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Conceptual design proposal for the EU-DEMO electron cyclotron ex-vessel waveguide system with enhanced remote maintainability

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ABSTRACT

The EUropean DEMOnstration power plant (EU-DEMO) project, a EUROfusion initiative, seeks to advance fusion power technology by developing a reliable Electron Cyclotron (EC) heating and current drive system capable of delivering up to 130 MW of auxiliary heating power presently through six equatorial ports. This paper introduces an innovative alternative to the baseline ex-vessel waveguide (EW) system design, which could be major for effective EC operations. The proposed design reduces vacuum-sealed interfaces significantly — from 173 to seven — minimizing failure points and reducing the need for extensive monitoring in confined port spaces. Enhanced for remote maintainability, the design simplifies maintenance tasks and mitigates vacuum breach risks. The vacuum dimple-plated casing, acting as the primary confinement boundary, ensures nuclear safety and enables integration with current infrastructure, while addressing challenges like dynamic loads and vessel movements to maintain structural integrity. These advancements indicate that the modular and sealless waveguide approach offers a more reliable, maintainable solution.

1. Introduction

The EU-DEMO reactor is a key milestone toward commercially viable fusion energy. Designed as a large-scale tokamak for sustained plasma operations, it serves as a functional prototype for fusion power production planned for the first half of the century [1].

The Electron Cyclotron Heating and Current Drive (ECH&CD) system is a core component of EU-DEMO [2], proposed to deliver up to 130 MW of power for plasma heating, stabilization (e.g., sawtooth suppression, radiative instability mitigation), and control (e.g., Neoclassical Tearing Mode control). Millimeter-waves generated by 2 MW gyrotrons are transmitted through waveguides and quasi-optical lines to enter the reactor via equatorial ports [3], where mirrors distribute them over plasma regions.

The challenges faced by EU-DEMO are distinct from those encountered in ITER. In EU-DEMO, the Ex-vessel Waveguide system (EW) must deliver reliable auxiliary heating while simultaneously addressing radiation safety, limited space, and the need for remote maintainability in a full-scale fusion power plant [5]. Unlike ITER, where each transmission line is individually bolted and vacuum-sealed (Fig. 1), EU-DEMO is designed to operate under substantially different conditions. For instance, while the tritium inventory itself may not directly affect the EC system design, the overall higher tritium throughput — estimated to be more than 1000 times greater [6] — reflects a more demanding radiation environment and integrated system challenges. These broader operational constraints necessitate an alternative approach that prioritizes compact integration and remote maintenance of the launcher system.

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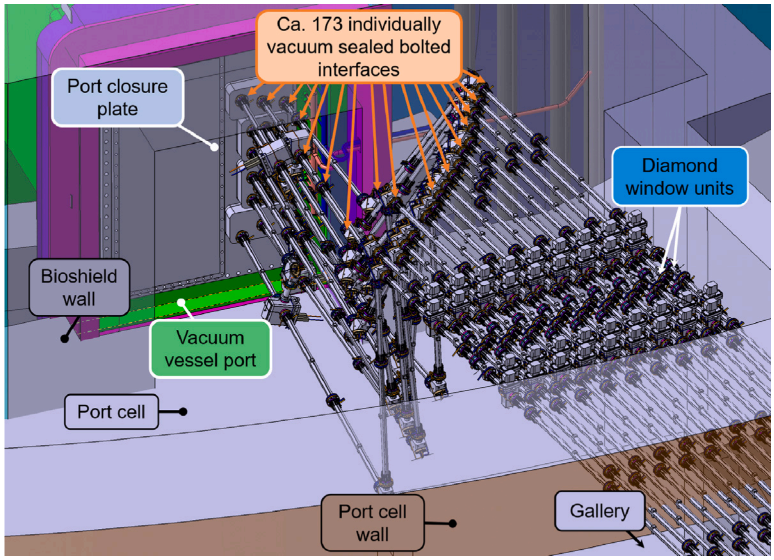


Fig. 1. Overview of the current design of the Ex-vessel Waveguide system (EW) inspired by ITER [4]. The system is located in the tokamak building (L1 level) and extends from the equatorial port closure plate to the perimeter walls of the gallery.

These more stringent operational requirements increase dose rates because radiation can stream through the unavoidable openings in the closure plate and bioshield where the waveguides pass. Our initial shutdown dose rate (SDDR) analyses (see Fig. 2) show that radiation levels in the equatorial port cell exceed 10 μSv/h [7]. Such high levels will necessitate remote handling for safe access and maintenance. This differs from the findings of [8], which assumed a fully plugged bioshield and therefore underestimated streaming effects. To avoid misleading comparisons, Fig. 2 presents results without a bioshield plug, reflecting more closely the impact of the waveguide openings in the bioshield.

This paper presents an alternative design for the EU-DEMO EW with a focus on the First Confinement System (FCS) in Section 2, detailing its implementation plan with a focus on manufacturing processes and remote maintenance strategies in Section 3. Section 4 addresses the design's response to operational stresses, focusing on routing, shielding, and structural stability to meet EU-DEMO's safety and operational standards. Section 5 provides a summary of the main improvements and potential optimization strategies for future work.

2. Description of the proposed ex-vessel waveguide system design

2.1. Goals

The design of the ex-vessel transmission line system was initiated through an intensive collaboration between the remote maintenance and heating and current drive teams, recognizing that remote maintenance capability is a critical design driver [9]. The general requirements for remotely maintained components include accessibility, modularity, simplicity, high reliability, and the implementation of positioning aids, gripping fixtures, and adequately designed flanges to facilitate remote operations. These guidelines ensure that components can be maintained efficiently and safely, even in high-radiation environments.

2.2. Modular configuration

Modularity is achieved by creating independent, robust entities with well-defined interfaces, ensuring that each module can be accessed, maintained, or replaced without affecting the surrounding systems. This approach aligns with the principle that modular components reduce maintenance time, simplify operations by enabling easier disconnection and transportation of components for repair or disposal.

Adopting a modular design, the reference system integrates 18 first confinement ex-vessel transmission lines — comprising waveguides and miter bends that require minimal maintenance — within a vacuum casing with an inner diameter of 63.5 mm. In contrast, isolation valves and diamond windows, which need regular preventive maintenance due to their moving parts and the challenges of brazing dissimilar materials, are organized into separate modules. By bolting these components in groups of three, the design saves space, enhances accessibility, and minimizes plant downtime through rapid detachment, transport, and replacement of modules (see Fig. 3).

2.3. Dimpled-plate casing

The dimpled-plate casing extends the Vacuum Vessel (VV) and serves as the primary nuclear boundary for the transmission line system, directly connecting to the torus vacuum. This ensures vacuum integrity critical for plasma operation, millimeter-wave functionality, and tritium containment. To reduce dose rates in the port cell, the casing will be filled with boron carbide shielding. Additionally, hot or cold water will circulate through the casing for system cooling and baking, with temperatures synchronized to the tokamak's operations to minimize thermal stresses.

The wavy, "pillow-shaped" surface enhances strength-to-weight and strength-to-space efficiency, providing structural resilience against atmospheric pressure and other loads. The dimpled features act as stiffeners, distributing inertial loads and preventing deformation and buckling by increasing the bending stiffness of the plate [10]. This ensures robust vacuum integrity and improves thermal performance [11], which is likely to offer a lightweight, cost-effective, and space-efficient solution [12].

Details of the novel folding techniques used in the manufacturing process are discussed in Section 3.1.1.

2.4. Sealless components

The current configuration (Fig. 1) requires individually sealing the first confinement EW, which extends from the closure plate to the diamond window units, resulting in 173 nuclear-grade bolted vacuum interfaces. In the proposed design, the components housed within the dimpled-plate vacuum casing are sealless (Fig. 4), reducing the number of vacuum-sealed and bolted interfaces by 96%, down to seven (Fig. 3). This approach minimizes the risk of vacuum breaches and decreases

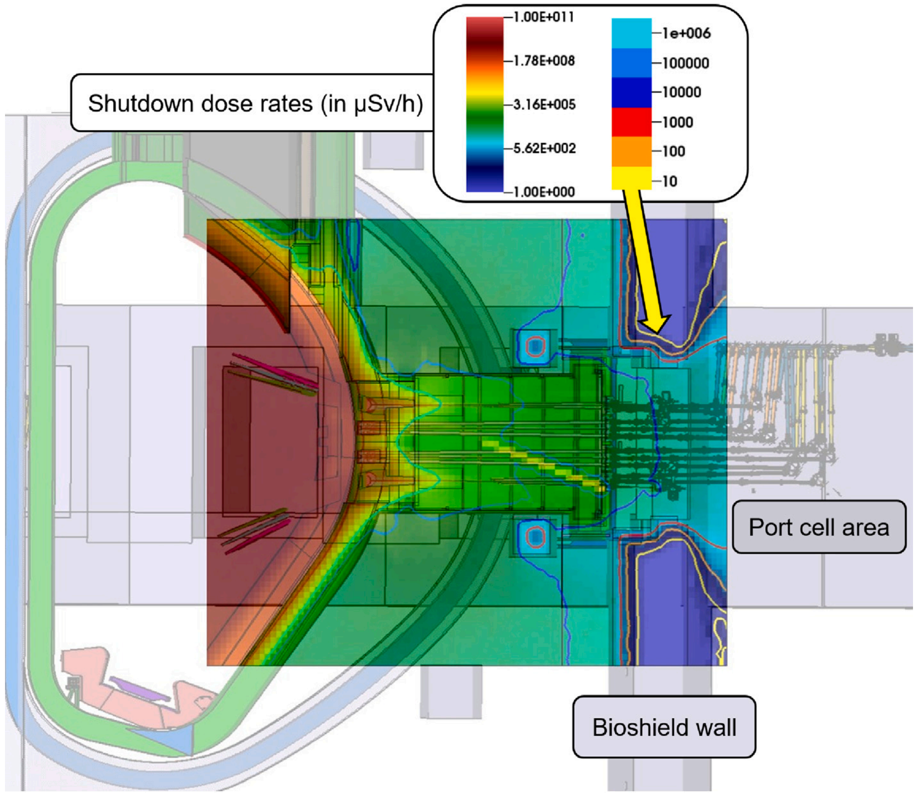


Fig. 2. Current DEMO reactor design overlaid with SDDR analysis [8], illustrating the need for remote maintainability of the Ex-vessel Waveguide system (EW). The color gradient across pixels represents localized radiation levels, while contour lines outline specific thresholds at 10, 100 μ Sv/h, and higher. The yellow contour, in particular, marks the 10 μ Sv/h threshold, indicating areas where radiation levels prevent human access [7].

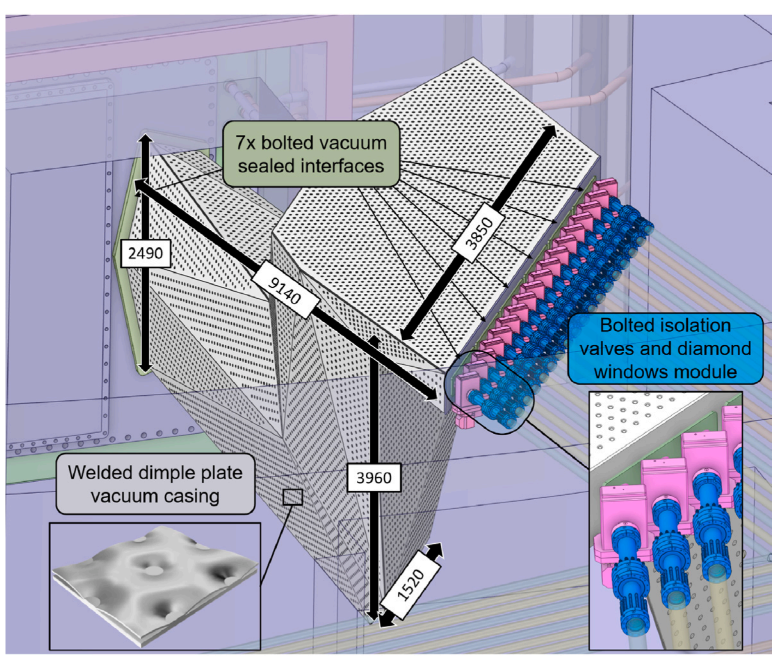
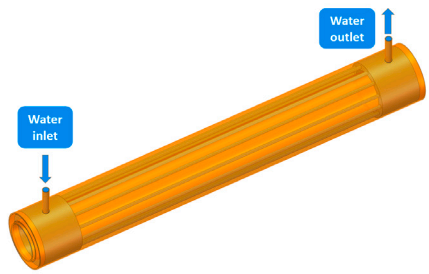
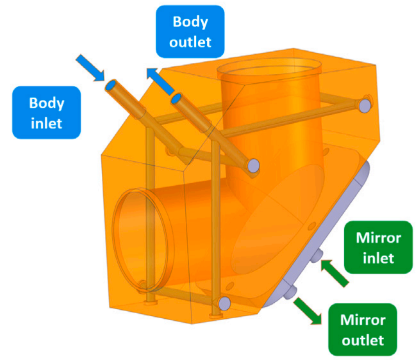


Fig. 3. First confinement ex-vessel waveguide system with a pillow-plate casing that houses the waveguides and miter bends (internal view shown in Fig. 5). Six modular units, each containing three isolation valves and diamond windows, are connected to the casing via single bolted flanges and will be protected from external loads by an additional structure not yet represented. The interfaces are sealed using a double spring-energized metal sealing solution, dimensions are given as a first preliminary indication in millimeters.



(a) Sealless waveguides with radial piping connections (lengths vary from 700 to 3000 mm).



(b) Sealless miter bends with angles between connected waveguide segments varying from 80° to 100°.

Fig. 4. Sealless transmission line components integrated within the new containment casing, eliminating the need for flanges and numerous bolts typically required for vacuum-sealed components [13]. Interfaces between these components are shown in Fig. 6.

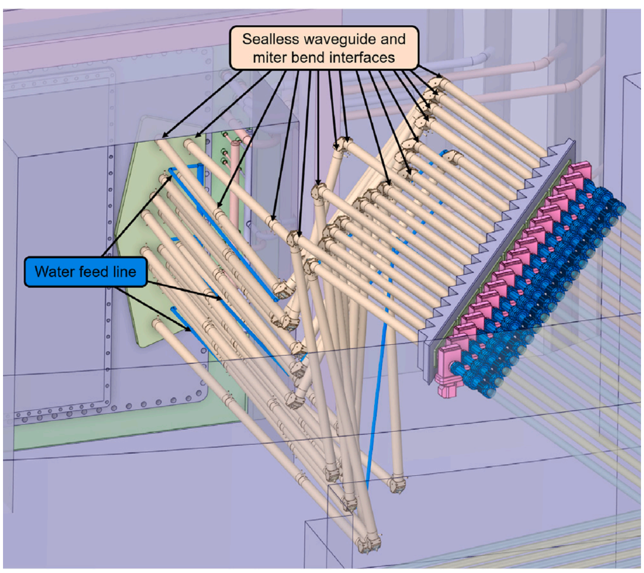


Fig. 5. Arrangement of the proposed Ex-vessel Waveguide system (EW), with the dimpled-plate casing hidden to reveal the sealless transmission lines. This design allows for the integration of a water feed lines within the interspace and enables the pre-assembly of the waveguides off-site, ensuring precise alignment during installation.

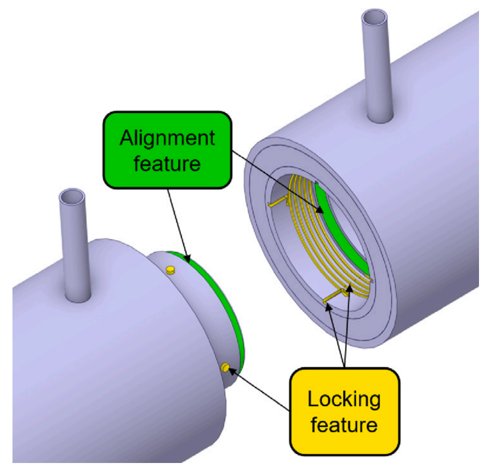


Fig. 6. Illustration of a bayonet mount interface used for quick connect/disconnect of sealless transmission lines within the vacuum casing. The spring mechanism ensures the pins remain securely locked in the slots, facilitating their integration.

the number of required monitoring lines in tight port areas, where numerous converging transmission lines, flanges, and bolts can impede accessibility. Additionally, it optimizes space, which is essential for integrating water feed lines (Fig. 5).

Interfaces between sealless EW components use bayonet mounts (Fig. 6), which offer a space-saving, quick-connect/disconnect solution with precision centering features. These twist-and-lock mechanisms ensure durable connections and strong resistance to vibrations [14]. Widely used in optical systems [15] and industrial assemblies, bayonet mounts provide the precision and mechanical integrity needed for secure, efficient assembly.

3. Implementation plan

3.1. Manufacturing process

3.1.1. Dimpled-plate casing

Dimpled-plate vessels are widely used in industrial applications, including fusion reactors like the WEST tokamak (Fig. 7), where two metal sheets are welded and pressurized to form a “pillow-shaped” surface. The proposed design introduces a novel approach: folding the casing at various angles to create a polyhedral structure (Fig. 3) before inflating the interspace, drawing inspiration from origami techniques [18].

This method, combining folding and inflation, is new to fusion systems and will require testing to validate its scalability and mechanical performance. The casing, constructed from low-cobalt stainless steel to meet nuclear safety standards, must also comply with strict dimensional and structural tolerances. The manufacturing sequence is as follows:

1. **Cutting:** Cut the metal sheets to the appropriate flat pattern geometry.
2. **Welding for water channels:** Weld the sheets to define the water channel paths, which will form upon pressurization.
3. **Spot welding for dimples:** Spot weld the sheets at designated points to create dimples upon pressurization.
4. **Folding:** Fold the assembly along predefined lines to form the casing’s shape.
5. **Edge welding:** Weld the edges to close and seal the casing.
6. **Inflation:** Pressurize the interspace to form the dimples and water channels.
7. **Heat treatment:** Apply heat treatment to relieve residual stresses and ensure structural integrity.

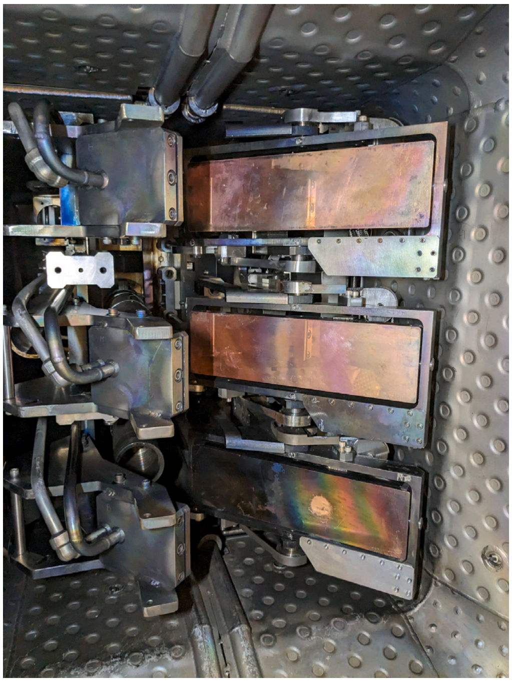


Fig. 7. Picture of the WEST EC system integrated in the dimpled-plate lining of the vessel [16,17].

3.1.2. Transmission line components

Transmission line components, including sealless waveguides and miter bends, are manufactured using precision machining techniques such as turning, milling, deep drilling, and honing to create the corrugations necessary for efficient millimeter-wave transmission.

For the FCS, CuCr1Zr[1] alloy is selected for its excellent thermal, electrical, and mechanical properties, making it ideal for high-power, high-frequency applications. The waveguides in the gallery are made from aluminum alloy, providing the flexibility required to accommodate vacuum vessel displacements. This flexibility is essential as the FCS moves in unison with the torus, as illustrated in Fig. 9, which demonstrates how the transmission lines in the gallery adjust to these movements.

Key manufacturing challenges include maintaining high precision over waveguide lengths up to 3 meters and ensuring ultra-straight alignment with consistent corrugation patterns.

3.1.3. Pre-assembly of the First Confinement System (FCS)

The pre-assembly process integrates transmission line components with the dimpled-plate casing, with a focus on precise alignment and cooling integration:

1. **Component alignment:** Transmission line components, including waveguides and miter bends, are aligned and fixed to casing flanges within sections of the dimpled-plate casing. Each component is equipped with metrology features (fiducials, targets) to correct geometric errors critical to manufacturing and assembly. Accumulated errors and misalignments in the vacuum vessel chamber will be addressed through adaptive machining corrections.
2. **Cooling line welding:** Cooling lines are welded to the transmission lines within the casing.
3. **Casing closure:** The casing is then closed and sealed to secure both the transmission lines and cooling infrastructure in the integrated structure. Inspection of the welds, testing.

The overall weight of the fully pre-assembled FCS is estimated at approximately 30 tonnes. This preliminary breakdown includes roughly 20 tonnes for the casing, 5 tonnes for the EC system, and 5 tonnes for anticipated ancillary features such as interfacing, rigidifying, piping, and shielding. Given the early stage of the DEMO design and its inherent uncertainties, this estimate carries a margin of ±5 tonnes. As discussed in Section 4, the current design faces challenges in optimizing the geometry to accommodate structural loads while ensuring efficient waveguide routing to maximize space utilization. These factors contribute to the overall uncertainty in the weight estimation. Given the size, weight, inertia, this will pose challenges for manufacturing, handling and installation.

3.2. Remote maintenance

The Remote Handling (RH) systems will handle a variety of in-situ tasks, including the precise manipulation of large, heavy assemblies as well as bolting, welding, and cutting operations. These tasks must be performed with high accuracy within the confined space of the equatorial port, using robotic systems designed to operate in high-radiation environments.

Fig. 8 outlines a proposed sequence for the RH installation procedure of the pre-assembled FCS (Fig. 3), which is designed to simplify the process and minimize the need for complex interventions within the port cell.

This proposed sequence streamlines assembly and alleviates the difficulty of managing remote maintenance systems in intricate waveguide networks. Unlike the ITER-inspired new EU-DEMO design (Fig. 1), which requires extensive bolting, cutting, and welding of 22 individual transmission lines in a confined, high-radiation environment, the alternative design proposed groups EW components into larger, remote-handling-compatible modules. While this approach sacrifices the ability to access individual transmission lines, the sophisticated routing of the waveguides makes single-line access impractical in any case.

4. Discussion

This modular, sealless design for EU-DEMO's ex-vessel waveguide system addresses critical challenges, yet further refinements are necessary. Optimizing the waveguide routing in confined port spaces remains a priority, as compact routing reduces waveguide lengths, eases maintenance, and improves stability. Algorithmic approaches for configuration optimization will be explored.

Integrating the bioshield door with the First Confinement System (FCS) requires balancing radiation shielding with the flexibility needed to accommodate torus movement. Features such as doglegs on the door and casing may reduce radiation streaming, with ongoing adjustments to ensure structural adaptability.

The FCS casing also faces structural pressures from vacuum and cooling requirements. Solutions under consideration include alternative shapes, such as various sandwich panel structures or convex structures, to distribute pressure and enhance resilience. Additional reinforcement, possibly through a skeleton structure, will improve handling compatibility. Given the limitations of pillow plate heat exchangers, including risks of warping and weld failure [12], experimental trials are planned to validate this design.

Additionally, the system must withstand seismic events, plasma disruptions, and accidental loads that could stress the casing and waveguide components. Because the casing doubles as an extension of the torus vacuum chamber, it will need to interface seamlessly with existing

[1] CuCr1Zr is the standardized designation according to EN 12163, EN 12420, and other material standards. In some engineering contexts, it is informally referred to as CuCrZr, but both terms refer to the same copper–chromium–zirconium alloy.

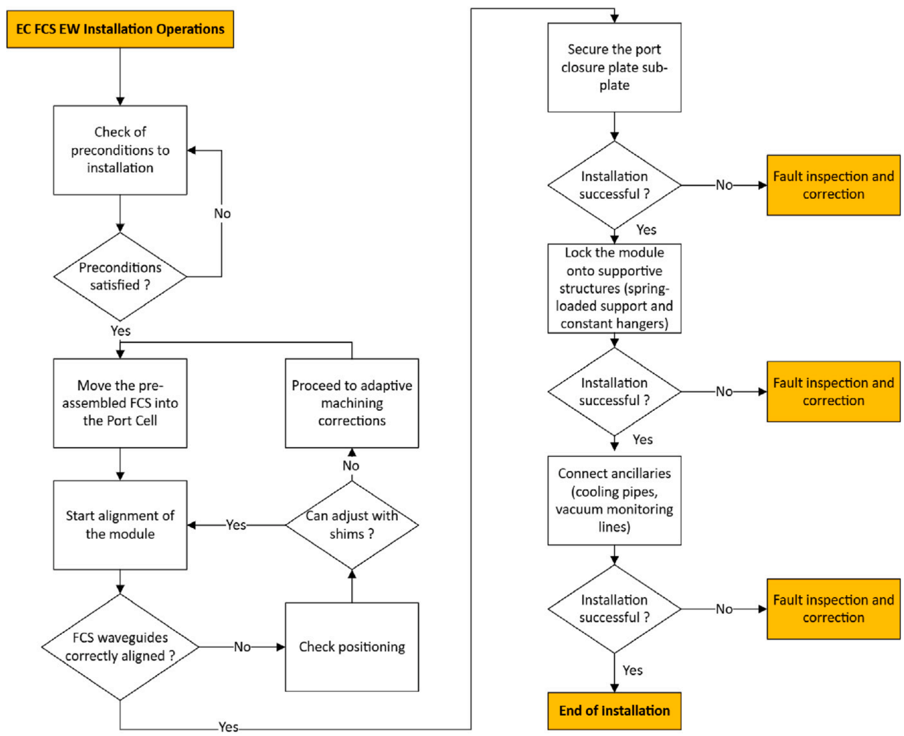


Fig. 8. Remote Handling (RH) installation of the FCS flowchart.

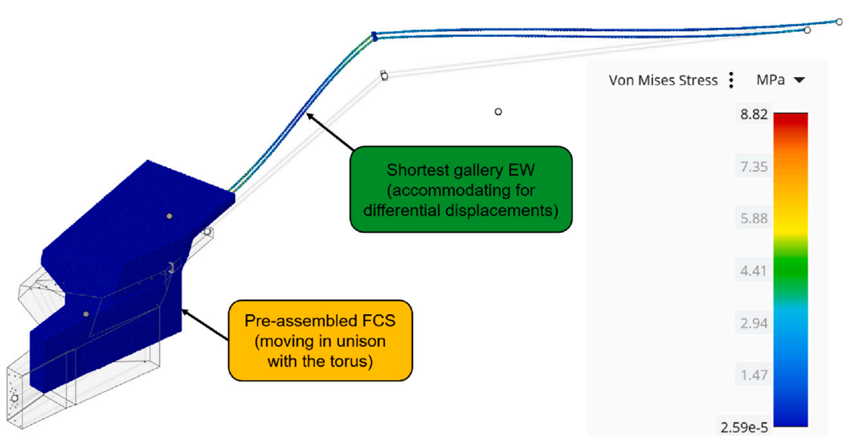


Fig. 9. Preliminary thermomechanical analysis during the baking scenario, showing the FCS moving in unison with the torus and the transmission lines in the gallery accommodating for this displacement.

vacuum infrastructure and incorporate a burst disk to safeguard operational integrity—a solution currently under investigation. To quantify these risks and identify appropriate countermeasures, we will perform comprehensive structural analyses. Depending on the results, we may introduce bellows to accommodate differential movement or additional burst disks to relieve overpressure in the event of unexpected coolant loss.

Finally, the functional aspects of mm-wave transmission — including sagging, offsets, and gaps — require further investigation to assess their impact on beam alignment and transmission efficiency. These functional issues are inherently linked to the thermo-mechanical behavior of the system; temperature variations and mechanical stresses can exacerbate structural deformations, leading to increased misalignments and stray radiation. In particular, the novel sealless couplings introduced in our design, while promising enhanced ease of assembly and maintenance, necessitate detailed characterization to ensure that their mechanical tolerances and thermal expansion do not compromise performance. A comprehensive evaluation of both the functional and thermo-mechanical aspects is essential to controlling losses and achieving a stable, reliable waveguide output.

5. Conclusion

The proposed conceptual design for the ex-vessel transmission line introduces key innovations that enhance maintainability, safety, and operational efficiency, specifically through modular configurations, sealless components, and a dimple-plated casing that serves as a collective vacuum boundary. The adoption of sealless waveguides and miter bends reduces the number of vacuum-sealed interfaces by 96%, lowering the risk of failure, simplifying maintenance, and significantly reducing the need for extensive monitoring. These improvements align with the EU-DEMO project's goals of reliability and safety, meeting current demands and anticipating future accessibility challenges.

Future work will focus on optimizing waveguide routing with algorithmic methods, assessing seismic and accidental load impacts, enhancing radiation shielding via neutronics simulations, refining the FCS casing's structural design, and conducting tests on the sealless waveguides and casing to validate their performance under operational conditions. Together, these efforts will further refine the ex-vessel transmission line, ensuring a robust, sustainable, and adaptable design for future fusion reactor needs.

CRediT authorship contribution statement

Daniel Birlan: Writing – review & editing, Writing – original draft, Methodology, Conceptualization. **Gabriele Benzoni:** Writing – review & editing. **William Brace:** Writing – review & editing. **Alessandro Bruschi:** Writing – review & editing. **Antonio Cammi:** Supervision. **René Chavan:** Writing – review & editing, Supervision, Conceptualization. **Oliver Crofts:** Writing – review & editing. **Saul Garavaglia:** Writing – review & editing. **Timothy P. Goodman:** Writing – review & editing, Supervision. **Jean-Philippe Hogge:** Writing – review & editing, Supervision. **Cinta Lucia Marraco Borderas:** Writing – review & editing. **Avelino Mas Sanchez:** Writing – review & editing. **Changyang Li:** Writing – review & editing. **Janne Lyytinen:** Writing – review & editing. **Hannu Martikainen:** Writing – review & editing. **Aditya Sinha:** Writing – review & editing. **Peter Spaeh:** Writing – review & editing. **Marc Torrance:** Writing – review & editing. **Anna Unt:** Writing – review & editing. **Chuanren Wu:** Writing – review & editing. **Huapeng Wu:** Writing – review & editing. **Anastasia Xydou:** Writing – review & editing.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) used ChatGPT and Perplexity AI in order to conduct research and improve the readability and language of the manuscript. After using this tool, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the published article.

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

The authors are unable or have chosen not to specify which data has been used.

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