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Development of the remote handling connector for ITER divertor diagnostic system

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ABSTRACT

Diagnostics is a vital system for ITER to collect information during operation. Mineral insulated cables route the electrical and optical diagnostics sensor signals from the divertor area to the diagnostic hall. The diagnostic divertor cassettes are replaced during maintenance, which raises the requirement for a connector between divertor cassette and in-vessel wall. Since it needs to be handled remotely during the installation of the 16 diagnostic divertor cassettes, it is called Remote Handling Connector. Its operating space is limited and its environmental conditions are ultra-high vacuum, baking temperature 350 °C, irradiation and challenging electromagnetic forces. The preliminary design of the Remote Handling Connector is based on the conceptual design of Outboard and Inboard Configurations and is highly impacted by finding an appropriate balance between the external and internal space limitations and system requirements. The design of the system has been an iterative process including several conceptual and mechanical design phases, thermal, magnetic and structural load analysis, risk analysis, and remote handling assessment. Mock-ups were manufactured and tested at Divertor Test Platform 2 and Remote Handling Connector Platform at VTT Tampere Finland. The developed system was evaluated at a preliminary design review meeting organized at the end of 2019. The preliminary design phase provides a baseline for the final design of the Remote Handling Connector system.

1. Introduction

The Remote Handling Connector (RHC) is an in-vessel system for ITER. It includes components to provide means and equipment required to transmit diagnostic signals from the 16 Diagnostic cassettes as part of the integrated electrical services up to the in port connectors at vacuum boundary (Fig. 1). The design descriptions of the RHC mentioned in this publication concentrate on the Outboard Configuration (OC) for standard and port cassettes and the Inboard Configuration (IC) for central cassettes. There are four sub-configurations for the OC, but for the sake of clarity, they are not discussed in this publication. The Detail Model designs for IC and OC are based on the divertor cassettes #26 and #40. Description of the divertor design and remote handling is described in [1] and [2].

Design for OC consists of Vessel Socket (VS), Bridging Link (BL) and Cassette Socket (CS), and the design for IC consists of VS and CS:

- VS is a permanently mounted socket on the vacuum vessel wall, from which a loom of Mineral Insulated Cables (MIC) exits to the in port connection boxes in the marshalling area
- CS is a cassette mounted plug socket, from which a loom of MIC connect to cassette mounted diagnostics.
- BL is a remote operated connecting component between the VS and CS.

These subsystems include components for routing the signals including MIC and terminations, flexible cabling, pins and inserts. Additionally there are frame structures, cooling and Remote Handling (RH) components and interfaces.

2. Design basis

Design of the RHC system is based on the Technical specification of the Preliminary Design Review (PDR) project, architecture defined in RH Connector System Level Design, defined requirements for RH connector in Annex B [3], applicable and reference input documents,

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historical work done on the topic, dialogue between individuals, and the shared vision established during the project. Design of systems for fusion reactors has the tendency to focus on certain established baselines due to the cost of studying design alternatives. Design changes are challenging to evaluate due to the limited data available on the alternatives [4]. Earlier design work on the system [5] has impacted the baseline of the preliminary design of the RHC. Design of the system merges the development of technologies related to remote handling, diagnostics, divertor, cooling and vacuum vessel. The design considerations include limited available space, compatibility with remote deployment, load cases, sensor signals, vacuum, irradiation and temperature conditions.

3. Limitations and configurations

Design of RHC is limited by the available space in the RHC locations. The RHC design inherits limitations from the vacuum vessel, divertor cassettes, cooling system, diagnostic MIC looms and the remote handling system. OC and IC have differing space limitations, as they are located on separate ends of the divertor cassettes pictured in Fig. 2.

The locations of the RHC configurations in the tokamak are presented in Fig. 3. There are minor differences in available space among the locations surrounding the RHC configurations. A global space envelope describing the space limitations for all RHC OC configurations was created to define common design and remote handling possibilities.

4. RHC design description

From 16 diagnostic cassettes 13 will be located in outboard and three in inboard. Developed design for OC is based on the Bridging Link approach where the cassette sensor signals are routed to the VS via a remote handled BL. Because of different space limitations, IC for the central cassettes utilizes the movement of the cassette and requires only VS and CS. Concepts are presented in Fig. 4.

The architecture of the main sub-assemblies for OC and IC are pictured in Fig. 5. The design for VS, CS and BL correspond to those introduced in Section 1.

RHC design is verified by testing. The OC has been tested in a Remote Handling Connector Platform (RHCP) presented in Fig. 6. The test platform around the prototype is built to the dimensions of the ITER Vacuum Vessel to reflect the narrow space available for RH operations.

The test platform is built specifically for the RHC remote operations. The test platform includes the divertor cassette mock-up, which has the necessary degrees of freedom to include the cassette motions to the RH testing. Similarly, IC is tested in a Divertor Test Platform 2 (DTP2), presented in Fig. 7, which is a suitable test platform for a central cassette.

The remote handling sequence for the outboard concept is such that the BL is first installed to the VS, then the divertor cassette is installed into position and after this the CS is connected to the BL. The IC connection sequence will not need any separate remote handling operations as it will be connected by the Cassette movement automatically.

The sequence of engaging the connectors is presented in detail in Fig. 8. BL and VS connection sequence is pictured from the point of no contact up to the connection being fixed into position. Similar principles are used also for the connection between CS and VS. The assemblies and components involved in the connection are described in the following sections.

At the time of writing, the specifications on tolerances are an issue that is still under development due to large amount of variables and uncertainties. An estimate of ±10.5 mm in radial, vertical and toroidal directions was made for the compliance and capture-range needed for the RHC system. This value is based on manufacturing and assembly tolerances, divertor rail positioning accuracy and displacements during operation.

4.1. *Outboard configuration - bridging link*

The RHC BL geometry is designed to accommodate both the external and internal space limitations and requirements. The external geometry is such that it fits in the allocated space at the same time taking into account the remote handling trajectory and the needed clearances during installation of the BL. At the same time the internal space requirement for the cables and clamps inside the link is considered. The BL external and internal components are presented in Fig. 9.

The Vacuum Vessel side of the BL and the VS is angled to reduce the internal cabling length at the same time maximizing the space available for cable routing. Manufacturability, minimum cable bending radiuses and remote handling operations affect the possible shape of the link. The space under the triangular support is extremely limited by the Vacuum Vessel, the divertor cassettes and the divertor cassette pipe tools and additional systems in the same area. The shape of the BL is derived from taking into account these limiting factors and the available space envelope.

The internal components needed for the divertor cassette sensor signal routing includes a high number of cables and terminations, electrical pins, inserts and cable clamps. Components needed for the RH operations include the RH interface attached to the BL frame, dowel pins and the fixation bolts and threads on the frame as indicated in the

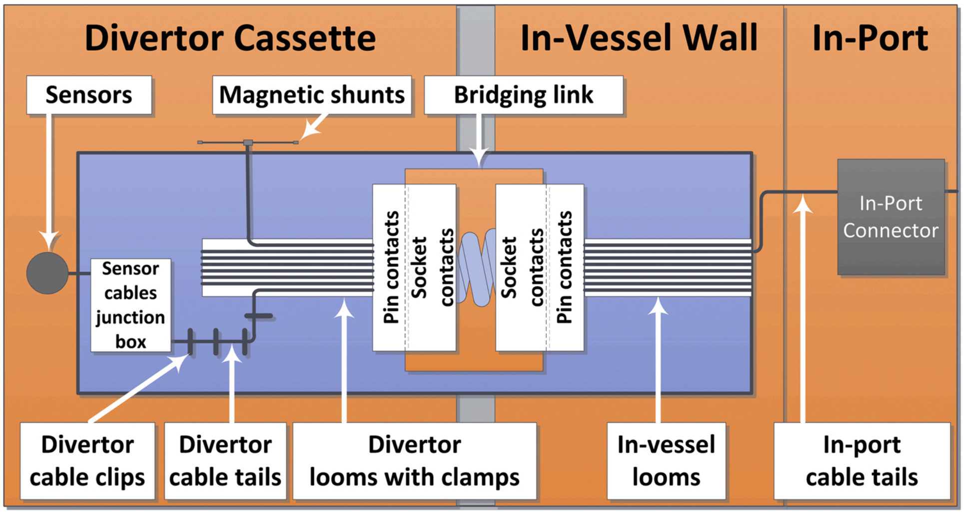

Fig. 1. Scope of the design of the RHC.

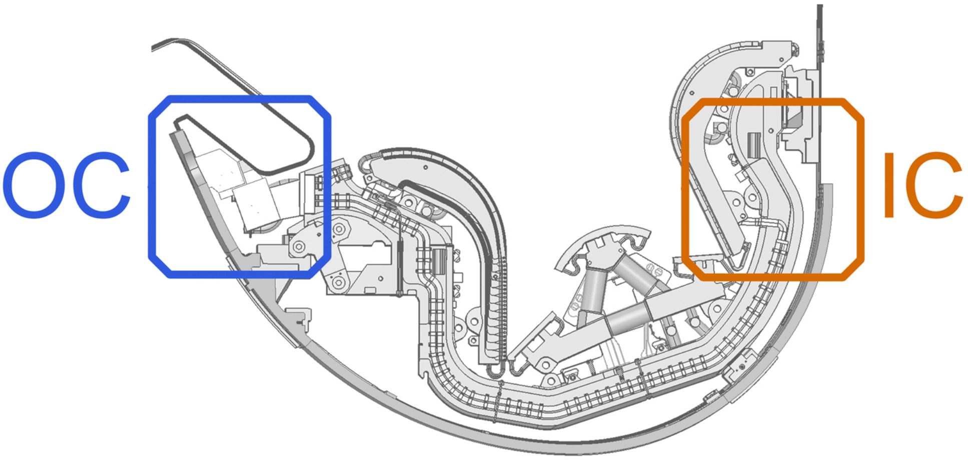

Fig. 2. Divertor cassette side view and OC location (blue) and IC location (orange).

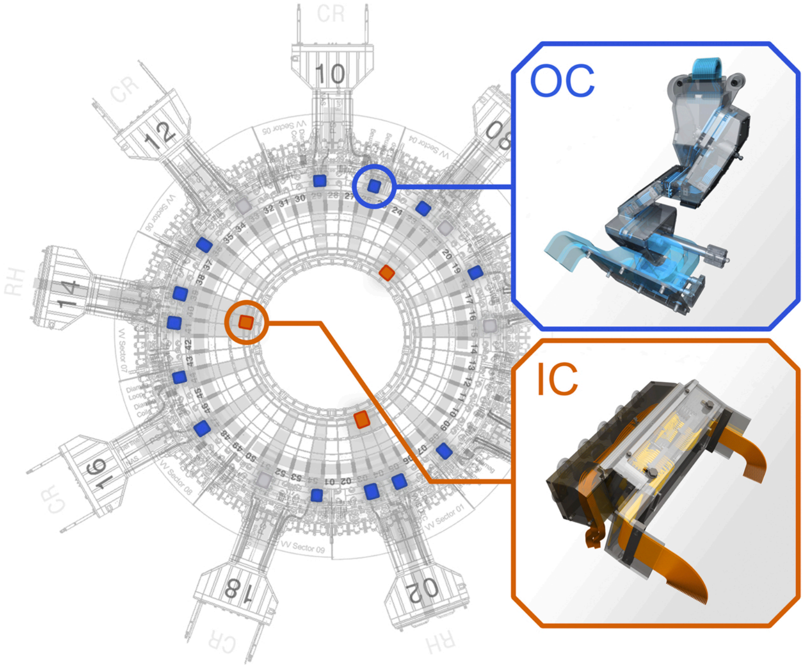

Fig. 3. RHC Configurations and locations in ITER tokamak.

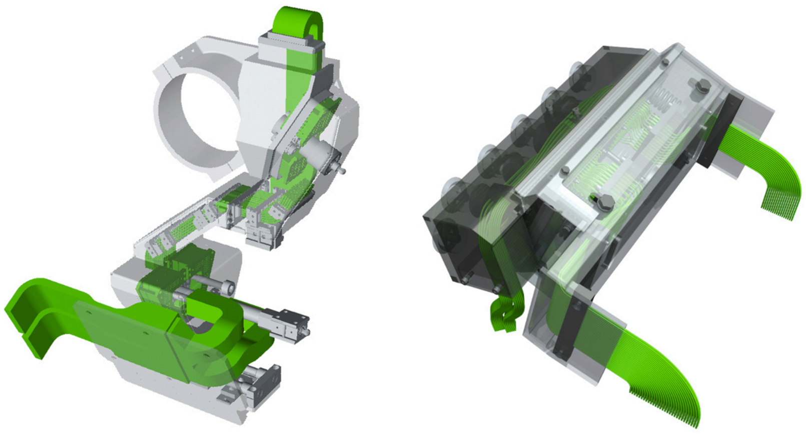

Fig. 4. Design for OC (left) and IC (right).

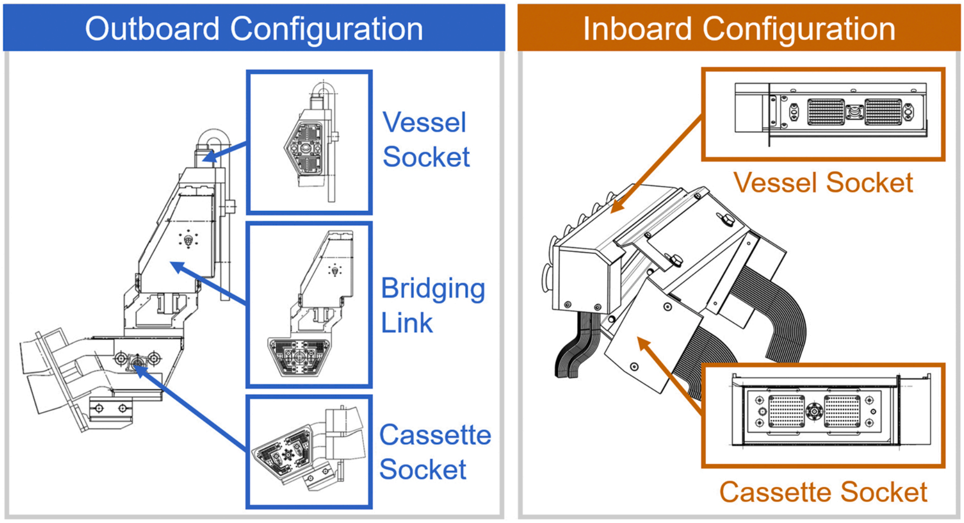

Fig. 5. Architecture for Outboard and Inboard Configuration.

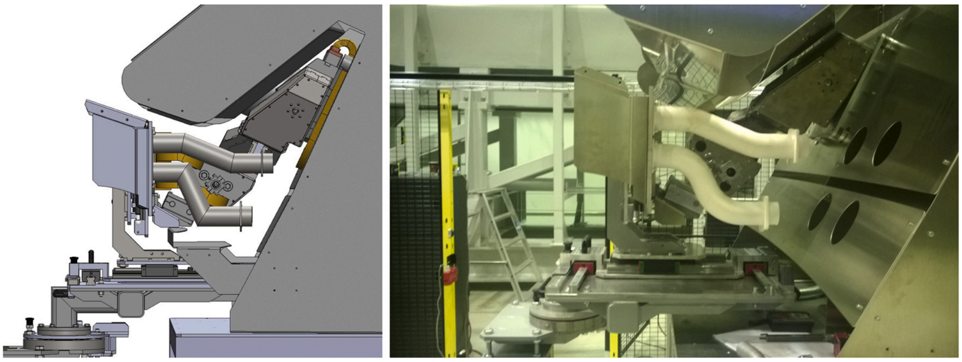

Fig. 6. Remote Handling Connector Platform (RHCP).

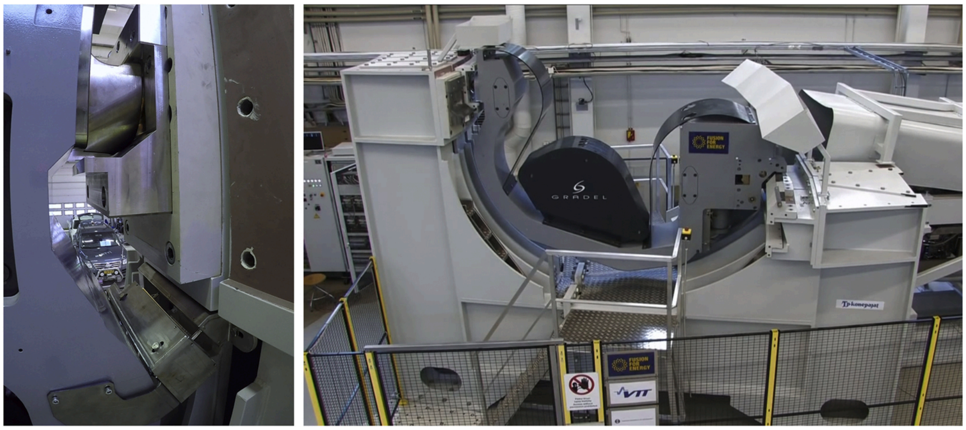

Fig. 7. Divertor Test Platform 2 (DTP2).

Fig. 10.

The BL frame consists of two welded frame structures and an electrically isolating plate between these structures as presented in Fig. 10. This insulation plate, made of ceramic material is added to the design to reduce the effect of the electromagnetic loads inside the Vacuum Vessel.

The EM forces during disruption events will be too high to the BL without the insulation of the BL body. Thus the EM forces and moments of the cables and the structural sheet structure of the BL could be minimized. Prototype of the BL can be seen in Fig. 11.

During the RH installation of the BL to the VS the manipulator is first directing the bridging link into position. Next, the manipulator releases the grip on the BL gripping interface to fetch a bolting tool to engage the fixation to the BL. When the grip on the BL is released the bridging link must stay in pre-locked position related to the VS.

4.2. Outboard configuration - vacuum socket

The VS is part of the RHC System, which is located inside the ITER

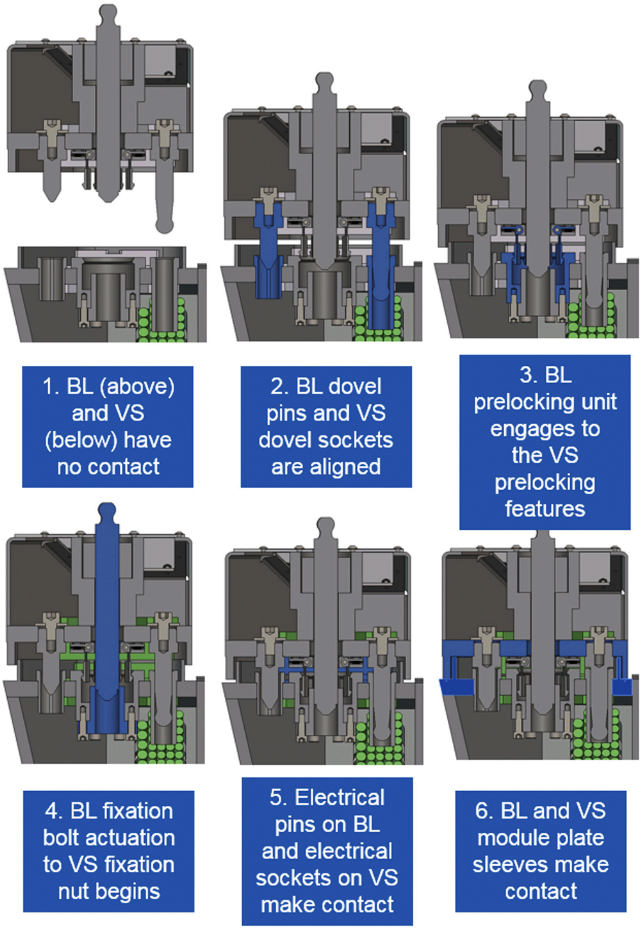

Fig. 8. Connection sequence.

reactor for the entire lifetime of the reactor. The VS is located under the triangular support of the Vacuum Vessel. Current option of the fixation is a design where the VS is supported by a fixing plate installed on the Vacuum Vessel wall with bosses and fixing collar on the Blanket cooling pipe, as presented in Fig. 12.

The BL is fixed to the VS by using the fixation bolt and two dowel pins. The VS has corresponding dowel pin sockets visible for positioning the BL during installation. The triangular support of the Vacuum Vessel and the Vacuum Vessel weld limits both the weld location of the bosses and the accessibility of the welding tools. The boss diameter was 30 mm according to the maximum accepted boss size for the Vacuum Vessel wall. Length of these bosses will be approximately 20 mm. The long and wide collar of the fixing plate with the boss will create sufficient cooling surface for the VS. The Vessel wall and the Blanket cooling pipe give excellent cooling effect with its massive profile. When installed on the Vacuum Vessel wall, the thermal conductivity is relatively good, because the wall is thick steel and the heat transferring effect is good through the surface bosses to the wall of the VV.

A prototype presented in Fig. 13 was built to test the RH operations. The prototype consists of the module plate of the VS including electrical pins and inserts, dowel sockets for guiding the BL during installation, pre-locking features and central thread for fixation. Prototype is missing the collar structure, which was not necessary for testing the mechanical capabilities of the OC.

4.3. *Outboard configuration - cassette socket*

Components mounted on the Divertor Cassette, including the CS are required to survive for the life of the Divertor Cassette. The Divertor Cassette movement during installations, removals and operations need compliance ability from the RHC. CS in Fig. 14 includes this compliance from OC point of view.

CS is located on a linear guide structure that captures the CS movement in toroidal direction. CS can move 110 mm on this toroidal guide, which enables CS to connect to the BL and to be out of the way of BL while cassette is being installed to its location. Linear guide enables clearance for the connector. CS is connected to the cassette looms through flexible cables that are covered within flexible shielding. Flexible cables and MIC within cassette looms are conjoined in termination module. A prototype of this termination module can be seen in Fig. 15. Restraining the movement is important if Electro Magnetic (EM) forces start to shake the BL. Therefore, CS is not allowed to be in an unrestricted floating state when connected to the BL.

CS is connected to the BL with a 22 mm central fixing bolt. This trapezoidal threaded bolt connects to a screw at the end of the BL that starts to push the CS towards the BL. This fastens the connection between pins and sockets. When disconnecting CS from BL, threaded bolt pulls CS away hence easing the disconnection. The mechanism behind here lies in a trapezoidal cylindrical nut moving in toroidal direction within a guiding stiffener in CS. The actual manoeuvring of CS to and off from the fixation point with BL is done with RH gripping tool interface that surrounds the fixing bolt. During transport of Divertor Cassette, CS is pre locked with spring plungers to the side of the support structure.

CS and BL are aligned together with dowel pins. Dowel pins close out degrees of freedom to allow direct connection for the pins. Dowel pins

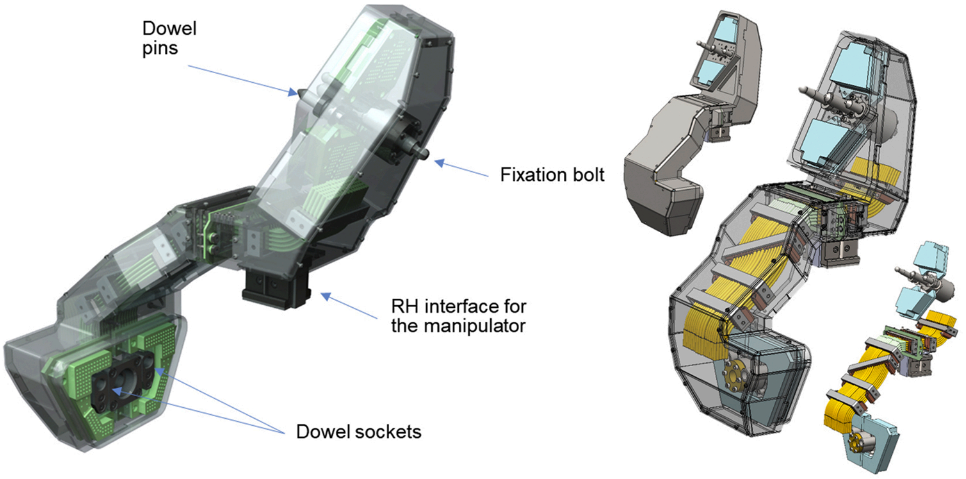

Fig. 9. BL external and internal components.

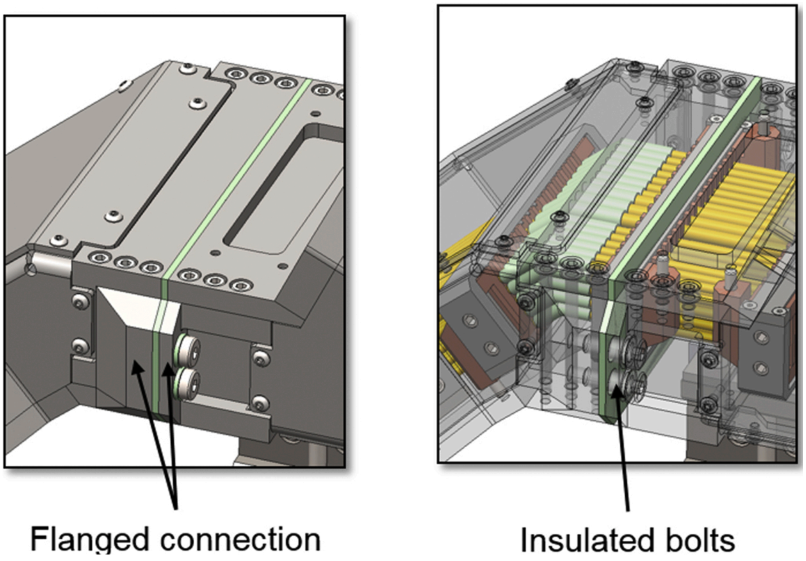

Fig. 10. BL frame insulation.

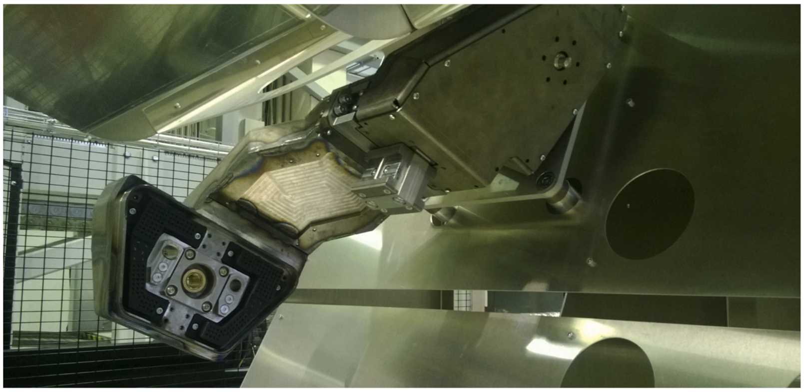

Fig. 11. BL prototype.

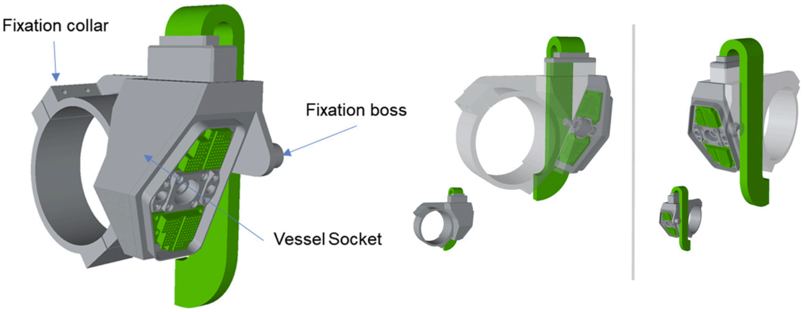

Fig. 12. VS Structure.

and central fixing bolt are RH manipulated from between the cassette cooling pipes. Dowel pins are able to be screwed to prevent cold welding and to enable access to inside of BL in case connectors are stuck together.

4.4. *Inboard configuration - central cassette connector*

There are three central cassettes inside the divertor with different diagnostic cables. In the case of the central cassettes, there is not enough space for an outboard solution. Because of this space challenge, a different solution for the central cassette connector is necessary.

The basic idea of the inboard connector, presented in Fig. 16, is simple. When the central cassette is loaded into the VV it simultaneously connects the diagnostic connectors together. This solution raises new functional and performance requirements towards Inner Cover Plate design. Based on the capture range of Cassette Socket dowel pin the design should be such that it guarantees acceptable deviation of the dowel pin before the dowel pin is contacting any part of the vessel connector. Additional safety factor should be included to account for manufacturing tolerances of the mating components. In the preliminary design phase, the dowel pins are designed according to the ITER Remote Handling Code Of Practice [6].

After removing the cassette, the floating insert plate assembly of the

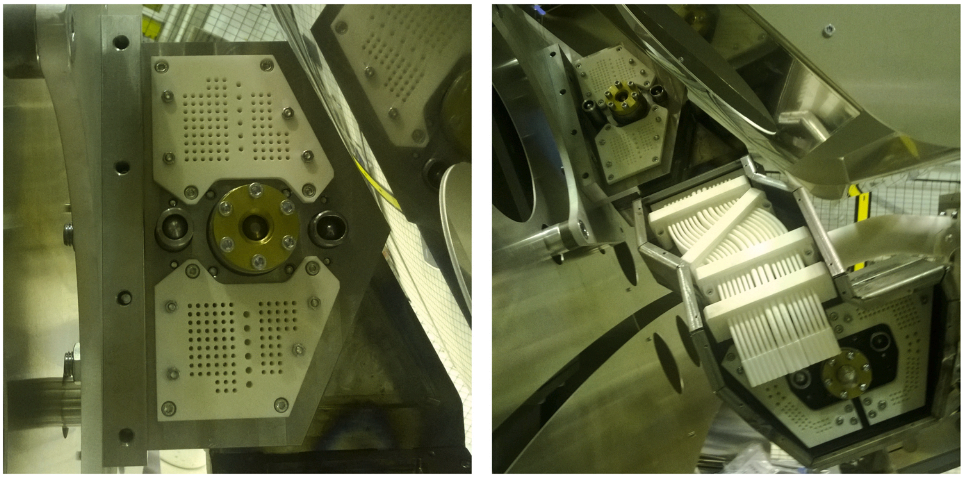

Fig. 13. VS Structure and BL internal components.

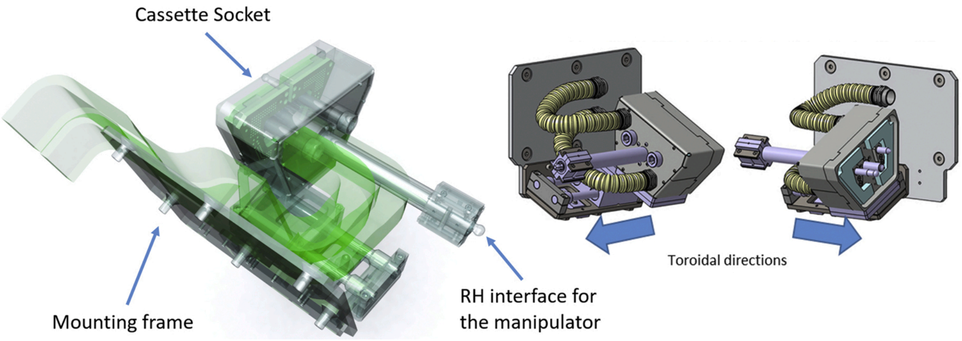

Fig. 14. CS Design.

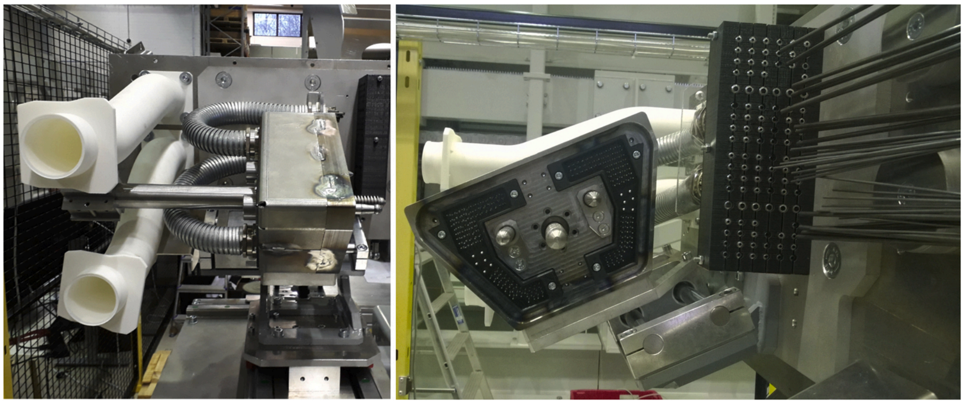

Fig. 15. CS Prototype.

cassette connector remains connected with the CS, but the dowel pins remain connected with the VS. This ensures that if the connection will not open, finally the cassette dowel pin will be damaged, not the VS. The dowel pins will be disassembled remotely, but in the end, the VS will remain in place. At this point, the dowel pins can be mechanically removed.

4.5. Cabling and inserts

The cabling of the RHC System is divided among rigid mineral insulated (MI) and flexible cables. Flexible cabling is to offer compliance during BL and CS connection, disconnection and operation of the RH Connector. It also make them compliant for vibrations and stresses.

The interface between MIC and flexible cables take place in MIC termination modules. The physical connection takes place in the pin-socket contacts, which are located in the inserts structures. They protect the contacts from mechanical impacts and offer thermal conduction. The inserts are dimensioned to fit the used pins and sockets, which are selected according to their electrical properties.

The maximum cross section needed for cables is in the space where the mineral insulated cables of cassettes are terminated. It is called as cassette connector below. In the bridging link and vacuum vessel side the number of cables is reduced since some twisted pair cables are merged to quad cores cables. The diameters of flexible cables is slightly

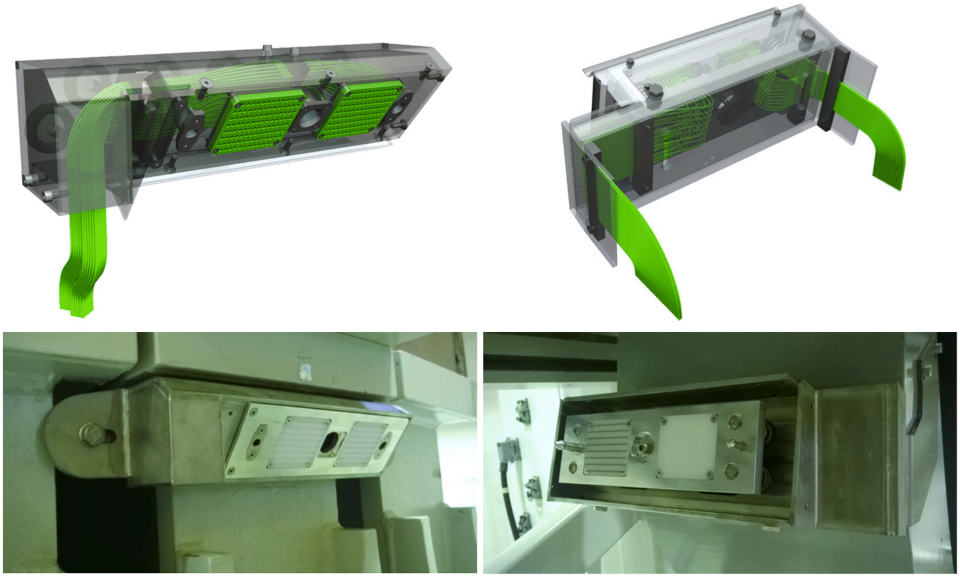

Fig. 16. IC Design and Prototype.

or considerably smaller than the diameter of MI cables.

The maximum cross section needed for mineral insulated cables is in Cassette #23, which the total amount of 133 cables. They need a surface of 4741 mm^2 considering its terminations and at least 1 mm space between them. The available space of the cassette connector is 20,250 mm^2 and the narrowest area through which the cables go in the bridging link is 7600 mm^2.

The most challenging space reservation of flexible cables will be the conduits located in the Divertor Cassette socket, which route the flexible cables from the Connector to the Divertor cassette. The most populated cassette has 124 cables in this space. They need a cross section area of 675 mm^2 in the conduits. The current design has two conduits, which have a total section of 2400 mm^2, which allows an average of 19 mm^2 per cable or 5 mm diameter per cable. In case that more space is needed to route all the cables, larger conduits could be installed as there is more than 3 mm available in each direction, in the CM of the system.

When designing cabling the most important electrical properties are voltage, current, frequency range and impedance. The sensors of the divertors define those parameters. It can be deduced that five different cable types can cover all the electrical properties needed. In theory needed cables are twisted pair, quad core, high current single core, thermocouple and coaxial. The divertor cassettes have about 17 different MI cable types since there is space and electrical requirements in the divertors, but for flexible and MI cables in the BL five different cable types is sufficient.

Typical radiation resistant insulation materials of flexible cables are PEEK (Polyether ether ketone) and Kapton®. They are not suitable for this case, since their maximum service temperature is below the standard baking temperature of 350 °C and they are not approved to be used in the vacuum vessel. Flexible cables have been a challenge for the selection for the CS. They will be specified finally during the next phase of the design. Cooperation with cable manufacturers will be needed. The currently known options for flexible cables with their pros and cons are presented in Table 1.

Insert structure design is affected externally by the dimensions and limitations of the RH Connector and internally by the pin structure. Consequently, the main guidelines for the design of the inserts have been manufacturability. Insert concepts are depicted in Fig. 17.

Inserts are made of ceramic insulation material Macor®. It offers good insulation as well as thermal resistance. An important aspect for the manufacturing is, that Macor® is possible to be machined with standard machining equipment and methods. In the PDR phase the pin inserts were manufactured with 3D printing. However, the machining capabilities of Macor® material was tested by manufacturing baking test sample mock-ups and additional drilling tests were done to determine the material properties.

Table 1
Options for the flexible cabling.

Ceramic or glass coated wires	• Pros: High temperature, radiation hard and enough flexibility. No outgassing. • Cons: Only very few cables in the market. Might be problems with thermal expansion and conduction of heat.
Glass or silica braided insulation	• Pros: High temperature, radiation hard and good flexibility. Many manufactures in the market. • Cons: Outgassing due lubricants used in manufacturing process of cable. Brittleness.
Nextel^{TM} braided insulation	• Pros: High temperature and good flexibility. Probably radiation hard. • Cons: Outgassing due organic-based sizing material. May become brittle when the temperature varies.
Alumina fish spine beads	• Pros: Easy to manufacture. High temperature, radiation hard and no outgassing. • Cons: Outer diameter bigger than other options. Movements of cable, e.g. vibrations, can cause beads to wear or break.

Pin inserts are divided into two parts consisting of a base and a cover plate. This structure form locks the pins within the insert structure, still offering access to the pins if needed. Since the design is affected by the external space reservations from RH Connectors, the insert structure has also seen many iterations.

4.6. Material definitions of connectors

ITER Vacuum Handbook [7] guides the design work. The ITER Vacuum Handbook Appendix 3 [8] defines accepted materials and design considerations regarding the vacuum. Most notable material choices for the system are stainless steel 316 L(*N*)-IG for frame structures, CuCrZr for thermal conductivity in cooling clamps and Macor® ceramic for electrical insulation in the connector pin inserts. Additional materials used are Aluminium bronze CA104, Aluminium, Inconel Alloy 625 and common materials used in Mineral insulated cables. Another relevant handbook to highlight is the ITER Remote Handling Code of Practice [6].

A notable issue with working in high temperature and in a high

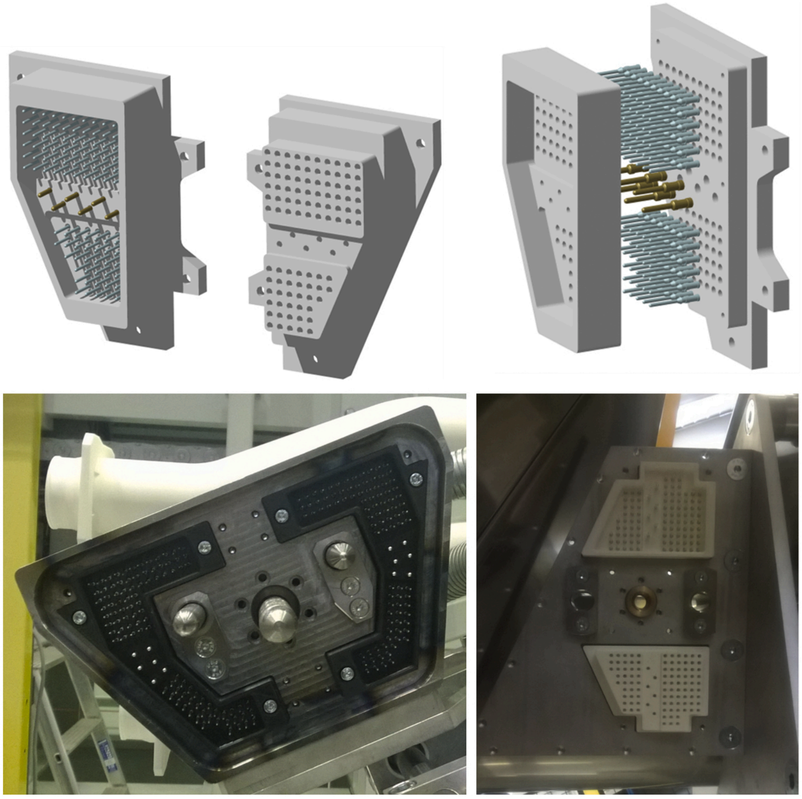

Fig. 17. RHC Insert design and prototype.

vacuum is the potential cold welding occurring between components. For instance, there is a risk of jamming with the Remote Handing Central Cassette Connector RHC in the dowel pins and electronic pins. This risk is mitigated with different material solutions in the socket part of the connector e.g. use of CuCrMg coating.

5. Verification of design

There are technical and administrative challenges in the design of the system. High level of complexity on multiple domains inflicts a need to perceive how the design of the system in regard to the technical specifications evolve, how the processes to follow evolve, and how the project timeline evolves. Design methodology must simultaneously define structures for the work and document the progress, but also enable dialogue and engineering creativity - a balance between pragmatism and innovation [9].

At the beginning of the design project, there are no defined details for the direction of development, rather the design details are defined through development. Unknowns in the design space compel design choices based on personal judgement and capabilities. These choices are developed into mature designs to be analysed, and then further developed, or redesigned with a new approach. This is the iterative nature of machine design, which is emphasized in ITER, where emergent technologies and the design of novel solutions for various interfacing systems are developed parallel to each other. There is scarce information available on adapting proven historical designs or best practices for the RHC and interfacing systems. The reasonable endeavour to verify the design here is by executing analysis, testing and expert review.

RHC has to withstand large Electromagnetic (EM), thermal, seismic and inertial loads during the plasma operation. The main failure scenario is related to the mechanical damage in RHC, which might have influence on the main functional task of RHC. Target is to create a design in which the structural stress levels are clearly below the material related allowable stress limits. Also any dynamic kind of damage like fatigue phenomena and the resulting lifetime of RH Connector have to be analysed carefully. The EM induced forces and moments are calculated and transferred to the structural mechanical model of RH Connector. In addition to the seismic acceleration values and deadweight loading due to gravity to be applied in structural model, also thermal model is created to calculate the acute temperature distribution in RH Connector.

Thermal analysis for outboard RHC is calculated describing normal plasma operation. The results give thermal data of RHC and for one representative cable TIEMF voltage. The temperature of the cables is between 119° - 328 °C. The temperature of the box is between 114 °C–290 °C. The Temperature along the chosen cable and the two-sigma values (2σ) containing 95 % of the produced error voltages are presented in Fig. 18. The max temperatures obtained are 290 °C and 328 °C in the box and cables, respectively. These values are reasonable because the baking temperature of the divertor is defined to be 350 °C.

Loads and related failure modes are provided to prepare for a structural assessment of the RH Connector. The most important is the EM-force distribution acting on the RH-connector. The total EM-force (in units [N]) is defined as a volume integral of the EM-force density over the modelled RH connector geometry.

The VDE III [10] 6 ms linear plasma disruption event is considered to be the most serious plasma disruption case due to RH Connector. In ITER IGM-model the disruption cases are typically modelled in three separate parts (poloidal field variation PFV, toroidal field variation TFV and halo currents). Halo currents are not calculated in these EM analysis for RH Connector. The total EM forces of the RH Connector calculated by the IGM/PFV analysis describes how the loads varies according to the electrical termination. Different electrical termination scenarios were analysed, which resulted in varying total forces.

All the loads including EM, Inertia and thermal static loads together result the maximum stress levels higher than acceptable material Yield stress level. By applying EM and Inertia loads the stresses are in the acceptable level when at least the BL cover is electrically insulated. The

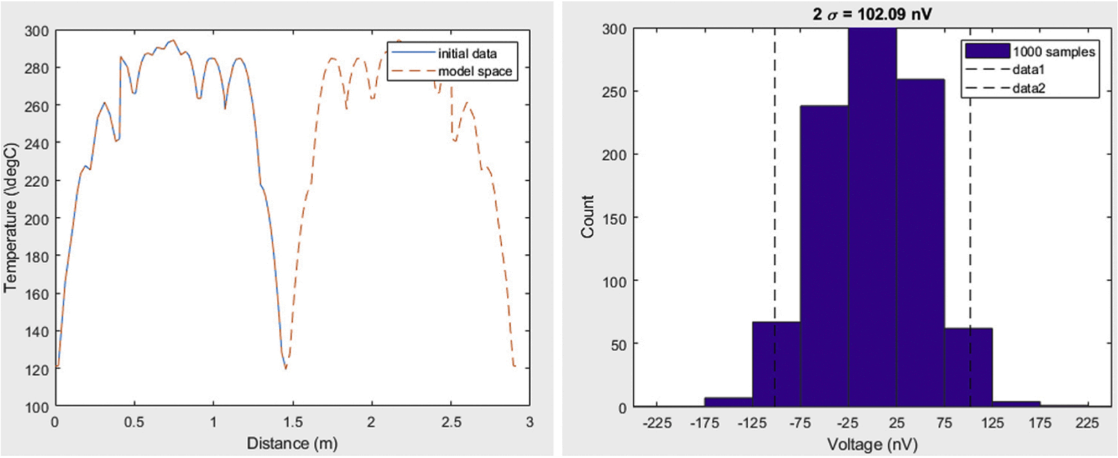

Fig. 18. Temperature along the cable and TIEMF error voltage: the two-sigma value (2σ).

thermal stresses due to the thermal expansion appeared to be a problem and perhaps e.g. material Alloy 718 is required in which the yield strength is several times higher than in material SS 316 L(*N*)-LG. The temperature of 200 °C is applied in the BL cover, VS and CS. The temperature of 300 °C is applied in the signal cables and clamps.

The thermal expansion coefficient as a material parameters are activated in the linear structural analysis. The highest stress peaks concentrate on very small and limited structural design details. This means that by the light geometry modification the stress concentrations can clearly be decreased which proved to be efficient solution in the earlier RHC evolution cases. One reason to the high stress levels is due to the high number of MIC, which are very stiff. A plausible solution would be using "Wobble" type of cables or adding flexibility in cable clamps. The same thing can also take place in VV bosses but the added flexibility in them would require support in the CS to limit the displacement and deformations of the RHC.

In addition to analysis described above, a PDR review meeting was organized at the end of 2019, where a F4E expert panel evaluated the developed system. Considerations were raised in the form of chits, which highlight areas for further development. The review process enables the enhancement of the developed system. However, the expert panel has limited possibility to contribute to the design choices done by the project team during the execution of the development, as the review is organized once at the end of the project.

6. Considerations for future work

The review comments from the PDR review meeting panel provide valuable information for the final design of the system. Additional aspects on the RHC from the design team as well as from PDR review resolution are presented here. The considerations described below involve flexible cabling, BL optimization, CS optimization, IC optimization, space limitations, thermal considerations, Remote Handling capabilities, and fusion reactors beyond ITER.

The developed IC and OC RHC systems utilize flexible cabling to provide compliance. The cables are one of the most challenging areas of development of the RHC system. The operational environment inside the ITER tokamak affects the acceptable material choices and space requirements of the cables. Close collaboration with cable manufacturers is necessary.

In BL of OC the location of the insulation break can be optimized in regard to minimizing the EM forces. The location can be moved to either end of the BL or to CS. The pre-locking feature of the BL can result in scenarios where the manipulator handling the BL experiences a sudden drop in the resisting force. Additionally the spring-loaded approach of the pre-locking is not preferred in the nuclear environment. The BL frames are shell-type structures aiming at supporting high load cases. For straightforward mock-up assembly and testing purposes, the structures of the RHC utilize bolted connections. The connections can be replaced with welded connections for the final design. Analysis can be further detailed on what type of supporting structure is necessary for the cabling.

Manipulator interface location on the CS for OC can be optimized to maximise the clearance between the manipulator gripper and the divertor cassette cooling pipes. Additional consideration in this regard is revising the dowel pins, and their extension function via rotation, and their length, with rigid dowel pin approach to introduce more freedom in defining the manipulator interface location, and additionally introducing more space for the cabling inside the CS. The proposed RHC architecture is based on the approach of providing sufficient compliance by utilizing flexible cabling. The compliance in the signal path can be located either in the CS as in the current architecture or in the BL.

When design of IC progresses, further optimization of the inner cover plates can be done to cover the requirements and ensure design integration. In addition, there is an optimization task for Final Design to dimension the dowel pins in such a way that the jamming caused by potential cold welding will be minimized, e.g. shaping the dowel pins shorter and with higher cone in sockets than recommended [6]. Also, cold welding can occur with the electric pin-socket connection making the shape design also crucial. Another additional solution to minimize the risk with the dowel pins is to use a weak point (mechanical fuse) designed in the dowel pin structure. The connection between pull screw and pull plate can be dimensioned to break before the damage of the vessel connector is reached. This enables the removal of the cassette without the jammed dowel pins of the cassette connector. The weak point of the dowel pin should locate off of the floating insert plate to provide cassette removal without pulling out the Vessel Connector. However, it is important to carry out optimal design and tests in order to ensure the pin socket connection with dowel pins will not jam.

From a purely RH point of view, the IC is the preferred approach over the OC approach if the RHC system is examined in isolation. When examining the bigger picture, and adding limitations set by interfacing systems, the need for the OC approach arises. High cabling density and limited space available for the inboard looms combined with increased cabling length to reach the inboard area make the OC an attractive approach. There are unfavourable space limitations for the design of both of the configurations as majority of the design space surrounding the configurations is improbable in acceptance of change requests.

Thermal considerations regarding the RHC system can be further taken into account. In the CS and the flexible cabling, the necessary cooling needs to be detailed by involving additional cooling elements. Inside the BL there are MIC clamps, whose thermal conductivity to the bridging link frame can be improved by increasing the contact surface area between the cooling clamp and the frame. Additionally the loom size in the BL can be optimized to minimize the size of the link to give more space for RH operations.

The RH tests done on the system were executed using an industrial manipulator without force feedback or haptics. Modifications were done on the CS regarding the linear guide bearing lengths to avoid jamming of the system when using the manipulator. The design considerations should be verified by executing tests with a system which corresponds to the mechanics and control of the manipulator to be used in ITER. At the time of writing different options for the manipulator are being considered. The choices made for the manipulator may have implications on the design of the remote handling interfaces and installation methods of the RHC.

Looking at fusion reactor systems beyond ITER, e.g. DEMO and PROTO, the most straightforward approach to design system similar to the RHC would be to introduce it early on to the conceptual design phases of the Divertor Cassettes and the Divertor Remote Handling System (DRHS), and integrate it into the Divertor cassette fixation system. For practical purposes, a space reservation of 380 cm^2 for the contacting module plates derived from the RHC design can be used as a starting point. The fixation system engaged by the DRHS is capable of providing the functions needed to align and mount the RHC into position along with the cassettes during maintenance. This approach would invalidate the need to duplicate the functions specifically for the RHC system in the outboard area, and would result in reduced overall machine system complexity.

7. Summary

The design and overall concept of the RHC have been defined. Concept is verified with a mock-up demonstrating mechanical characteristics and capabilities. The design was reviewed by F4E and ITER organizations during the Preliminary Design Review process, which is integral part of the design procurement of the RHC.

The RHC component has important implications for the ITER architecture mainly considering vacuum vessel. VS is required to be installed before the first plasma, as the component is permanently installed in the vacuum vessel and is required to survive during the whole operating life of the ITER reactor. Other impacts are derived from diagnostics as sensor data from divertors are paramount for the research purposes of the ITER project.

Showcased design demonstrates a potential concept to connect a diagnostic divertor cassette to vacuum vessel with a BL. Though developed concept considers critical interfaces and is designed according to external and internal space reservations, there are also other concepts that could offer plausible outcome.

Declaration of Competing Interest

The authors report no declarations of interest.

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[1] Some references are unfortunately restricted access for the general public due to the nature of the development work presented in this publication, but it is possible to contact ITR.support@iter.org and the request will be considered, on a case by case basis, and in light of applicable ITER regulations.