNC-MP) has foreseen a hands-on maintenance task to replace detectors unit equipment in case of failure. Despite not precluding workers access, the radiation field at shutdown in the PC Interspace zone requires optimization of hands-on operations to enable the minimization of occupational radiation exposure under the ALARA (As Low As Reasonably Achievable) principle.

The relevant complexity and dimensions of the Ex-Port RNC requires a maintenance evaluation method different from a physical mock-up. The Virtual Reality technology may help to create a digital mock-up for evaluating the detectors replacement operations. The paper aims to demonstrate the potentialities of such technologies, in a field where safety and worker ergonomics are primary priorities. Thanks to the virtual scenario built, the RNC-MP updated steps are evaluated, improved and finally validated. The VR simulation is as well validated via a simple physical mock-up of the detector box.

1. Introduction

A nuclear fusion power plant such as ITER (International Thermonuclear Experimental Reactor) represents a hazardous environment in terms of safety in the zones in proximity to the Vacuum Vessel (VV) where the fusion reactions are happening. The first area outside the VV is called Port Cell (PC) Interspace zone, where several diagnostics are assembled, among other components. The diagnostics may require maintenance activities, preventive or corrective. For such activities, the harsh environment characterizing the PC Interspace zone raises the necessity of a dedicated maintenance plan, as prescribed by the ITER MPR (Maintenance, Surveillance and Inspection Program).

The complexity of the ITER project and of the integration of its diagnostics suggests exploring advanced simulation methods for validating the maintenance operations, training the maintenance works and predicting (and optimizing) the maintenance time.

A powerful tool that is revolutionising the approach to design and test is the extended reality (XR). Among the different XR types (virtual, augmented and mixed reality), the Virtual Reality (VR) is the most suitable tool for creating a totally digital world [1]. This is desirable for studies on components before the production of physical mock-up, such several ITER diagnostics and other PC Interspace components.

The XR tools have already found applications in the nuclear fusion research field [2,3]. In the WEST project, an immersive scene of the VV was developed for simulating the assembly sequences and for checking components, and for showing temperature data in a 3D view [1]. An assembly operations sequence has been also simulated for the Magnets Infrastructure Facility for ITER (MIFI), checking the accessibility using contact interaction and force feedback [1]. The augmented reality has been used for integrating the Air-Fed Suit worn by operators inside a replacement operation simulation for the ITER Test Blanket Modules (TBM) [3].

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https://doi.org/10.1016/j.fusengdes.2025.114980
Received 17 January 2025; Received in revised form 12 March 2025; Accepted 18 March 2025

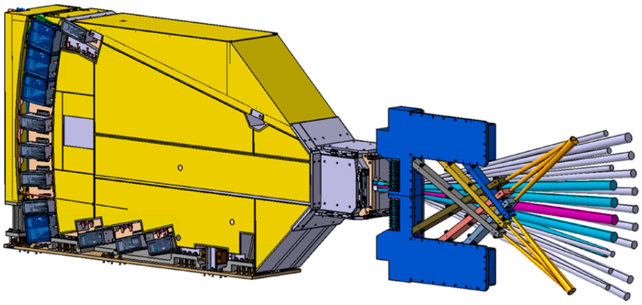


Fig. 1. Radial neutron camera, in-port and ex-port.

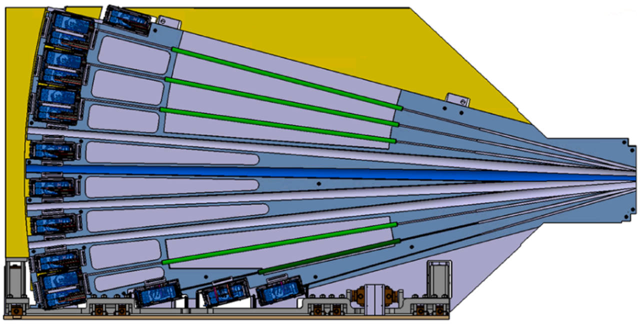


Fig. 2. LOS and detector cassettes of Ex-Port RNC – a detail of the RHS plane.

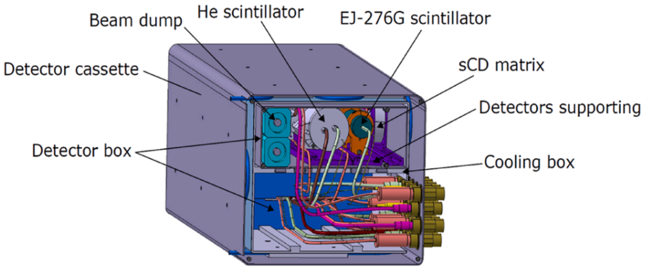


Fig. 3. Ex-port RNC's double detector cassette.

In this paper, the operation of the replacement of an ITER Radial Neutron Camera (RNC) detector located in the PC interspace is simulated with high fidelity for validating the RNC Maintenance plan. The VR simulation created for this scope can constitute a methodological framework for the assessment of the maintenance procedure for different components of a fusion reactor such as ITER, by considering the minimization of the exposure time, the environmental constraints, and the implementation of the ergonomic guidelines.

2. Maintenance activities of the ITER RNC

2.1. Ex-port RNC design description

The RNC is an ITER diagnostic designed to measure the un-collided 14 MeV and 2.5 MeV neutrons from deuterium-tritium (DT) and deuterium-deuterium (DD) fusion reactions, through an array of detectors covering a poloidal plasma section along collimated Lines Of Sight (LOS) [4]. Located in ITER's Equatorial Port 1, it is composed by two collimating structures viewing the plasma radially: the In-Port RNC, located inside the port and devoted to plasma edge coverage, and the Ex-Port RNC, devoted to the plasma core coverage (Fig. 1).

The Ex-Port RNC is located in the PC Interspace zone (the first area outside the Vacuum Vessel) of ITER Equatorial Port #1 and contains 16 LOS distributed in two radial planes: Left-Hand Side (LHS) plane and the Right-Hand Side (RHS) plane. The LHS contains 10 LOS (one of which shared with an interfacing diagnostic), while the RHS contains 6 LOS plus 4 LOS belonging to two interfacing diagnostics. The Ex-Port RNC system includes several detector units mounted within a shielding structure inside the 12 Detector Cassettes located at the end of the collimating path (on the left side of Fig. 2). The Detector Cassettes are only accessible from the RHS.

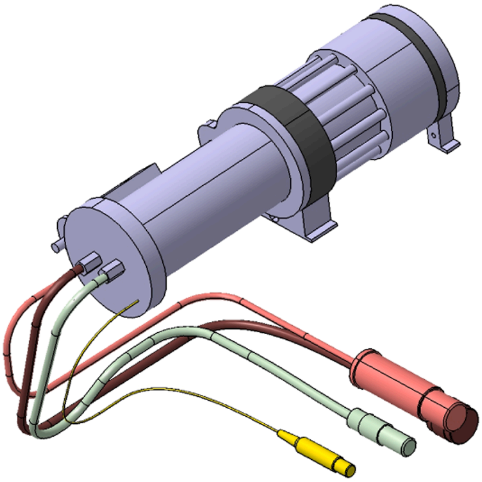


Fig. 4. 4He scintillator detector.

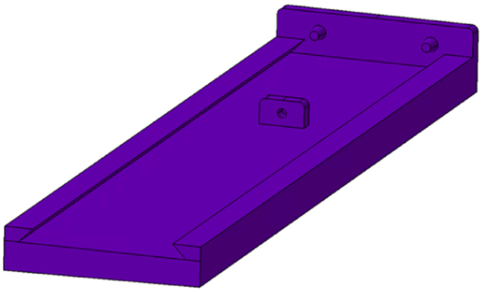


Fig. 5. 4He scintillator fixed support.

The set of detectors for each LOS is composed by a ^{4}He Scintillator (for full power DT reactions measurement), a EJ-276 G Plastic Scintillator (for low power measurement) and a single Crystal Diamond detector (as a backup for full power measurement) [5]. The set of detectors is mounted inside a Detector Boxes, in turn assembled in the Detector Cassette (Fig. 3). The Detector Cassette can be a Double type (i.e. containing two Detector Boxes, as in Fig. 3) or a Single type (i.e. containing one Detector Box).

This paper focuses on the simulation in VR of the replacement of the ^{4}He Scintillator (Fig. 4), a 1.7 kg cylindrical detector with a diameter of 70 mm and a total length of 245 mm. The ^{4}He Scintillator has been chosen as representative of the maintenance operations of RNC detectors since the sequence of operations for the replacement of the ^{4}He Scintillator is the same as for the replacement of the EJ-276 G Plastic Scintillator and for the sCD detector. Moreover, the number of cables of the ^{4}He Scintillator that must be unplugged/plugged (4 cables) is the same of the Plastic Scintillators and higher than that of the sCD detectors (1 cable only). Therefore, the choice of the ^{4}He Scintillator also for this study guarantees conservative estimation of the measured time for the operation.

For insertion inside the Detector Box, the ^{4}He Scintillator slides on dovetail rails belonging to the ^{4}He Scintillator Fixed/Sliding Detector Supporting Structure support, welded inside the Detector Box (Fig. 5).

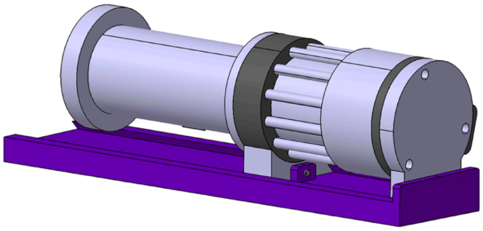


Fig. 6. 4He scintillator locked on its fixed support.

Table 1
4He scintillator substitution procedure [7].

TASK	TASK DESCRIPTION	STEP	STEP DESCRIPTION
1	Remove the Detector cassette front cover	1.1	Loose the Detector cassette front cover M4 cylinder head screw
		1.2	Remove the Detector cassette front cover
2	Remove the Detector box front lid	2.1	Loose the Detector box front lid M4 cylinder head screw
		2.2	Remove the Detector box front lid
3	Unplug the connectors	3	Unplug the connectors from the feedthrough panel
4	Remove the failed detector	4.1	Loose the 4He Scintillator M4 cylinder head screw
		4.2	Slide the 4He Scintillator along the dovetails guides towards the Detector box's opening
		4.3	Remove the old 4He Scintillator
5	Install the new detector	5.1	Place the new 4He Scintillator on the dovetail guides
		5.2	Push 4He Scintillator along the dovetails guides towards the stopper
		5.3	Tighten the 4He Scintillator M4 cylinder head screw
6	Plug the connectors	6	Plug the connectors from the feedthrough panel
7	Mount the Detector box front lid	7.1	Place the Detector box front lid
		7.2	Tighten the Detector box front lid M4 cylinder head screw
8	Mount the Detector cassette front panel	8.1	Place the Detector cassette front cover
		8.2	Tighten the Detector cassette front cover M4 cylinder head screw

The Fixed support presents two truncated cones for detector centering located at the end of the dovetail rails and a vertical plate in the middle of the rail with a M4 threaded hole (toroidal stopper).

To lock the toroidal movement of the inserted 4He Scintillator, an M4 screw is then screwed in the toroidal stopper (Fig. 6).

To extract the detector, first the screw must be removed and then the ^{4}He Scintillator can slide. These operations will be followed during the simulations.

2.2. Maintenance plan of RNC

The crucial importance of the maintenance activities in the ITER project is reflected in the ITER MPR [6]. The ITER MPR prescribes detailed rules to conduct every operation in the safest way, in accordance with regulations for occupational and nuclear safety of the Host Country, France. The maintenance strategy is primarily divided into Preventive (in turn divided in Periodic, Predictive and Planned) and Corrective Maintenance (Run-to-failure and Unplanned failure). For each maintenance approach, and depending on the location of the maintenance activity, dedicated regulations are specified.

A maintenance plan has been developed for the RNC (RNC MP) based on the ITER MPR. A maintenance procedure must be foreseen only for those components whose probability to fail is higher than 10 % over the expected plant operation period (that is equal to 20 years) according to reliability, availability, maintainability and inspectability (RAMI). The only components which respect this requirement are the detector boxes, and for this reason their maintenance activities are designed. Every maintenance activity is detailed reporting the location, the components to be maintained, and the type of maintenance. Then, on each maintenance activities, the operations step-by-step are specified, as well as the number of operators, the time expected and the tools necessary.

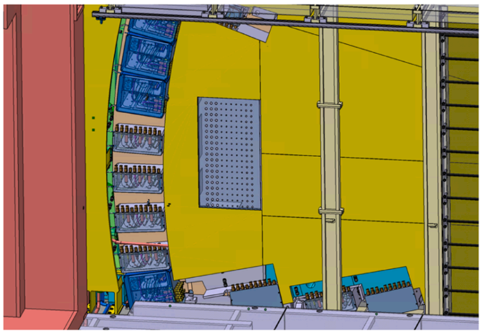


Fig. 7. Access to the detector cassettes from the ISS walkaway.

For the ^{4}He Scintillator, a Hands-On-Tool (HTL) activity for replacement (Corrective, Run-to-failure) is planned to be executed directly on the Interspace zone. The step-by-step procedure is taken from [7] and reported in Table 1.

The total time for the replacement operation of the ^{4}He Scintillator has been estimated on the basis of the maintenance experience from previous tokamak devices, e.g. JET [7]. In particular, each task is decomposed in elementary operations (e.g. cable connection/disconnection, bolting/unbolting) for which a tabulated time is available. The total time results from the sum of all the elementary operations multiplied by the frequency of their occurrence. For the ^{4}He Scintillator replacement the estimated time is 66 min.

As indicated in Table 1, the simulation of the replacement starts with the hands-on operation of removing the Detector Cassette's cover. The access to the Detector Cassettes inside the environment of the Interspace zone of the Equatorial Port #01 has been preliminarily evaluated. The operator can access standing on the walkaway of the Interspace Supporting Structure (ISS) (Fig. 7). The ISS elements that may obstruct the access are removable. The current study is focused on the Detector Cassettes only, considering the access already cleared.

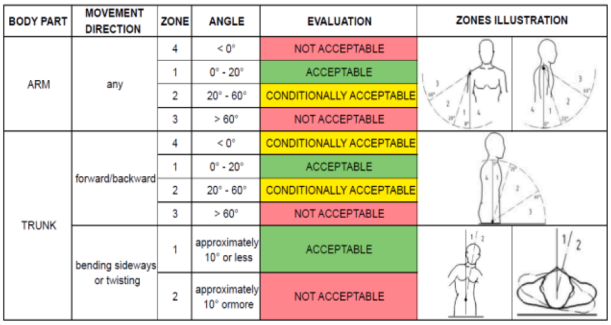
2.3. ITER ergonomic guidelines

To proceed with the maintenance procedure evaluation, the ergonomics of the operations must be analysed. Ergonomics is a science that studies the interactions between worker, machines and environment in a work system, with the aim to improve performances and effectiveness of operations, ensuring worker's health and safety. A particular conformation of the work environment in combination with neglecting the physical body constraints can exert a significant physical strain on workers which, if continuous and repetitive, can lead to musculoskeletal disorders [8].

The ITER Ergonomic Guidelines (ITER EG, [9]), based on the normative EN 1005–4:2005 [10], give prescriptions on the correct body posture by dividing the evaluation into three zones.

The *Acceptable zone* (green colour) comprehends every movement or static position that repeated over the time does not present the risk of pathologies. The *Acceptable zone under certain conditions* (yellow colour) concerns all the hazardous activities that require special preventive measures or are permitted for a limited time. The *Unacceptable zone* (red colour) includes all the movements or static positions that involve a high risk of injury or the appearance of pathologies if repeated over time. The three zones are identified by a geometrical decomposition and analysis

Table 2
ITER EG for arms and trunk position [10].



BODY PART	MOVEMENT DIRECTION	ZONE	ANGLE	EVALUATION	ZONES ILLUSTRATION
ARM	any	4	< 0°	🟥 NOT ACCEPTABLE	
		1	0° - 20°	🟩 ACCEPTABLE	
		2	20° - 60°	🟨 CONDITIONALLY ACCEPTABLE	
		3	> 60°	🟥 NOT ACCEPTABLE	
TRUNK	forward/backward	4	< 0°	🟨 CONDITIONALLY ACCEPTABLE	
		1	0° - 20°	🟩 ACCEPTABLE	
		2	20° - 60°	🟨 CONDITIONALLY ACCEPTABLE	
		3	> 60°	🟥 NOT ACCEPTABLE	
	bending sideways or twisting	1	approximately 10° or less	🟩 ACCEPTABLE	
		2	approximately 10° ormore	🟥 NOT ACCEPTABLE	

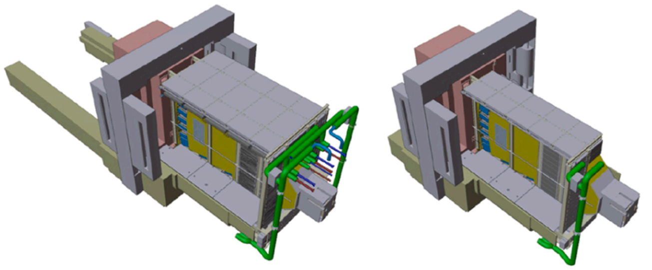


Fig. 8. Ex-port RNC in the port interspace zone before the optimization (left) and after (right).

of the operator's body, as shown in Table 2.

The ITER EG prescriptions will be implemented in the VR simulation for evaluating the RNC MP under the ergonomic point of view. The study is focused on the upper part of the body: right arm, left arm, trunk.

Within the regulations, the limits related to the weight of objects to be lifted are also reported. The maximum acceptable weight of a lifted object is 15 kg. If the weight is less than or equal to 5 kg, the risk is considered almost negligible. The weight of the ^{4}He Scintillator is 1.7 kg, which is heavier than the other objects handled during the replacement operation. Thus, the weight is negligible for the ergonomic assessment of the operation.

3. Virtual reality simulation vs physical mock-up

A VR environment of the PC area of the Equatorial Port #1 has been implemented via Unity coding to simulate the ^{4}He Scintillator replacement procedure. To validate the VR code, a realistic physical mock-up of the detector cassette has been realized and used for replicating the same maintenance procedure (Table 1). If the procedure times of the two simulations are comparable, the VR code is validated.

3.1. VR simulation set-up

For realizing the VR environment, the Unity software has been chosen for its versatility and its wide-spread use in the gaming industry, which allows to have a considerable number of guidelines and tutorials [11]. The Ex-Port RNC CAD model is first lightened in graphic rendering terms: components not involved in the maintenance procedure and not visible to the operator during the procedure are removed, the ones not involved and visible are simplified, for example by transforming solid bodies into surfaces. We obtained an identical model but lighter, for avoiding undesirable lagging during the simulation (Fig. 8).

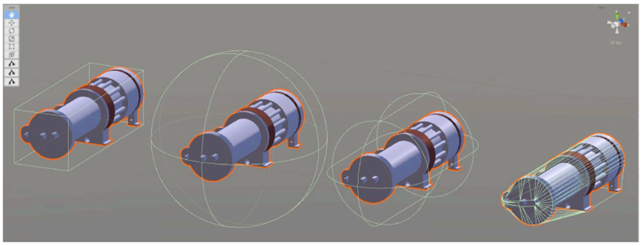


Fig. 9. Different unity collider type (from left to right): square, sphere, capsule, mesh.

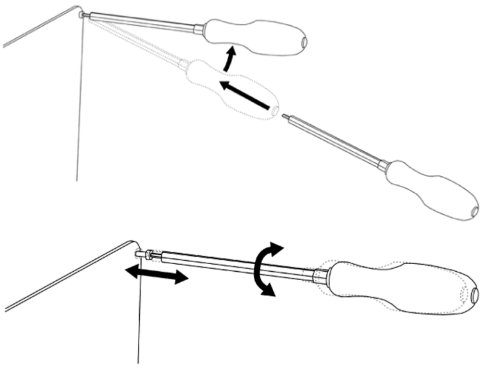


Fig. 10. Screwdriver behaviour for the screwing operation: alignment (up) and roto-translation (bottom).

For each one of the components involved, its physical behaviour is defined by coding. A volume occupation with a non-penetrability characteristic is given to each body by setting the appropriate Unity *collider*. Among the different types, the one that best suits the ^{4}He scintillator's shape is chosen (Fig. 9).

Once the physical behaviour of the objects is defined the components can be grabbed by the VR operator. Afterwards, actions (e.g. directional movements) are assigned to each component based, needs to be assigned

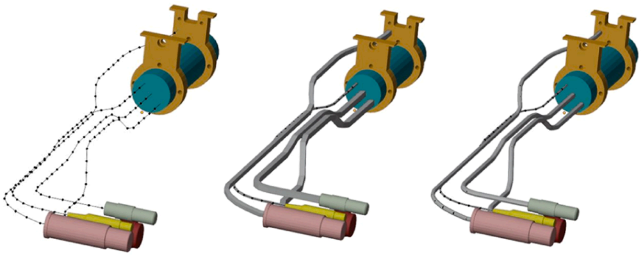


Fig. 11. Cables virtual modelling: segmentation, enveloping in a coarse skin, skin smoothing.

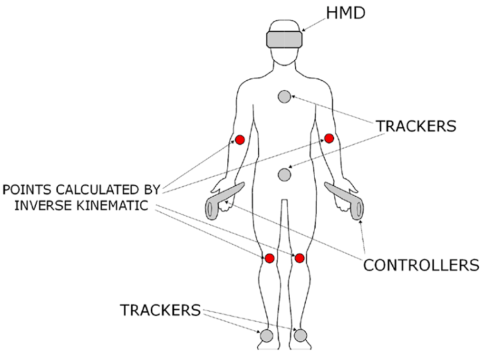


Fig. 12. Operator body's skeleton reconstruction.

Fig. 13. Comparison between real operator movement and the virtual reconstruction.

to each component based on its function within the maintenance procedure. For example, he behaviour of the screwdriver is divided into two phases. First the screwdriver, when it is placed near the screw and triggered by its collider, aligns with the screw's axis. Second, once aligned, the two bodies are simultaneously characterized by a roto-translation movement acted by the operator (Fig. 10).

To complete the virtual model, each detector cable has been modelled taking care of the cable flexibility and its spatial occupation. For the modelling, the software Blender has been used. Starting from the original CAD model, each cable has been divided in a number of segments that give the physical behaviour to the cable. Then, an outer skin has been applied on each segment for giving the cable its original aspect. Finally, a smoother mesh has been applied on the skin (Fig. 11).

Although this resulted in a highly time-consuming activity, due to a lack of literature on the cables modelling and to the non-replicability of each cable, the cables have been properly modelled because they significantly increase the accuracy, the reliability and the sensation of realism of the VR simulation.

Now, the virtual presence of the operator within the created VR world must be assessed. The HTC Vive Pro 2 set is used because of its effectiveness in the research field [12]. It includes: a headset (for visualizing the VR world), two controllers (for interacting with it), four body trackers and two room fixed sensors. The four trackers, along with the headset and the controllers equipped with trackers too, are seen by the two room fixed sensors, and their position triangulated. Based on these six points, a virtual skeleton is built (Fig. 12).

To complete the operator's body, four additional points are set by calculation via inverse kinematics, so that the operator's virtual body fully responds to the real movement of the player (Fig. 13).

For evaluating the ITER EG, they have been implemented by replicating the geometrical decomposition of the operator's body of Table 2. To do this, the 11 body points (Fig. 12) are linked for creating segments, in turn used for calculating the angles prescribed in [9] for separating the three ergonomic zones. To visualize the permanence in each zone, a User Interface (UI) is realized with a pop-up stick figure that appears in the headset superposed on the simulation while playing. Each analysed part (right arm, left arm, trunk) is coloured in real time in red, yellow or green, depending on the player pose. Table 3 lists the possible movements, player and virtual body poses, and the UI stick figure for the arms movement.

To complete the set-up, a script for timing the operations has been written.

3.2. Physical reality mock-up

To validate the VR simulation code, a physical mock-up has been manufactured. To choose what components to build, a multi-objective study has been carried out. The aims are minimizing the mock-up costs, times and dimensions as well as the affordability of maintenance steps (Table 1) executed with the mock-up. A plywood Double cassette, containing ABS 3D printed detectors, connected with aerial

Table 3
Summary of arms movement.

MOVEMENT	USER POSE	VIRTUAL BODY POSE	UI MONITORING
neutral position			
lateral arms raises			
			

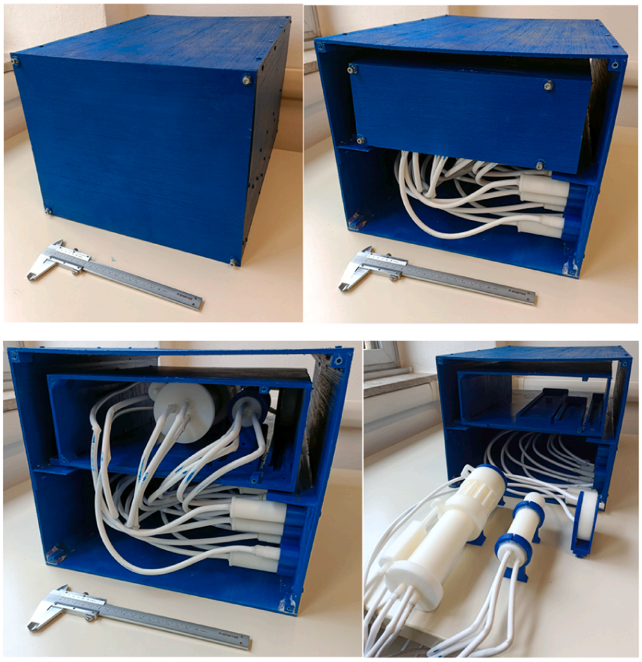


Fig. 14. Physical mock-up of ex-port RNC double cassette.

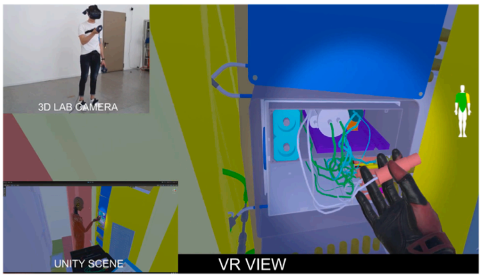


Fig. 15. Connectors unplugging sub-step: different views for the same action.

cables to ABS 3D printed connectors (Fig. 14), has been realized.

4. Simulations results

4.1. Ergonomics results

Fig. 15 shows a snapshot of the VR simulation: the operator acting (3D LAB camera), what can be seen in the headset (Unity scene and VR View), the ergonomics stick figure (in the VR View).

The ergonomic results of the simulation are given in Fig. 16. The total time of each maintenance step is divided in percentages of each zone that the body part was covering during the simulation. The bars are coloured accordingly to the zone colour and its amount.

The right arm highlights a less ergonomic behaviour, with red zones especially in the operations of removing and reinserting the ^{4}He scintillator. The difference between left arm and right arm is due to the fact that the operator was right-handed. Thus, the right hand was more inclined to fail the ergonomic precepts. To reduce the ergonomic errors, the future analyses will be focused on different approaches to failing procedure step. For example, if the Detector cassette is found to be too high (thus forcing an excessive arm inclination), a ladder may be foreseen for rising the operator's body while decreasing the arm's inclination. In parallel, the virtual skeleton will be refined by adding one or more trackers on the physical operator, thus decreasing the skeleton's point calculated by inverse kinematics, in turn increasing the virtual

Fig. 16. Ergonomics results of the maintenance procedure: Left arm (top), trunk (middle) and Right arm (bottom).

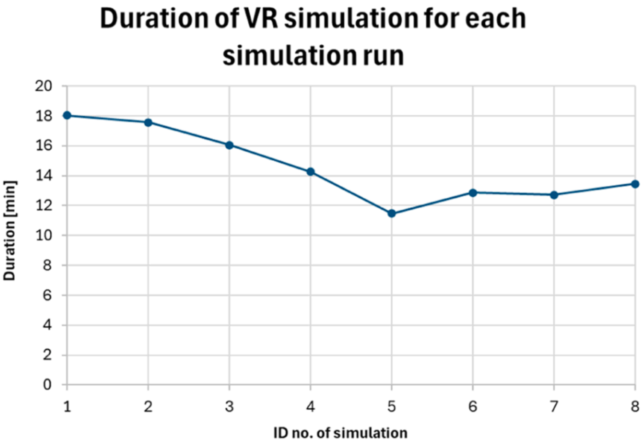


Fig. 17. Duration of VR maintenance operation Vs number of simulation performed.

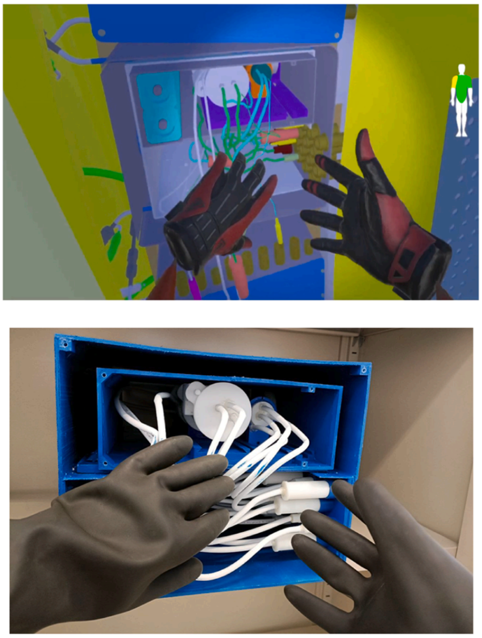


Fig. 18. VR simulation (top) and physical simulation (bottom) of the substitution procedure.

body precision and reliability.

4.2. Time durations of the simulations

The VR simulation of the maintenance task has been repeated 8 times. The time requested for completing the replacement procedure decreases and then stabilizes around 13 min after the simulation is repeated several times, as shown in Fig. 17. This is due to the increasing knowledge of the VR model and the maintenance tasks gained by the operator. This demonstrates how useful the VR tool can be for the training of the operator prior the real maintenance operation. Thanks to the training, the operation can be executed by following the ALARA principle by minimizing the operator's exposure time.

Fig. 18 shows the same procedure step on the two maintenance simulations, VR and physical.

Fig. 19 compares the time results of the VR simulation with the physical reality simulation. In both cases, 5 simulation runs are considered (for the VR simulations, the last 5 runs from Fig. 17 are considered, thus from no 4 to no 8).

The total time, averaged on the 5 runs, of the VR simulation is 13.4 min. The mean total time of the physical reality simulation is 8.2 min. The same trend is observed in both graphs in Fig. 19. The difference lies in steps 5 and 12 (unplugging/plugging the connectors plug), that primarily affect the overall time. The physical connectors, even though 3D printed, are more reliable in terms of time for unplugging/plugging than the VR simulated ones. Thus, the times difference can be improved by refining the VR model in the connectors area. A further solution may be using a different type of manipulator, such as a haptic glove, which increases the precision and the realism of the finger movements.

5. Conclusions

The VR simulation verified the maintenance procedure of the ^{4}He Scintillator. The procedure steps can be executed within the time estimated (13.4 min simulated vs 66 min estimated). The difference is explainable with the approach used for the time estimation (see §2.2). The VR simulation has been validated thanks to a physical mock-up; thus, we can consider the VR model as conservative (13.4 min vs 8.2 min of the physical simulation). In terms of ergonomics, the maintenance procedure can be accepted, but different improvements can be adopted, in particular for the acting hand. The VR simulation has been confirmed as a powerful and faithful approach for the V&V process.

The VR tool has been also useful for the minimization of the procedure times (see §4.2). This feature highlights how useful a VR tool is for the training of the operators prior the execution of the real operation. Thanks to the training with a faithful VR model, the operation can be executed by following the ALARA principles.

The paper presented an application of a VR tool for the V&V process of the maintenance procedure of a nuclear fusion device diagnostic. The integration of the ergonomic guidelines within the maintenance simulation enriched the usefulness of the VR tool. In conclusion, this work can be adopted as a powerful methodological framework for assessing the maintenance procedures of other nuclear fusion device components.

CRediT authorship contribution statement

Enrico Occhiuto: Writing – review & editing, Writing – original draft, Software, Methodology, Investigation, Data curation, Conceptualization. **Domenico Marzullo:** Validation, Methodology, Conceptualization. **Danilo Nicola Dongiovanni:** Writing – review & editing, Visualization, Validation. **Ugo Bonavolontà:** Software, Methodology. **Francesco Malaroda:** Software, Formal analysis, Data curation, Conceptualization. **Daniele Marocco:** Writing – review & editing, Validation, Supervision, Project administration. **Basilio Esposito:** Writing – review & editing, Visualization, Validation, Supervision, Project administration.

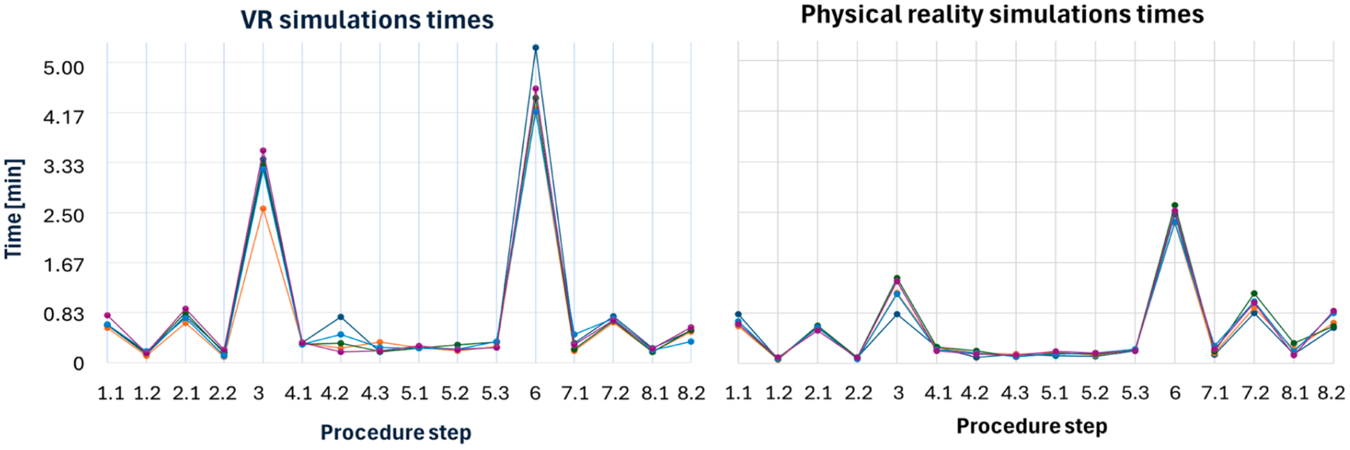


Fig. 19. VR and physical simulations measured times.

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

The work leading to this publication has been funded partially by Fusion for Energy under the Specific Grant Agreement F4E-FPA-327 SG07. This publication reflects the views only of the author, and Fusion for Energy or ITER Organization cannot be held responsible for any use which may be made of the information contained therein.

Data availability

Data will be made available on request.

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