TOPIC: TEC-HCD

THE DESIGN OF THE EC UPPER LAUNCHER AND EX-VESSEL WAVEGUIDE SYSTEMS FOR ITER

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Abstract. The EC Upper Launcher (UL) and Ex-vessel waveguide (EW) are integral components of the ITER Electron Cyclotron (EC) system [1], which plays a key role in achieving and maintaining the high temperatures required for nuclear fusion within the tokamak, providing plasma heating and current drive, and magnetohydrodynamics (MHD) stabilization, which are crucial for ITER's operational success. The EC system is increasingly becoming the reference mechanism for plasma heating in both present and future devices. Notably, ITER is placing significant reliance on the EC system, with the recent re-baseline proposal initially doubling the EC installed power from 24 MW to 48 MW, ultimately reaching a final configuration of up to 80 MW. The F4E contribution to the current ITER baseline configuration comprises four Upper Launchers and five sets of ex-vessel waveguides.

The UL and EW systems, currently in its Final Design phase under the frame of a Procurement Agreement between Europe and ITER Organization, have released the Final Design Documentation Package, which is here described, as input to the Final Design Gate Review that took place in July 2025. The full set of documents released is composed by: 1) a Design Description Dossier composed by a UL & EW Design Description (DD) document and supported by a set of 3D models, drawings and diagrams; 2) a Design Justification Dossier encompassing a set of end-to-end engineering analyses verifying the functionality and structural integrity of the components according to the applicable requirements, and the RAMI analysis of both systems; and 3) a Product lifecycle Dossier covering documentation for subsequent phases including manufacturing, assembly, installation, commissioning, operations, maintenance and decommissioning. Furthermore, the validation of the design is supported by currently on-going activities of prototyping and testing of the most critical components.

1. Introduction

Fusion For Energy (F4E) is the European Procurement Agency for ITER, and it is responsible for the design and manufacturing of four upper launchers and five sets of ex-vessel waveguides, for a total of more than 500 components to be delivered to the highest nuclear quality and nuclear safety standards. The design effort presented in this paper started in 2021 from the work performed in previous phases of the project, which included successful Conceptual and Preliminary Design Reviews, as well as several prototyped components (e.g. blanket shield module, waveguides, miter-bends, diamond windows) and RF tests in FALCON test stand in Lausanne. This paper focuses on detailing the main design evolution, verification analyses, qualification campaigns, and prototypes performed for the finalization of the design of the UL and EW systems.

2. System overview and main requirements

The ITER Electron Cyclotron Heating system [2] will deliver up to 80 MW of 170 GHz mm-wave heating and current drive to the plasma. Its functions include providing plasma heating and current drive, and magnetohydrodynamics (MHD) stabilization, which are crucial for ITER's operational success. The EC Upper Launchers are located in dedicated ITER VV upper ports (12, 13, 15 & 16), at level L2 of the Tokamak system. The Ex-vessel Waveguides System connects the EC launchers (four Upper Launchers and one Equatorial Launcher, see Figure 1) inside ITER Vacuum Vessel ports to the Gyrotron plant, as an extension of the Transmission Lines.

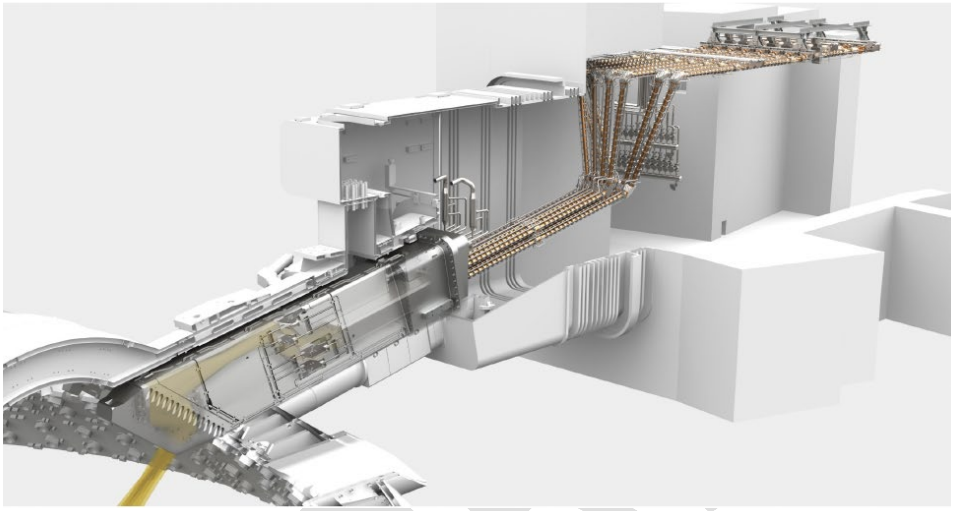

Figure 1: Integrated Upper Launcher and Ex-vessel Waveguides in their location at the Tokamak Complex

a. Upper Launcher system

The UL are located in dedicated ITER Vacuum Vessel (VV) upper ports and include the front-end quasi-optical components of the EC system (mirrors M1, M2, M3 and M4 and eight in-vessel waveguides), the Blanket Shield Module (BSM) serving as plasma first wall, the launcher body and the required ancillaries including cooling, diagnostics, cabling and feedthroughs, and He gas pipes (see Figure 2).

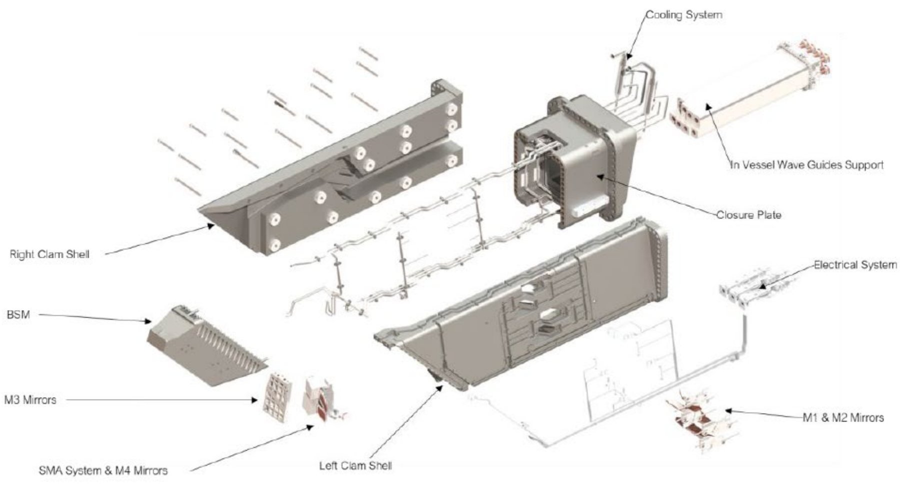

Figure 2 – Illustrative exploded view of UL

The Quasi-optical System (see Figure 3) transmits the RF power from the EW system to the plasma. It is composed of: (a) 8 in-vessel waveguides, arranged in two rows of 4 waveguides each, which are installed inside a massive steel block (the In-Vessel Waveguides Support) housing the cooling/baking circuit (by means of gun-drilled water channels) for the in-vessel waveguides; (b) a set of four mirrors (M1, M2, M3, M4), water cooled and attached to the left clamshell by means of bolted connections. The last mirrors M4, which launch the RF beams to the plasma, incorporate a Steering Mechanism Assembly (SMA) which enables the orientation of the mirror towards the desired point in the plasma.

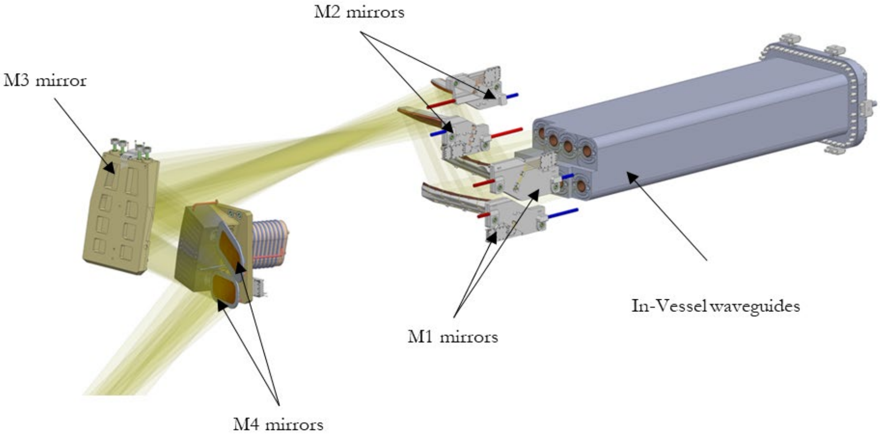

Figure 3: UL Quasi Optical System

The SMA design is based on a pressure-controlled, helium-filled chamber with a bellow working against an rring second inner constant pressurized chamber (a second internal metallic bellow is used). The linear motion is transformed into a rotational movement by means of frictionless flexure pivots. This concept ensures a frictionless mechanical transmission to avoid bearings, bushings, push rods that will reduce the lifetime of the component and would jeopardize the vacuum requirements. The SMA has four main subsystems, which are depicted in Figure 4 below. This design has been prototyped, and it is being tested to verify the functionality of the integrated system.

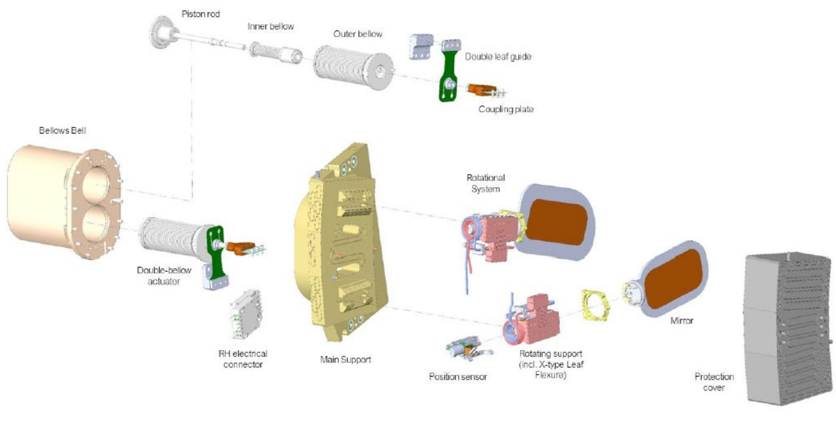

Figure 4: M4 SMA Exploded View showing main subsystems

The primary UL functions are to direct the beams to the appropriate target in the plasma [3], provide shielding and provide vacuum and primary confinement of radioactive and hazardous substances. The UL design has evolved and matured through several phases; main design evolution during the last three years has been driven by: 1) pursuing more conventional manufacturing techniques to a level affordable for standard industry -mainly for the UL Body. The UL Body has been conceived as a clamshell concept following the design developed for the Diagnostic Shielding Modules (DSM) of the ITER European Diagnostic Ports. It is now divided into two halves individually manufactured and joined together by means of transverse super-bolts. The manufacturing of the UL Body halves -right and left clamshells- also follows conventional manufacturing techniques. Both clamshells are fabricated in a robust monolithic architecture filled with interconnected milled water channels and closed with welded lids, as in the DSM halves front areas (manufacturing process already validated/qualified for ITER European Diagnostic Ports). Water is used both for shielding and cooling purposes; and (2) the simplification of the assembly process, especially for the UL Body, the in-vessel piping and electrical equipment. The assembly strategy foresees to mount all the mirrors in one of the two clamshells of the launcher body, allowing the monitoring of their final position throughout the whole process by laser tracker means. The attachment of the two clamshells once the optical system is assembled, is done by means of super-bolts.

b. Ex-vessel waveguide system

The EW are comprised of several components (see Figure 5), mainly the corrugated CuCrZr 50mm diameter waveguides (WG), mitre-bends (MB), Diamond window units (DWU) with a brazed diamond disk, and complementing Isolation Valves (IS), all of those assisted by a dedicated cooling system, support structures and instrumentation (see Figure 2). The EW system assembly relies on bolted flanges with Double-metallic-seals (DMS) with vacuum monitored interspace, and detailed support systems to allow the required flexibility while minimizing transmission losses to less than 2%. The system requirements include also Primary Confinement for Tritium and activated dust and Ultra-High Vacuum boundary. Moreover, the design has been verified against nuclear code RCC-MRx Ed. 2022 when subject to ITER operational scenario, including 1MW mm-wave loads per line from Gyrotron operation, nuclear heating from plasma, electromagnetic forces, and dynamic loads from seismic events. Additionally, the confinement requirements require double metallic seals leak-tightness while the assembly shall accommodate several millimetres of uncertainty in the position of the VV ports and other interfacing components.

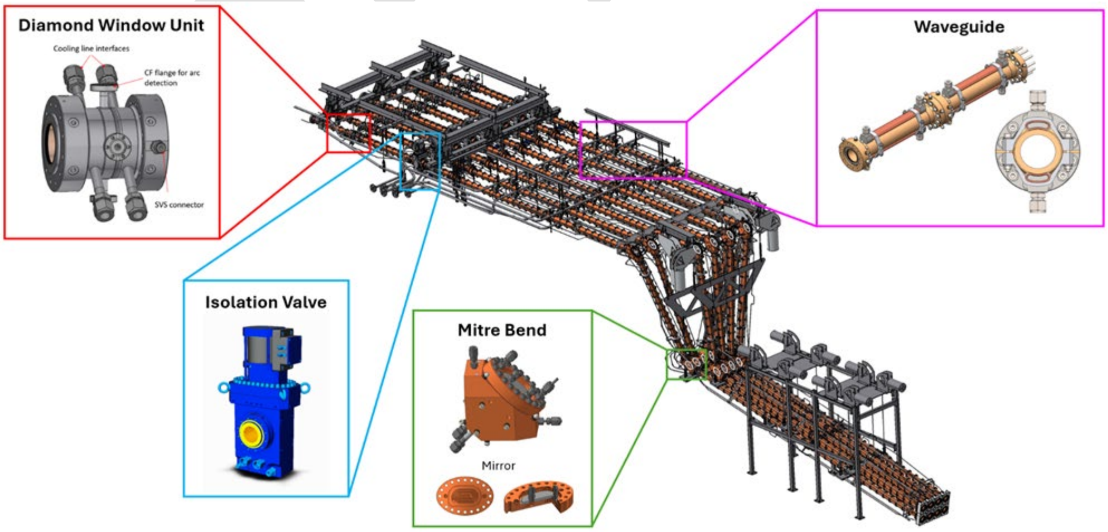

Figure 5 - Illustrative exploded view of EW for an upper port

3. Design and engineering challenges

The method used for the validation of the Upper Launcher and Ex-vessel Waveguide design has been mainly engineering analysis. An integrated engineering analysis methodology has been developed and implemented considering all the loads that the components will face in ITER and the end-to-end analysis has been run encompassing neutronics, electromagnetic, mm-wave propagation, thermal and structural calculations. Special attention has been devoted to the modelling of the propagation of stray radiation [4], [5] in the launcher, identified as one of the main risks of the project. For the modelling of stray radiation and mm-wave propagation, a thorough assessment and selection of most appropriate software has been performed and complemented with a fully integrated exhaustive benchmarking including experimental data from IPP Greifswald MISTRAL chamber and EPFL-SPC FALCON test facilities.

4. Prototyping and testing

In addition, two high power RF tests have been envisaged 1) on the Mirror 4 Steering mechanism highly sensitive to RF loads, this test has been successfully performed at MISTRAL in January 2025, it successfully evaluated the SMA structure's RF shielding capacity, the thermal behaviour of both actively and non-actively cooled components, and the effectiveness of the shielding covers in preventing RF excessive heating [6]; 2) on the launcher quasi-optical path, a test to evaluate the stray radiation load in the UL with a full-size mockup has been successfully performed at FALCON in July 2025, and the results are being post-processed [7].

These experimental outcomes are crucial for optimizing the performance and reliability of the EC Launcher within ITER's complex Tokamak environment, offering a robust foundation for future operational deployment.

5. Next steps

The effort will be put in the final verification of the design presented in this paper, including the finalization of the prototypes and tests and the preparation towards the manufacturing design phase.

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