Preconceptual Design of the Port Cell Section for the EU DEMO Equatorial EC System

Peter Spaeh, Alessandro Bruschi, Francesco Fanale, Thomas Franke, Saul Garavaglia, Dirk Strauss, and Minh-Quang Tran

Abstract—**The EU demonstration power plant (DEMO) Tokamak will be equipped with an electron cyclotron (EC) system for plasma heating and magnetohydrodynamic (MHD) control. Up to six launchers will be installed into equatorial ports with the aim to inject maximum 130-MW millimeter-wave (mm-wave) power at dedicated positions into the plasma. The mm-waves will be generated in gyrotrons placed in a distinct building at distant location. From this gyrotron hall, a combined transmission line (TL) system of quasi-optical multibeam mirrors and individual waveguides (WGs) will propagate the mm-waves into the tokamak building. That followed, an optical system, composed of miter bends, diamond windows, valves, and microwave bellows, connects the TL through the gallery and the port cell with the EC launchers. This article presents the preconceptual computer-aided design (CAD) of this latter section of the EC system. Based on its general scheme and the given WG trajectories, the model takes into account the available space in the port cell with respect to required clearance for supply systems, assembly, and maintenance. At the preconceptual state, the design includes CAD models of all relevant mm-wave components in realistic dimensions at a level of details, appropriate to demonstrate the feasibility of the concept.**

Index Terms—**Computer-aided design (CAD), demonstration power plant (DEMO), electron cyclotron resonance heating (ECRH), heating and current drive, magnetohydrodynamic (MHD) control, port plug.**

I. Introduction

FOR the EU demonstration power plant (DEMO) tokamak, electron cyclotron (EC) launching systems for plasma heating, magnetohydrodynamic (MHD) control, and thermal instability suppression are under development. Since during the preconceptual design phase no plasma scenario has been finally qualified for DEMO, the preconceptual design study of the EU DEMO equatorial EC system is carried out on the basis of the 2017 engineering baseline, the 2018 physics baseline, and the blanket separated design (BSD) approach. In Fig. 1, an overview of the EU DEMO preconceptual design with its main systems is given [1], [2].

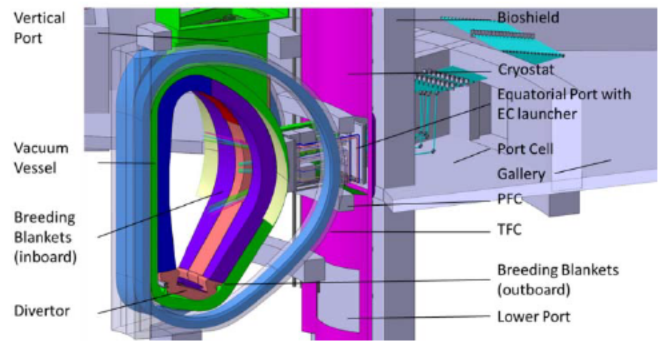

Fig. 1. Overview of the EU DEMO EC system integration.

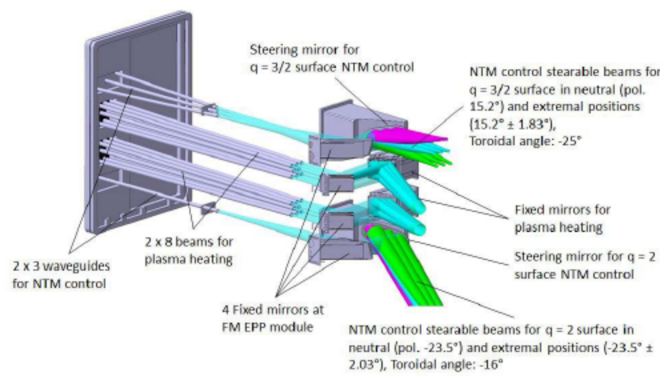

Fig. 2. Preconceptual design of the optical system of the EC launcher.

Up to six of these launching systems will be installed into equatorial ports with the aim to inject a delivered radio frequency (RF) power of maximum 130 MW at the frequencies of 170 and/or 136/204 GHz [1].

The reference design study of the EC launchers features the concept of MHD control [mainly neo-classical tearing modes (NTM)] by two midsteering antennas (MSAs) [3] with a partially quasi-optical beam layout and steerable mirrors at a recessed position behind the outboard breeding blanket (BB) segments. These antennas consist of three beamlines each and are installed into the upper and lower areas of the equatorial ports. The upper antenna targets the $q = 3/2$ surface and the lower antenna targets the $q = 2$ surface for power deposition in the plasma.

For plasma heating purposes, an open-ended waveguide (WG) concept with 2×8 beamlines and a set of two times two fixed mirrors (FMs) is designed. The plasma heating system is arranged by two bundles, staggered in poloidally symmetric

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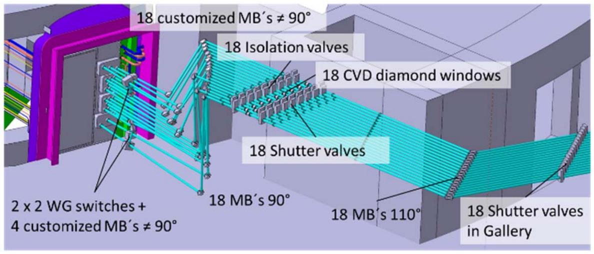

Fig. 3. Preconceptual layout of the TLs of the EC system in port cell 10.

positions with respect to the toroidal DEMO reference plane (tokamak midplane) in the center area of the port. In Fig. 2, an outline of the EC launcher optical system is given.

The millimeter-wave (mm-wave) power will be generated outside the Tokamak building in gyrotrons in a dedicated RF building. From there, it will be transmitted into the EC launching system by transmission lines (TLs), guided through the assembly hall into the gallery and afterward into the port cell of the Tokamak building.

The current reference TL configuration for the confinement system features two-frequency gyrotrons as RF sources. In a dedicated area in the assembly hall, for each EC system port, two clusters of nine beams each, coming from two space-saving multibeam TLs (MBTLs), are split into single-beam TLs and continue their paths through evacuated WGs up to the launcher [1]. In the port cell, an isolation valve and a diamond window separate the tokamak vacuum from the TL vacuum. This is also the confinement barrier to prevent any release from tritium to the outside. The computer-aided design (CAD) model of the EC port cell section comprises the TLs from the rear side of the port (i.e., the first confinement system's structural barrier) up to the safety class 2 (SIC-2) valve between the gallery and the assembly hall.

To set up the CAD model of the EC port cell section, CAD data for the Tokamak building, the TL trajectories (constraining skeletons), and the EC launcher system were prepared and integrated into a CAD assembly. Then, the required components of the TL system were created and constrained with the geometry skeletons. The microwave components of which the TL system is made of are sketched in CATIA as dummies with realistic dimensions on a preconceptual level only in order to demonstrate the feasibility of the concept, regarding space constraints, installation, and maintenance.

II. EC Port Cell Transmission Line Preconceptual Design

Hereinafter, the work carried out in 2021 on the port cell section of the equatorial EU DEMO EC system is described in detail. For a first overview, Fig. 3 shows the preconceptual EC system port cell TL CAD model at a glance.

A. Input Data

The preconceptual design of the EU DEMO EC launcher is carried out through several work packages and dedicated tasks, which are assigned to specialized European design groups. For integral systems as the EC port cell system, it is essential to define interfaces properly and to integrate design studies from different tasks coherently. To set up the CAD model of the EC port cell section, the following input data were collected from associated partners.

1) TL routing with beam trajectories.
2) Tokamak building with bioshield.
3) EC launcher integration model.

B. Port Allocation

The current EU DEMO tokamak layout features 16 ports of each type (upper, equatorial, lower ports) in different levels. They are arranged equally with an angle of 22.5° around the vertical axis of the central Tokamak coordinate system (CS). For the EC systems location, equatorial ports in the Tokamak building level L1 are defined. Two potential arrangements are sketched: one with EC, IC, and neutral beam injection (NBI) heating systems (not discussed in this article) and a second one with EC only. The latter is currently chosen to be the preferred one.

The input data CAD models of the TL trajectories are created with their radial extension aligned to the CATIA *xz* plane of the tokamak global CS (TGCS), which is, simply said, the CAD design reference plane agreed for all DEMO components.

For setting up a suitable CATIA assembly for the EC port cell system, it is necessary to arrange the input data relative to the dedicated positions. This has been made for the EC system WG trajectories in ports 10, 12, and 14, according to the reference layout. The positioning of the three WG trajectories components was achieved by angular constraining around the *z*-axis of the TGCS.

1) Port 10: −146.25°.
2) Port 12: −101.25°.
3) Port 14: −56.25°.

The 3-D components of the CAD assembly of the port cell EC system then are constrained to the dedicated port skeleton (i.e., WG trajectories).

C. Tokamak Building Integration

The relevant components of the Tokamak building are integrated into the CAD model in order to analyze interfaces and potential collisions between the building and EC system components on a preliminary basis. The EC port is located at the equatorial port level (i.e., level L1) of the tokamak building.

It must be mentioned that further integration with remote maintenance (RM) is expected to add new requirements, e.g., since the transfer cask will require further clearance (if this concept is chosen) of up to 300 mm between the outer edges of components and all building elements affected. Fig. 4 shows the EC port cell system integrated into the port 10 building structure. The floor of L2 (i.e., the ceiling of L1) is not shown in the picture.

III. Optical System Layout

For the optical system, several concepts have been investigated [1], and a preferred configuration with the splitting mirror (see green box in Fig. 5) in the assembly hall has been chosen. The schematic layout is shown in Fig. 5. It features the safety class 1 (SIC-1) isolation valve between the EC port

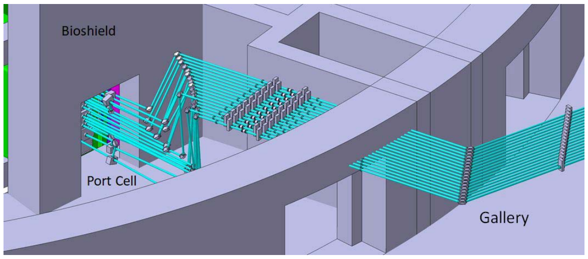

Fig. 4. Port 10 EC system building integration (floor L2 in no-show mode).

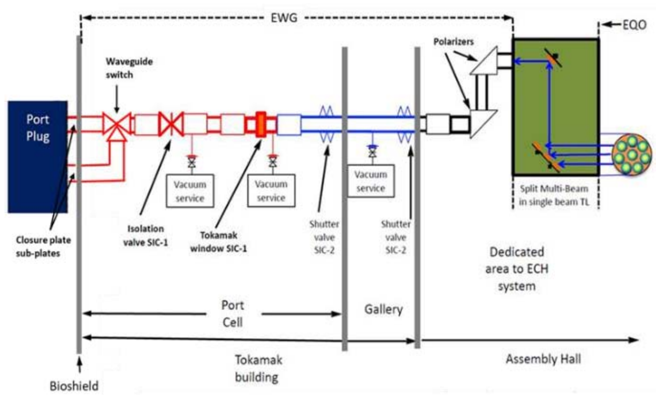

Fig. 5. TL scheme (reference configuration).

and the diamond window and a SIC-2 shutter valve between the window and the rear sided port cell wall. Another SIC-2 shutter valve is installed behind the port cell wall inside the gallery. All sections between the particular valves are equipped with vacuum service components. The valves allow the enclosure of dedicated sections of the TLs in case of failure of the window or during maintenance.

2×3 TLs are connected with the MHD control antennas and 2×8 TLs provide megawatt power to the plasma heating antennas. Since 18 TLs are installed into the port cell, four of them can switch the provided power between the MHD antennas and the plasma heating antennas by WG switches. Numbering the TLs from 1 to 18 from right to left, the TLs are connected to the antennas as follows.

1) TL 1: Upper MHD control antenna.
2) TLs 2–5, 7, and 8: Upper plasma heating antenna.
3) TLs 6 and 9: Upper MHD control antenna/upper plasma heating antenna.
4) TL 10: Lower MHD control antenna.
5) TLs 11–14, 16, and 17: Lower plasma heating antenna.
6) TLs 15 and 18: Lower MHD control antenna/lower plasma heating antenna.

IV. Optical System Dummies

In order to set up a CAD assembly of the EC port cell section, the relevant components must be known and available in CAD. The detailed design of these components (i.e., valves, WGs, diamond windows, etc.) is complex and thus not included in the preconceptual design phase. Nevertheless, a CAD model with the potential to evaluate the feasibility of the preconceptual design requires such components at least on a level, which mimics their typical dimensions. Thus, for the relevant ones, 3-D CAD dummies were created on the basis of comparable components, designed for International Thermonuclear Experimental Reactor (ITER). The WG inner diameter of the ITER components, from which the dummies are basically derived, is 50 mm. Thus, for the dimensions of potential DEMO components with an inner diameter of 63.5 mm, an increase of the dimensions by a factor of $63.5/50 = 1.27$ would be logic. However, this was not made yet, since also technical innovations might allow a more compact design of the DEMO port cell components.

A. Waveguides

The WGs for the EC system TLs are expected to be actively cooled. This can be achieved by machined cooling channels in the WG structure or alternatively by heat conduction toward rigidly attached cooling sleeves or cooling stripes attached to the outer surface of the WGs. The consequence of such a design is a moderate increase of the diameter of the WGs and also of the joint flanges. For the preconceptual CAD model of the port cell TLs, detailed cooling design was not part of the task, but the main dimensions of the WG dummies were derived from the ones, designed for ITER. The standard WG length was chosen to be 4200 mm, and the inner diameter is 63.5 mm (2.5 in). The outer diameter of the WGs is 75 mm, and the diameter of the joint flanges is 120 mm.

There are standardized WGs with a length of 500 mm as well which connect the optical components (diamond windows, valves) in the port cell, but apart from that, all other WGs are of individual length due to the nonsymmetric layouts. This is why the length of the WG was parameterized in the CATIA specification tree in order to adjust the length particularly for the required dimension. The length ranges from 220 up to 5722 mm. Especially for the longer ones ($>$4200 mm), the acceptance of WGs of such length requires further check regarding material choice, manufacturing, mechanical properties, cooling aspects, and handling.

The flanges of the WG joints are subject to an integration of double metallic seals (DMSs), alignment rims, and suitable bolt holes for stable and precise assembly to each other. An alternative joining solution is supposed to be realized with welded seals to ensure optimum tightness of the joints. However, none of the features mentioned above were designed in detail at the preconceptual level of the EC system.

B. Miter Bends

The trajectories of the TLs in the port cell and the gallery are sharply bent several times. For the preconceptual design, the technical implementation of these sharp bents is considered to be realized by miter bends. Such miter bends are used in the EC TLs in ITER, and they are designed by Swiss Plasma Centre (SPC) [4] for the ITER port cell section and by the US ITER Project Office (USIPO) for the gallery and assembly hall sections. Based on the main dimensions of the SPC design, miter bends are modeled for the EU DEMO EC system as preconceptual dummies (see Fig. 6, left side).

The miter bends have a typical dimension of ca. 200×200 mm^2 along the direction of the trajectories and a width of ca. 140 mm. The flanges for WG-attachment have a diameter of 120 mm. The angle between the WG channels is 110° for the set of miter bends in the gallery (in between the shutter valves) and is 90° for the set of miter bends

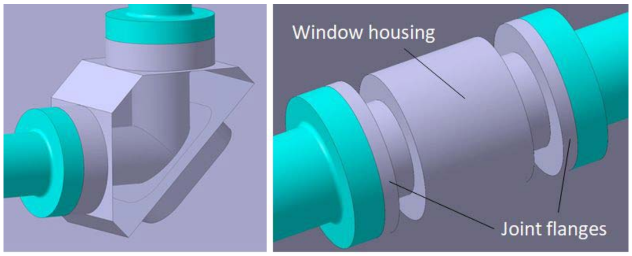

Fig. 6. Dummy CAD models of TL miter bends (left) and CVD diamond window (right).

connecting the quasi-vertical section of WGs and the WGs heading toward the closure plate. For the remaining miter bends, the angle between the WG channels is individual. It is currently between 86° and 99° and can be adjusted in the CAD model by changing the angular parameter in the driving geometry. No cooling channels, joints, or connectors is included in the dummy models, since so far they serve as placeholders in the TL layout only.

C. Windows

mm-waves must be injected into the Tokamak vacuum chamber with a minimum loss of power, which is why a dielectric component shall separate mechanically the WGs in the port cell from the ones in the evacuated torus, where the fusion reaction is taking place. Diamond offers optimum dielectric and thermal characteristics, which is why an artificial variant of diamond [created by chemical vapor deposition (CVD)] is used as a confinement barrier, providing excellent properties for low-loss transmission of electromagnetic waves.

KIT has designed the CVD diamond windows for ITER with an internal WG passage of 50 mm diameter, operating at a frequency of the mm-waves of 170 GHz at a maximum power of 1.3 MW [5]. For DEMO, two types of CVD diamond windows are considered. First, the fixed frequency ITER-like windows with the diamond disk installed perpendicular to the EC waves with a slightly larger inner diameter of 63.5 mm. Second, the so-called Brewster-angle broadband windows which are needed for the frequency step-tunable EC system. For the latter, a much larger disk diameter is required to achieve the 67.2° Brewster angle, creating an elliptical CVD diamond barrier, which is necessary to allow broadband transmission of frequencies around 170 GHz as foreseen in the system variant, in which frequency steering is used for NTM stabilization using step-tunable gyrotrons [6]. At the present stage of the design, no final decision on the type of window that will be used for the DEMO EC system has been made. Thus, for the setup of the EC system port cell model, a dummy of an ITER-like CVD diamond window has been created because no conceptual design of a Brewster window is available so far. This dummy allows the illustration of the concept and the evaluation of space constraints regarding installation and maintenance of the window independently of its type, since both variants of diamond windows are expected to be related in diameter and the different lengths are not an issue for the integration of the window into the TL.

The dummy model of the window has a length of 160 mm, a diameter of 115 mm for the window housing, and of 120 mm for the joint flanges. The model is shown at the right side of Fig. 6.

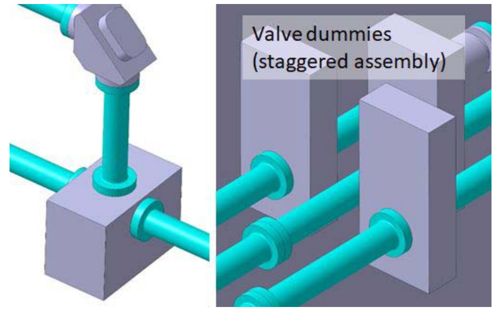

Fig. 7. Dummy CAD models of WG switch (left) and shutter/isolation valves (right).

D. Waveguide Switches

The mm-wave power for NTM-control as well as for plasma heating by EC is generated in gyrotrons in the RF building and then transmitted through 18 TLs per port. Twelve TLs are used for plasma heating and two TLs serve for MHD control exclusively. The remaining four TLs are equipped with WG switches, which are installed into the straight WG sections nearest to the closure plate. These switches allow to apply the beam power either to plasma heating WGs or toward MHD control WGs.

Currently, no EU DEMO WG switches is available as CAD models; thus, the concept of these WG switches is derived from the ITER TL switches [7], designed by ITER-US for switching EC power between the upper and the equatorial launchers in ITER.

Based on this type of WG switch, corresponding dummies for the DEMO EC system port cell layout were modeled in CATIA. The WG diameter is chosen to 63.5 mm and the outer dimensions are $350 \times 250 \times 200$ mm^3. Apart from the WG passages, no internals is designed. An illustration of the WG switch dummy is given on the left side in Fig. 7.

E. Isolation and Shutter Valves

The schematic optical system layout indicates three valves in the EC TL, of which one is a shutter valve of SIC-1 and two more are isolation valves with SIC-2. They can provide confinement barriers in case of failure of a component (e.g., an unlikely crack of a diamond window and resulting leakages) or they can separate the TL sections for the maintenance of the system.

Based on the preliminary design of the ITER EC shutter valves [8], CAD dummies were created for the model of the DEMO EC port cell TLs. The typical dimension of the ITER valve is $467 \times 230 \times 150$ mm^3. The dummy model has typical dimensions of $470 \times 230 \times 100$ mm^3. The lower radial extension was chosen since the flange joints were not modeled for the DEMO valve dummy, as the radial extension of the valve is uncritical for feasibility checks. The dummies are used for both SIC-1 and SIC-2 valves in the port cell system assembly (see Fig. 7, right)

F. Waveguide Feedthroughs

In total, 2×3 WGs for NTM—control and 2×8 WGs for plasma heating have to be guided through the closure plate of each EU DEMO EC equatorial launcher. The feedthroughs

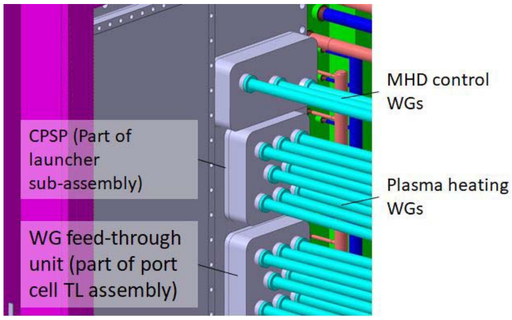

Fig. 8. CPSP/WG-feedthrough dummy CAD models.

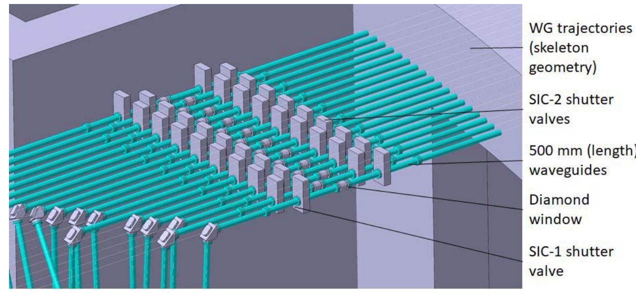

Fig. 9. Arrangement of SIC-1 isolation valves, diamond windows, and SIC-2 shutter valves in port 10.

must be capable to align the optical systems on both sides, in-vessel and ex-vessel, properly and they must guarantee safe integrity of the first containment barrier. Moreover, they must allow effective and quick disassembly for maintenance tasks. The preconceptual design of the EU DEMO EC launcher features the so-called closure plate subplates (CPSPs) as feedthroughs for the in-vessel side, to which dedicated bunches of three (MHD control) or eight (plasma heating) WGs, respectively, are connected.

Since it is not yet defined, whether the CPSP's have to contribute to thermal insulation between the in-vessel and the ex-vessel section of the EC system, additional WG feedthrough dummies were sketched with a thickness of 200 mm, being part of the ex-vessel system and allowing the integration of cooling channels and fastening and alignment elements. A reasonable change of the thickness of the feedthroughs in the future is seen as uncritical in terms of the functionality of the system. Fig. 8 shows the CPSP/WG-feedthrough dummies in position with associated WGs attached.

V. Port Cell TL CAD Model

The port cell CAD model of the TLs was constructed in its entirety for port 10, since also the EC launcher CAD assembly is positioned at this port.

An essential design requirement is the required clearance between the TLs, especially at locations, where mm-wave components other than WGs are located. For the trajectories, the clearances in critical areas are summarized in the following.

1) Minimum clearance next to closure plate for the installation of WG switches: about 200 mm.
2) Horizontal clearance for SIC-1 valve, diamond windows, and SIC-2-port cell valve: about 196 mm.
3) Horizontal clearance for SIC-2 valve in the gallery: about 170 mm.
4) Vertical clearance between the trajectories and L1 ceiling: 250 mm.

The section with the SIC-1 isolation valve, the diamond window, and the port cell SIC-2 shutter valve was positioned close to the port cell wall at the elevated section of the trajectories in order to allow compact integration into a mounting frame, which can be positioned underneath the ceiling of L1. Such a mounting frame (not contained in the model) has the advantage of deviating forces and moments coming from the WGs from sensitive components like valves and diamond windows. As a starting value, the valves and the windows are arranged with

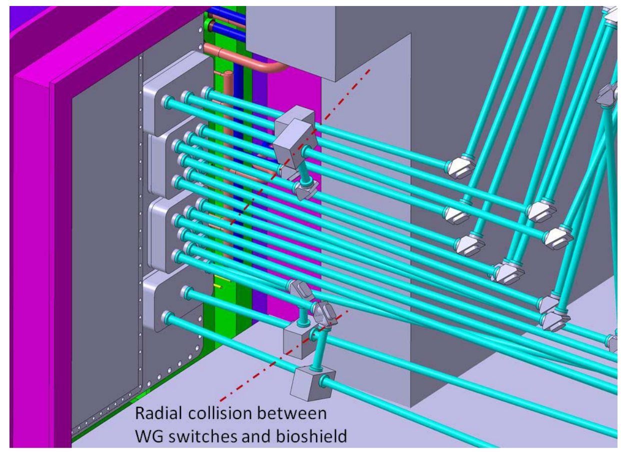

Fig. 10. Radial collisions of WG switches and bioshield.

WGs of 500 mm length in between each other. The position of this section is displayed in Fig. 9.

To inject the mm-wave power either into the MHD—control system or into the plasma heating system, WG switches are installed into the section of the TL, which is next to the closure plate. The WG switch dummies were constrained in the CAD assembly related to the beam trajectories and their intersection points.

The shutter valves in the gallery were installed in the section, where the trajectories are approximately in parallel with the port cell rear wall. They are connected with the miter bends by standard WGs with a length of 4200 mm. This choice is made randomly and can be easily adapted to any purpose (e.g., maintenance needs).

The TLs break through the rear wall of the port cell (see Fig. 9). No detailed design of this penetration has been made so far. It is expected that either an integral WG element will be mounted into the wall with joint flanges on both sides to connect with the TL WGs or an opening will be designed, which allows convenient installation and maintenance for the TLs. Operational isolation requirements of the port cell, mm-wave losses, and installation and maintenance considerations will be the main drivers of this design decision.

As a first analysis of the EC port cell TL integration, the subsequent observations can be stated.

1) There is a potential clash between the WG switches and the bioshield due to similar radial position in the port cell (see Fig. 10). Thus, further investigation on the concept

of the bioshield door and/or the radial position of the WGs is required.

2) The distance between the WG trajectories at the position of the port cell valves and the diamond window is currently 196 mm. This does not cause clashes between any components (at least as long as valves are not at the same radial position); however, for convenient installation and maintenance, an increase of the horizontal distance (which is 300 mm in ITER for a similar installation) is recommended.
3) The isolation and shutter valves in their current position and with current dummy dimensions have collisions with the ceiling of L1 of 85 mm. A potential solution might be an installation of the valves in an upside-down position.
4) The WG trajectories in the gallery have a horizontal distance of 170 mm. This clearance is rather small and might create issues with installation and maintenance of the SIC-2 shutter valves and the miter bends as well. However, an increase of the distance between the trajectories by 250–300 mm would be possible only with the modification of the gallery structural elements or working on two-levels WG assemblies.

VI. Maintenance Considerations

Even at the early stage of a preconceptual design of EU DEMO components, it is essential to take into account the maintenance considerations. For the EC port cell section, first maintenance considerations have been made with the setup of the CAD model.

Approaching the transfer cask for port plug maintenance toward the closure plate requires a substantial clearance. A first engineering guess assumes this clearance to be 300 mm toward all sides. For the TLs in port 10, this preliminary requirement is fulfilled; however, the transfer cask will not pass the valves in the port cell; in case, their collision with the ceiling would be resolved by turning them upside-down.

The maintenance concept for the EC port plug describes removal of the steering mirror (SM) equatorial port plug (EPP) [9] module without dismantling the ex-vessel WGs/TL assembly. This procedure, performed by a standard cask, being able to take components with a cross section of the maximum extent (e.g., the closure plate) would not pass the section, where the ex-vessel WGs are attached to the WG feedthroughs. For this concept, either a "half-width" transfer cask must be available or the standard transfer cask must be able to approach the closure plate in a position with an offset to the left (looking toward the plasma).

Removal of the FM EPP module [9] requires removal of the front section of the TLs, nearest to the closure plate (i.e., the WGs, connected with the WG switches, the first set of miter bends and the vertical WGs, heading toward the ceiling of L1, see Fig. 11). In order to minimize human access, it is expected that the whole assembly of that section will be removed as a unit.

Repair/maintenance of TL components right underneath the ceiling is expected to be uncritical, if nuclear safety regulations are met. The shutter valves allow the break of the vacuum in particular sections, and the space situation is relaxed to allow either human access or to approach dedicated remote handling tools. Repair/maintenance of TL components in the gallery seems to be uncritical at this early stage.

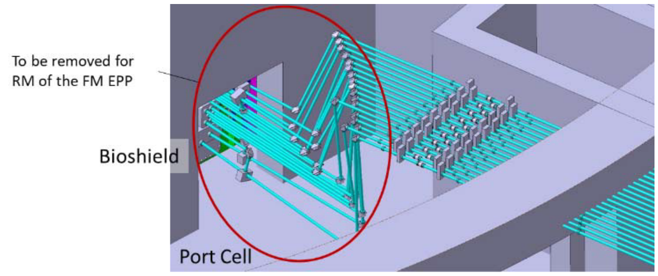

Fig. 11. Components to be removed for FM EPP RM.

VII. Conclusion

A CAD model of the EC port cell section has been set up. It features relevant elements of the Tokamak building, the EC equatorial launcher assembly, a set of geometrical skeletons which control the assembly of the system, and the EC port cell system itself. The 3-D components of the EC port cell section were designed as dummies with realistic dimensions on a preconceptual level. The EC TL section was modeled for equatorial port 10 and serves to proof the feasibility of the concept in terms of space allocation, clearance between the components, and RM capability.

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Views and opinions expressed are, however, those of the authors 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.

References

[1] M. Q. Tran *et al.*, "Status and future development of heating and current drive for the EU DEMO," *Fusion Eng. Des.*, vol. 180, Jul. 2022, Art. no. 113159.

[2] C. Bachmann *et al.*, "Containment structures and port configurations," *Fusion Eng. Des.*, vol. 174, Jan. 2022, Art. no. 112966, doi: 10.1016/j.fusengdes.2021.112966.

[3] T. Franke *et al.*, "Integration concept of an electron cyclotron system in DEMO," *Fusion Eng. Des.*, vol. 168, Jul. 2021, Art. no. 112653, doi: 10.1016/j.fusengdes.2021.112653.

[4] P. S. Silva *et al.*, "Thermal mechanical analyses of the mm-wave miter bend for the ITER electron cyclotron upper launcher first confinement system," *Fusion Eng. Des.*, vol. 136, pp. 650–654, Nov. 2018, doi: 10.1016/j.fusengdes.2018.03.047.

[5] G. Aiello *et al.*, "Design evolution of the diamond window unit for the ITER EC H&CD upper launcher," *Fusion Eng. Des.*, vol. 146, pp. 392–397, Sep. 2019, doi: 10.1016/j.fusengdes.2018.12.075.

[6] C. Wu *et al.*, "Basic design considerations for a frequency step-tunable electron cyclotron wave system to suppress NTMs in DEMO," *Fusion Eng. Des.*, vol. 173, Dec. 2021, Art. no. 112931.

[7] D. L. Youchison, A. M. Melin, A. Lumsdaine, C. R. Schaich, and G. R. Hanson, "ITER ECH switch design and analysis," *Fusion Sci. Technol.*, vol. 72, pp. 1–7, Jul. 2017, doi: 10.1080/15361055.2017.1333855.

[8] A. M. Sanchez *et al.*, "Mechanical analyses of the ITER electron cyclotron upper launcher first confinement system," *Fusion Eng. Des.*, vol 123, pp. 458–462, Nov. 2017, doi: 10.1016/j.fusengdes.2017.02.105.

[9] P. Spaeh *et al.*, "Structural pre-conceptual design studies for an EU DEMO equatorial EC port plug and its port integration," *Fusion Eng. Des.*, vol. 161, Dec. 2020, Art. no. 111885, doi: 10.1016/j.fusengdes.2020.111885.