EUROfusion

# Vacuum vessel analyses for interface components with divertor system

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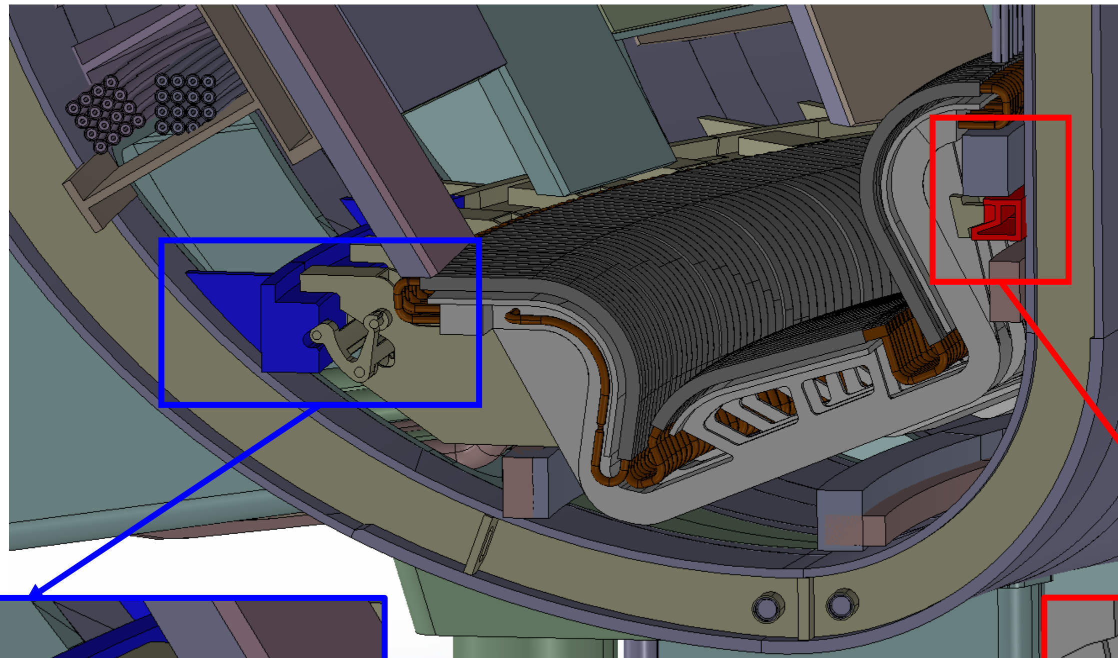
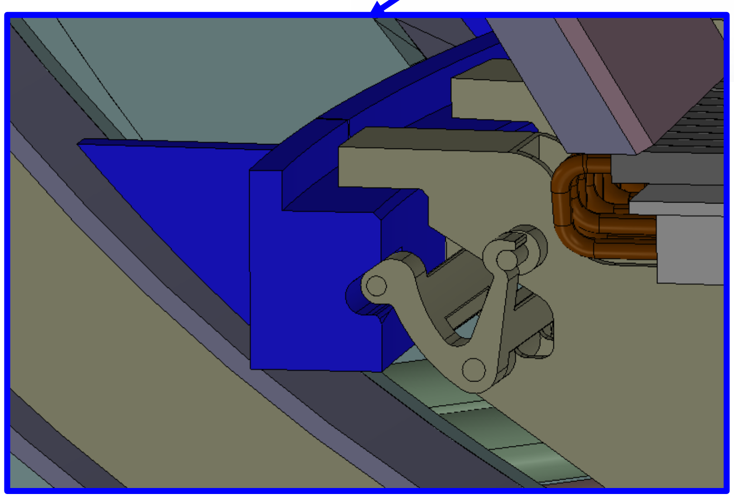
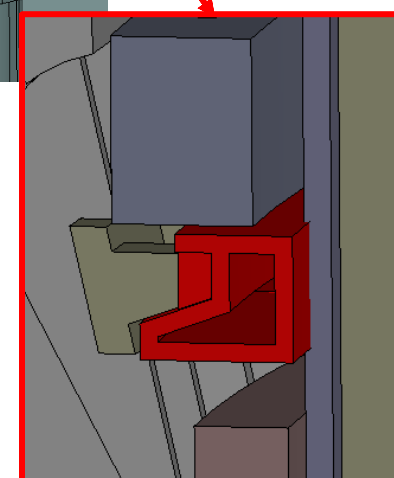
The views and opinions expressed herein do not necessarily reflect those of the European Commission.

# Introduction to Vacuum Vessel – Divertor interface





First sketches of Outboard and Inboard VV – Divertor system interfaces



# Workflow: V-model based design

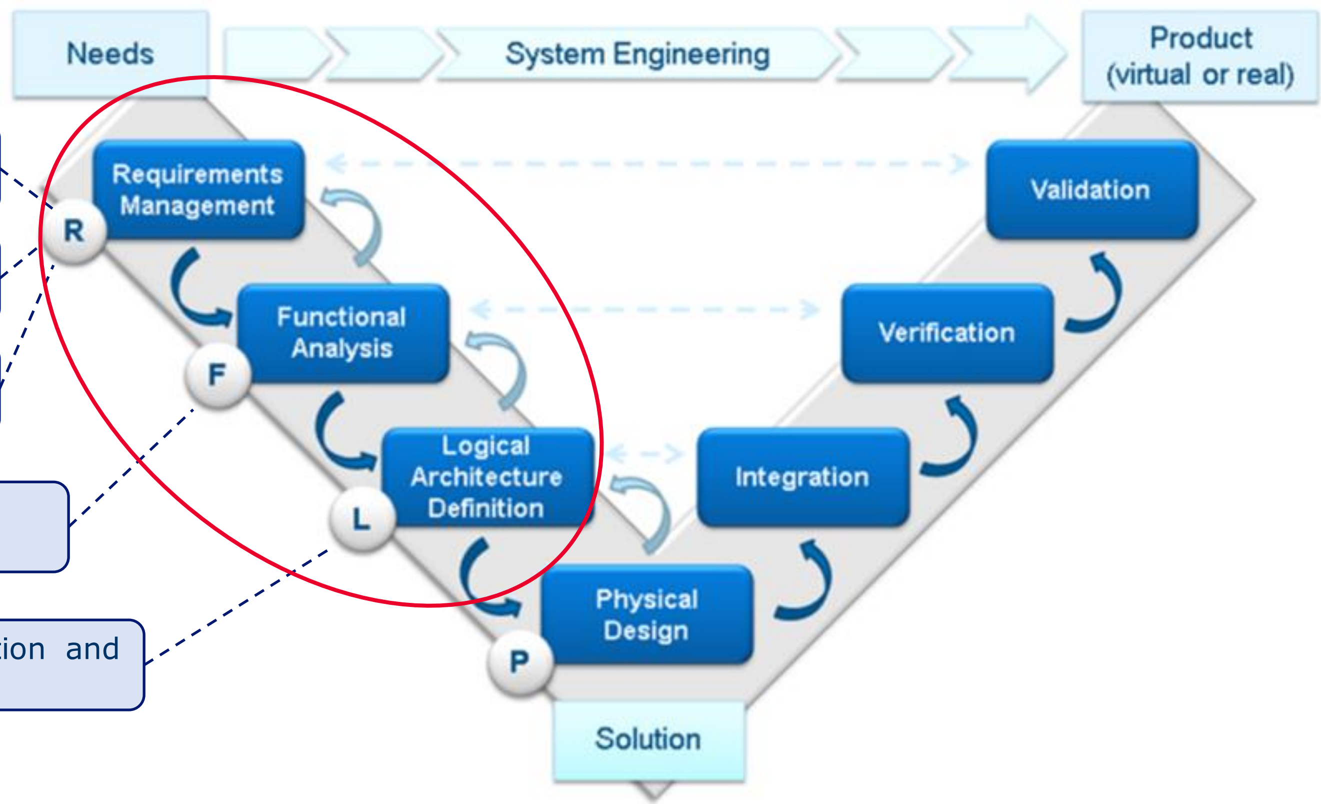
Vacuum Vessel requirements

**Divertor system** requirements

Remote Handling requirements

Load specification

System decomposition and concept design



# Vacuum Vessel - Divertor interface requirements

The Vacuum Vessel – Divertor interface needs to cope with the requirements of three different sectors:

**Vacuum Vessel Requirements:**

- The interface and its fixing points to the VV shall not compromise structural integrity of the VV
- The interface shall include elements to compensate VV possible dimensional manufacturing errors

**Divertor Requirements:**

- The interface shall sustain all loads applied on the divertor during operation
- The Interface shall align the cassettes along vertical, radial and toroidal directions (for the alignment of adjacent high heat flux components)*
- The interface shall be compatible with the divertor locking system
- The interface shall be compatible with the path of the divertor cooling pipes

**Remote Handling Requirements:**

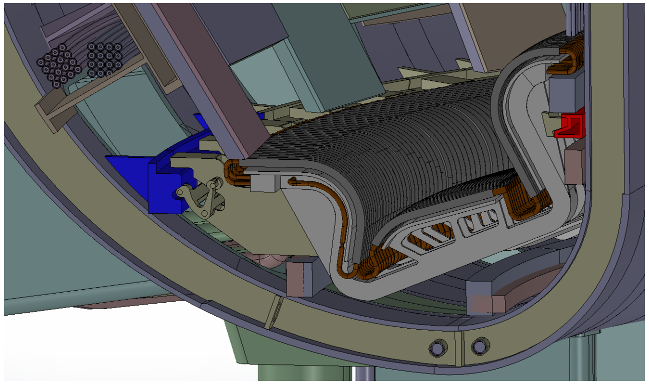
- The interface shall be used to guide the Cassette Toroidal Mover (CTM)
- The interface shall provide sufficient clearance with other IVCs for the motion of the cassette inside the vessel
- The interface shall provide a parking position for standard cassettes during their dismounting
- The interface shall provide sufficient clearance for the operation of the CTM tools

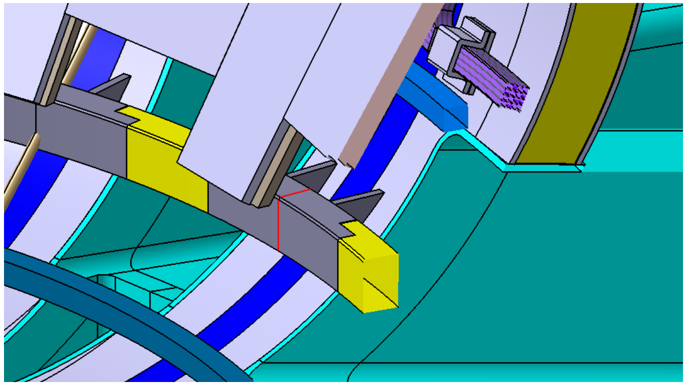
*ITER_DDD_2.3_Chapter_2_Divertor Remote Handling Equipment_2MGT8M_v1_0

# VV – Divertor interface general requirements

The VV – Divertor interface shall also fulfil more general requirements:

- The interface shall guarantee the electrical connection (radially) between the cassette and the VV
  - The electrical connection shall be designed to carry the maximum halo and eddy currents in case of disruption events
- The interface shall implement electrical isolation (toroidally) to prevent circulation of toroidal currents
- The interface shall minimize radial, toroidal and vertical misalignment between adjacent modules (max $\pm 0.5$ mm for ITER rails*)
- The interface shall transfer load to VV under any **load configuration**



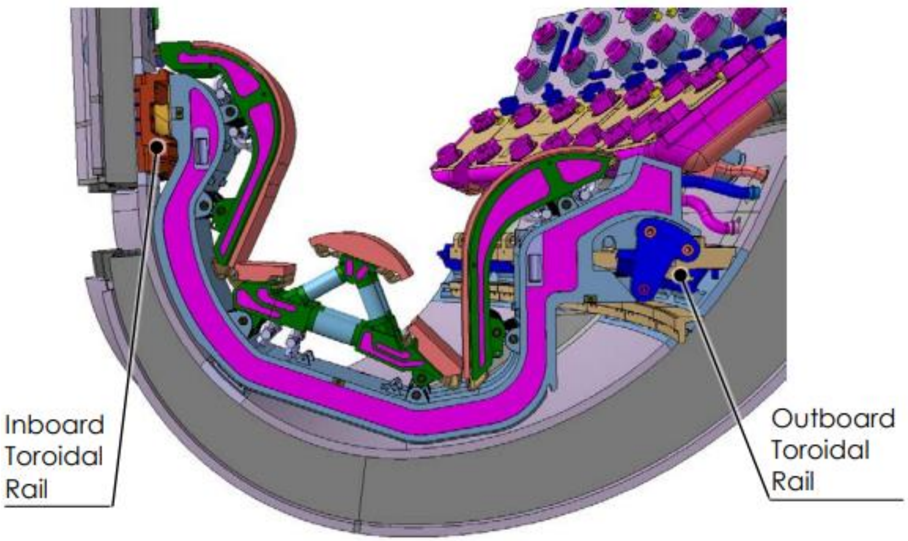


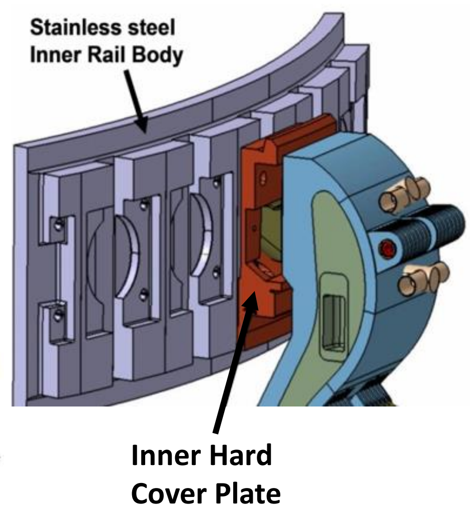
*ITER_R-2 DDD_23-02_Divertor_RH_System_2MGT8M_v2_3

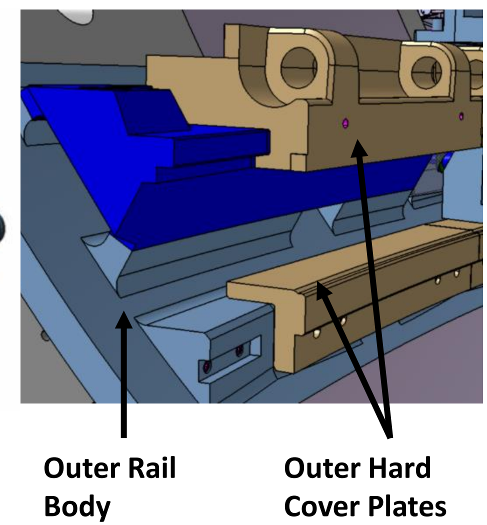
# State-of-art: ITER solution

- Inboard and Outboard Toroidal Rails, each one made of 2 main elements:
  - The stainless steel (316 L) rail body, attached to the vacuum vessel wall
  - The so-called "**hard cover plates**" made of high strength AISI 660 and bolted to the rails body able to cope with high contact pressures and friction due to wheels, pinions, and support contact surfaces

However, it is important to avoid contact between equal or similar materials to prevent possible bonding at high temperatures

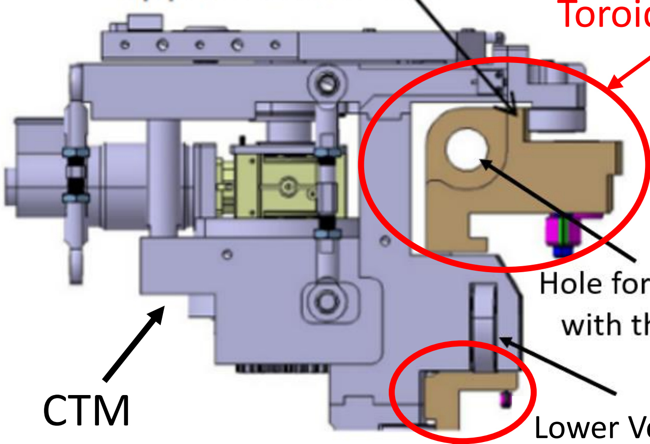


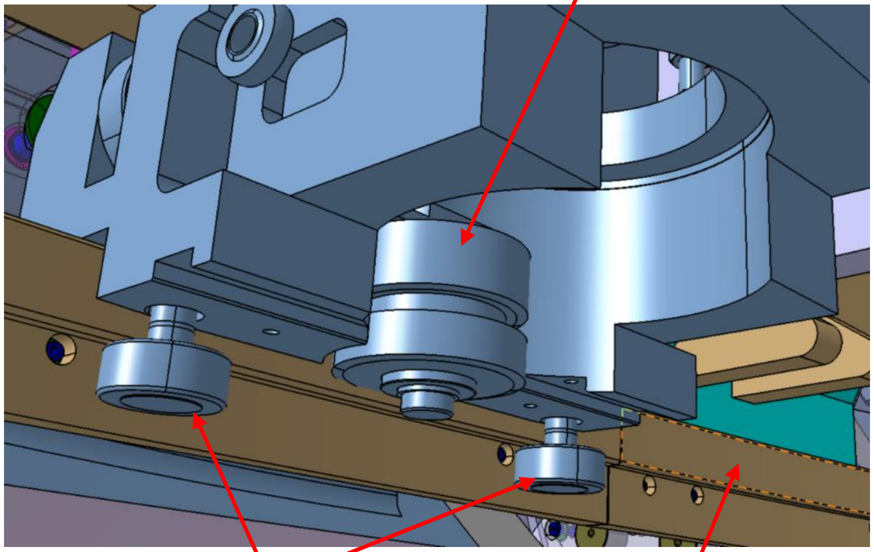



# State-of-art: ITER solution

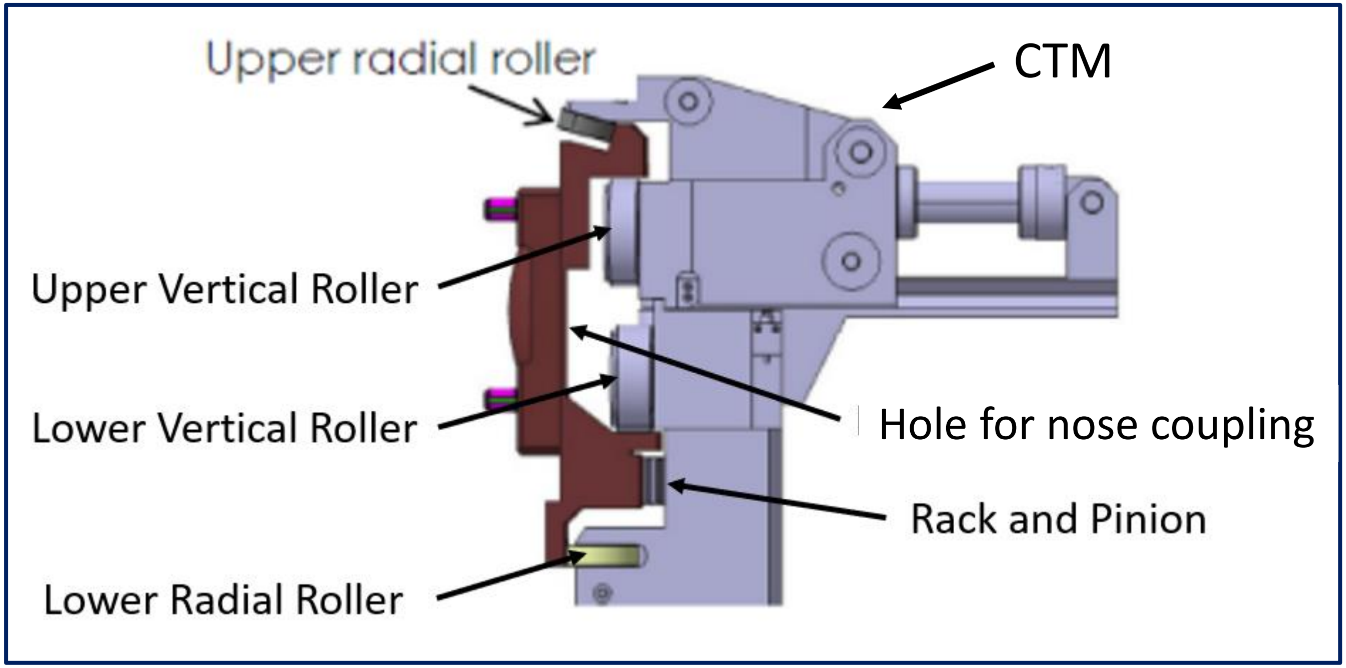
- **ITER Outboard Toroidal Rail** is made of two sub-rails:
  - **Upper Outboard Toroidal Rail** hosting surfaces for upper radial roller rotation and the hole for connection with the knuckle
  - **Lower Outboard Toroidal Rail** hosting surfaces for lower radial rollers rotation and the rack to allow CTM toroidal movement



# State-of-art: ITER solution

- **ITER Inboard Toroidal Rail** is a single rail hosting:
  - Hole for coupling with the nose
  - Surfaces for CTM inboard rollers rotation
  - Rack to allow CTM toroidal movement



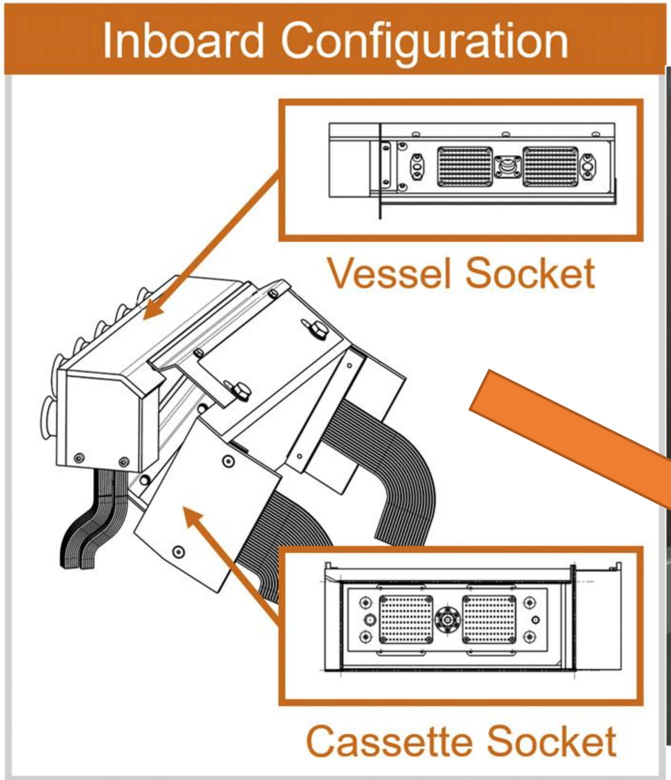
# State-of-art: ITER solution

- **Embedded instrumentation and diagnostics**

The divertor shall be equipped with operational instrumentation (aimed at measuring the thermo-mechanical response under operation) and diagnostics

A first concept with design analyses is given in [IEEE Sensors Journal, Vol. 21, Issue 16, 2021, pp.17898-17905]

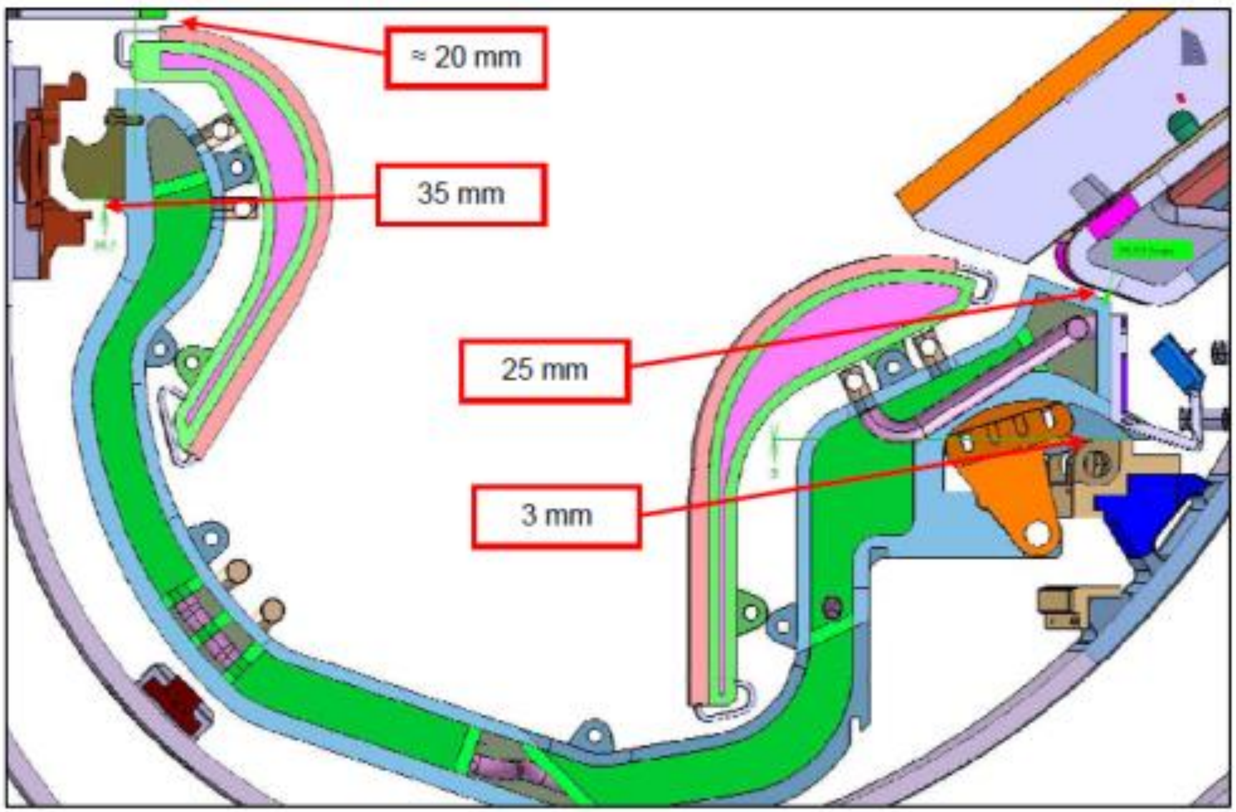
Signal connectors shall be integrated in the locking-alignment system (preferred solution) or be remote handling compatible




https://doi.org/10.1016/j.fusengdes.2021.112243

# State-of-art: ITER solution

- ITER Toroidal Rails are compatible with the RH requirements and guarantee the toroidal motion of the cassette with the represented clearances

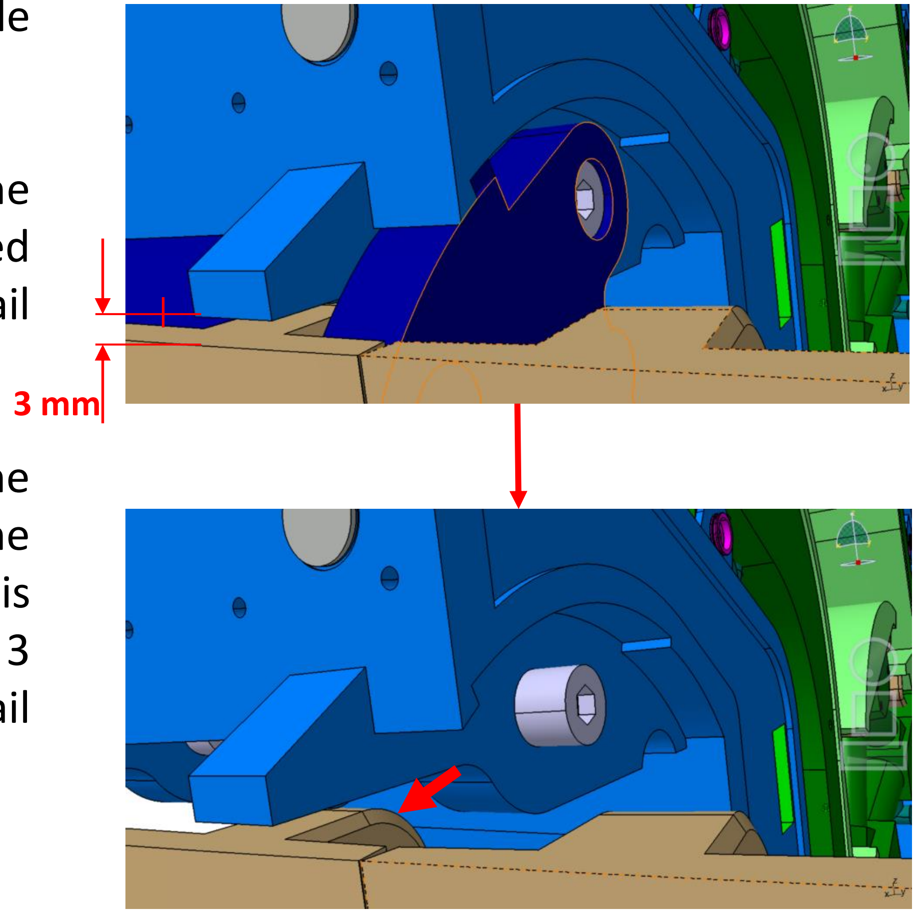


# State-of-art: ITER solution

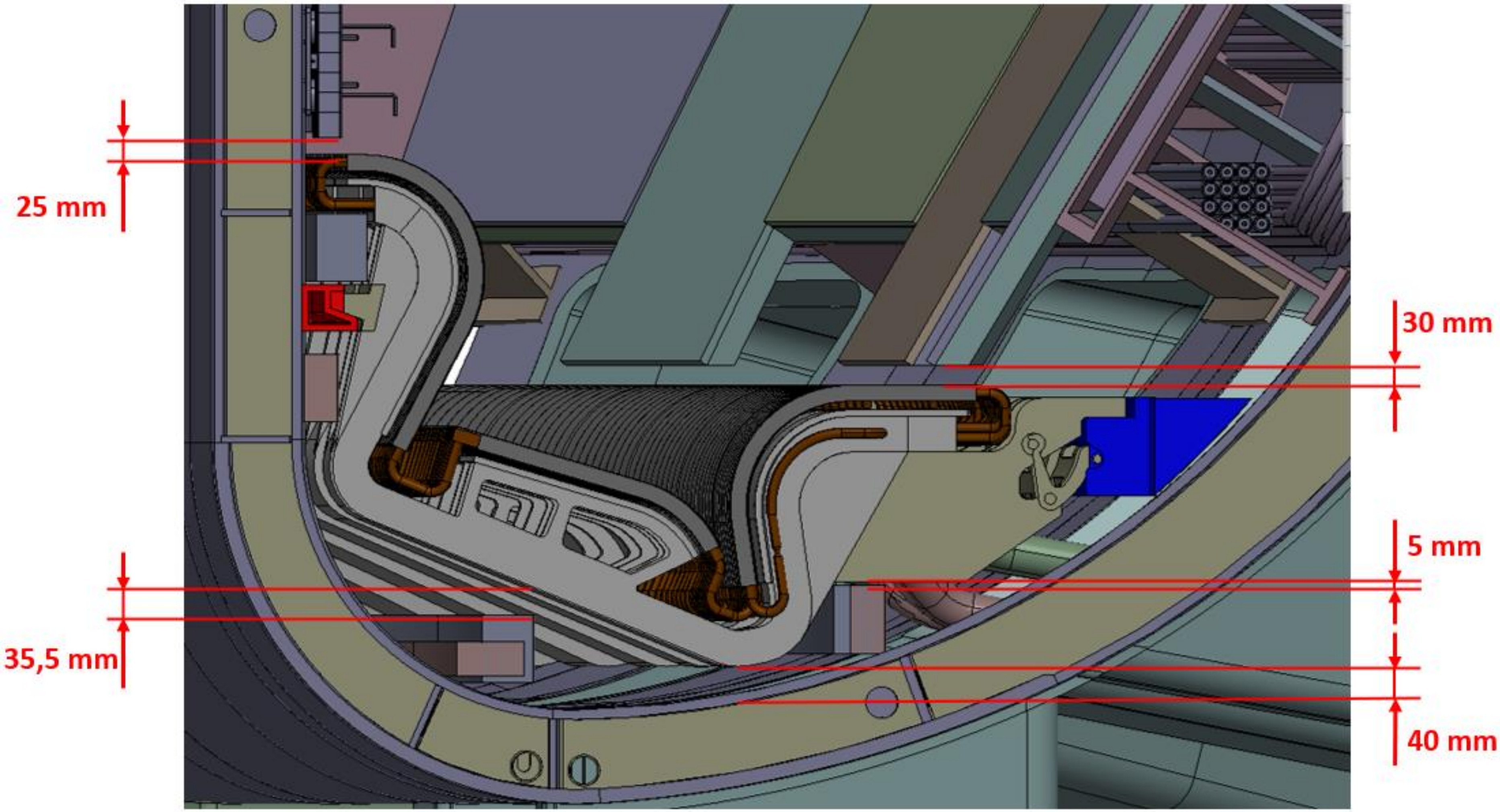
- ITER Outboard Toroidal Rail provides a surfaces for cassette resting while in **“parking position”**:

    1. In operating position, the cassette is preloaded and lifted from the Outboard Toroidal Rail with a clearance of 3 mm

    2. During the removal, when the knuckle is disengaged and the preload realised, the cassette is pushed outward closing the 3 mm gap and resting on the rail before be gripped by the CTM



# DTT DIV – VV interface



# Loads specification – different load configurations

1. Divertor loads

| Operating Condition | Preload (65 kN) | DIV Weight Force (~210 kg) | Thermal Load (~130 °C) | Coolant Pressure | Baking Thermal Load (~240 °C) | Disruption Loads |
|---|---|---|---|---|---|---|
| 1. Assembly Condition | X | X | | | | |
| 2. Plasma Operation | X | X | X | X | | |
| 3. Disruption Event | X | X | X* | | | X** |
| 4. Baking | X | X | | | X | |

*The exact thermal load distribution on the cassette in case of disruptive events needs to be studied
**Resultant forces and moment on the most loaded cassette during a plasma DVDE slow @ 0.143 s, Fz eddy + halo peak (CARMA0NL model) [EUROfusion deliverable DIV-IDTT.S.11-T001 - D003]:

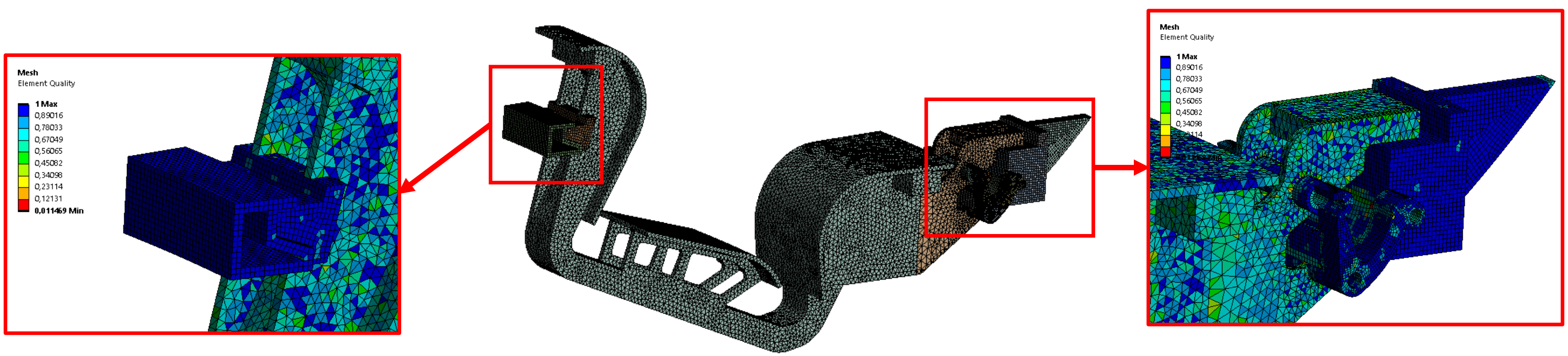
| Fx [N] | Fy [N] | Fz [N] | Mx [N·m] | My [N·m] | Mz [N·m] |
|---|---|---|---|---|---|
| -2.025E+5 | 5.642E+3 | -2.344E+5 | -4.759E+2 | -5.750E+4 | -6.494E+3 |

2. Divertor + CTM weight force during RH operations of about 700 kg overall (ENI – CREATE estimation***)

***DTT-RHS-TEC-01

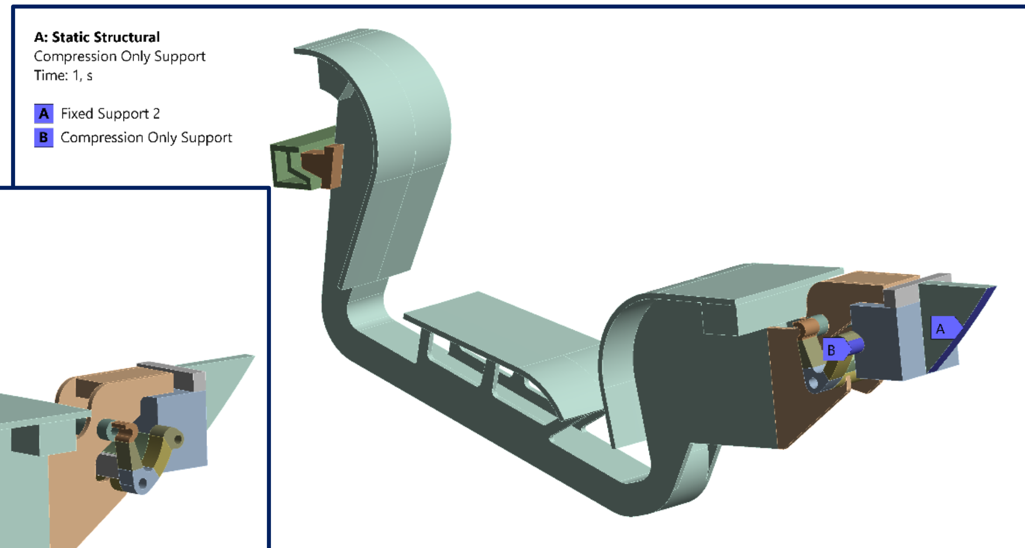
# FE Analysis to determine Divertor – VV force reactions

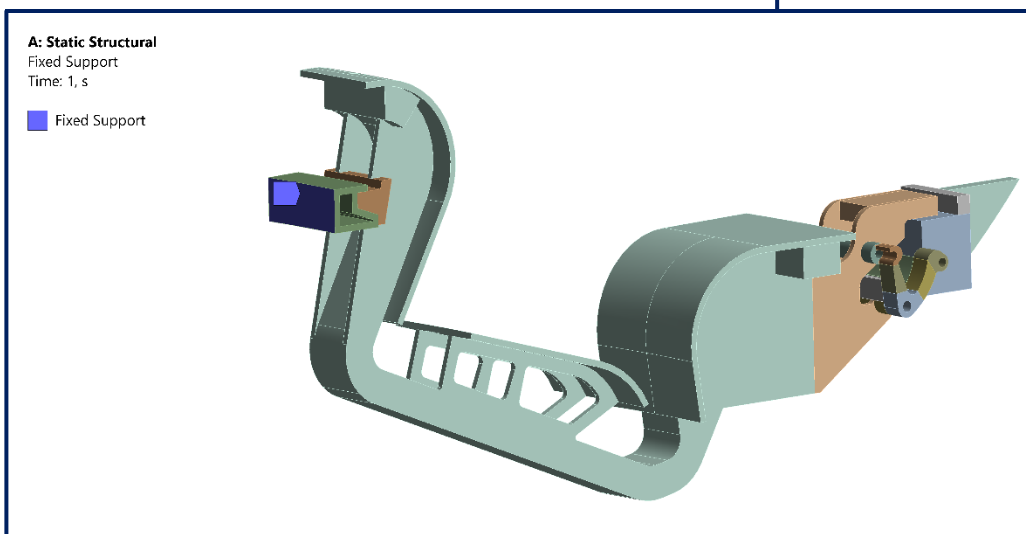
- Software: Ansys Workbench 2021 R1
- Implemented model includes:
  - Divertor Cassette without PFUs (simulated as points of mass)
  - Divertor fixing components (Wishbone and Nose)
  - A preliminary design of inboard and outboard interfaces
- Mesh:
  - Hexahedral mesh (for better quality) on fixing components and rails
  - Tetrahedral mesh on the divertor cassette (on which a separated analysis has already been realized)
  - ✓ 407769 nodes - 151224 elements



# FE Analysis to determine Divertor – VV force reactions

- The VV has been supposed as rigid in this preliminary analysis. Therefore, it has not been implemented in the analysis and “Fixed supports” have been assigned to the mating surfaces between the inboard and outboard interfaces and the VV.
- An integrated analysis also including the VV is foreseen as part of the next steps

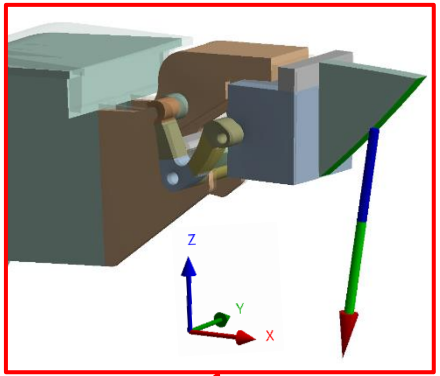


# FE Analysis to determine Divertor – VV force reactions

Load conditions applied in four different sub-steps:

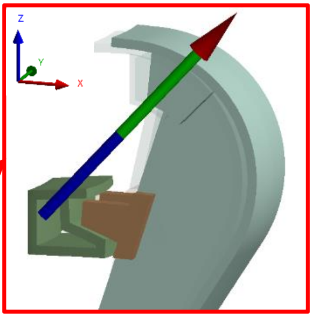
1. Assembly Condition (AC)
2. Plasma Operation (PO)*
3. Disruptive Loads applied on the cassette centre of gravity (DL)
4. Baking (B)




*The coolant pressure has not been implemented in the model

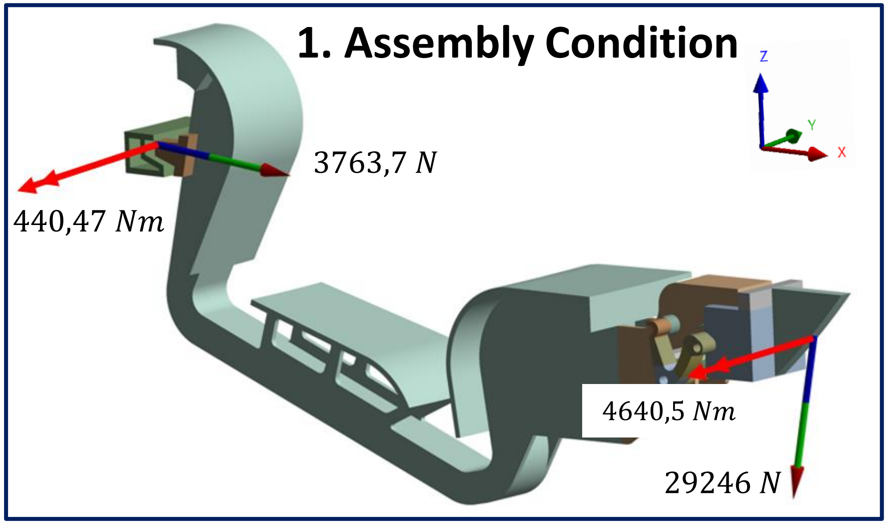
| **Outboard** | Force Reaction (X) [N] | Force Reaction (Y) [N] | Force Reaction (Z) [N] | Force Reaction (Total) [N] |
|---|---|---|---|---|
| **AC** | -5924 | 37 | -28640 | 29246 |
| **PO** | -15255 | 37 | -99920 | 1,01E+05 |
| **DL** | 50045 | -6854 | -17610 | 53494 |
| **B** | -30070 | 39 | -2,13E+05 | 2,15E+05 |

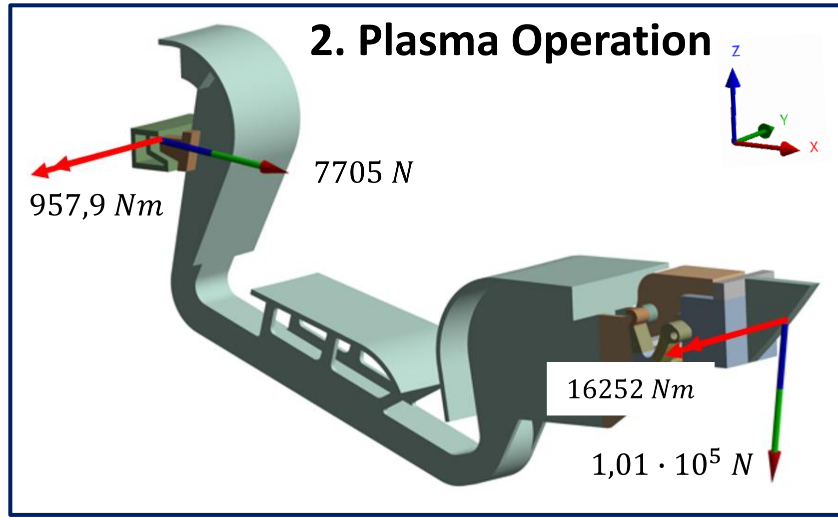
| **Inboard** | Force Reaction Inboard (X) [N] | Force Reaction Inboard (Y) [N] | Force Reaction Inboard (Z) [N] | Force Reaction Inboard (Total) [N] |
|---|---|---|---|---|
| **AC** | 3742,7 | -37,36 | -394,84 | 3763,7 |
| **PO** | 7648,9 | -37,704 | -927,27 | 7705 |
| **DL** | 1,45E+05 | 1211,5 | 1,51E+05 | 2,09E+05 |
| **B** | 13929 | -43,75 | -1811,8 | 14047 |

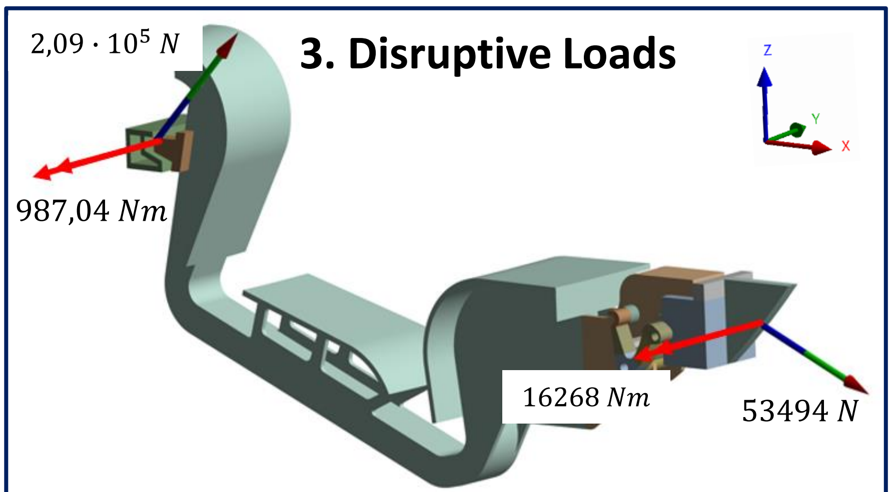


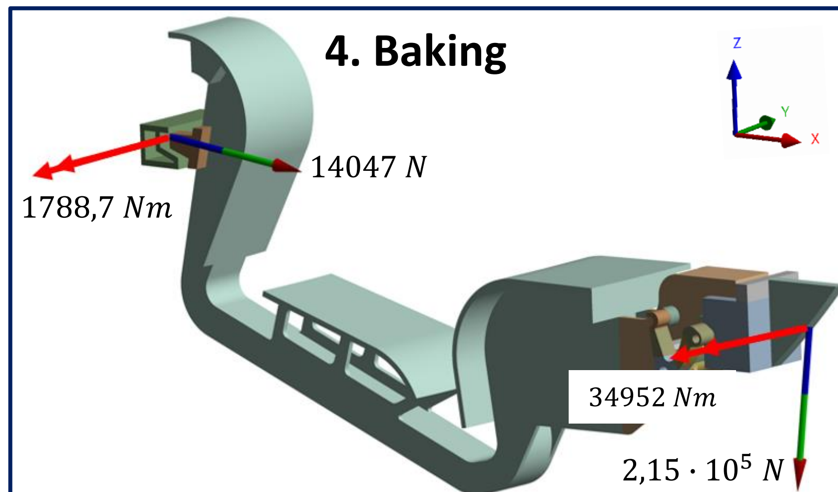
# FE Analysis to determine Divertor – VV force reactions

Forces Moments



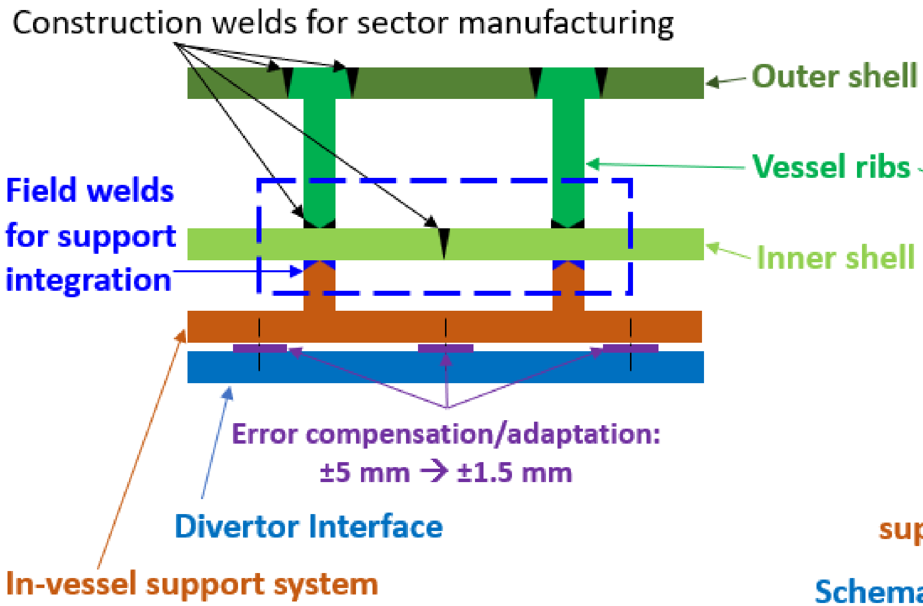



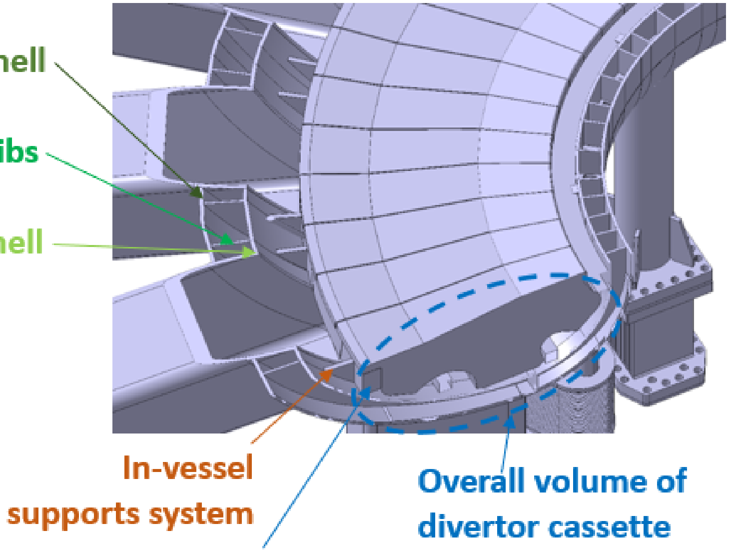



# Conceptual design of an ITER-like solution for DTT: outboard divertor interface

In a first concept, the **outboard divertor interface** has been divided in two modules:

- **In-vessel support system** welded to the VV (full penetration field welds), since there is no need of dismounting it
- **Divertor interface**, bolted to the in-vessel support system to allow the presence of in-between elements to compensate possible VV manufacturing errors in the radial direction



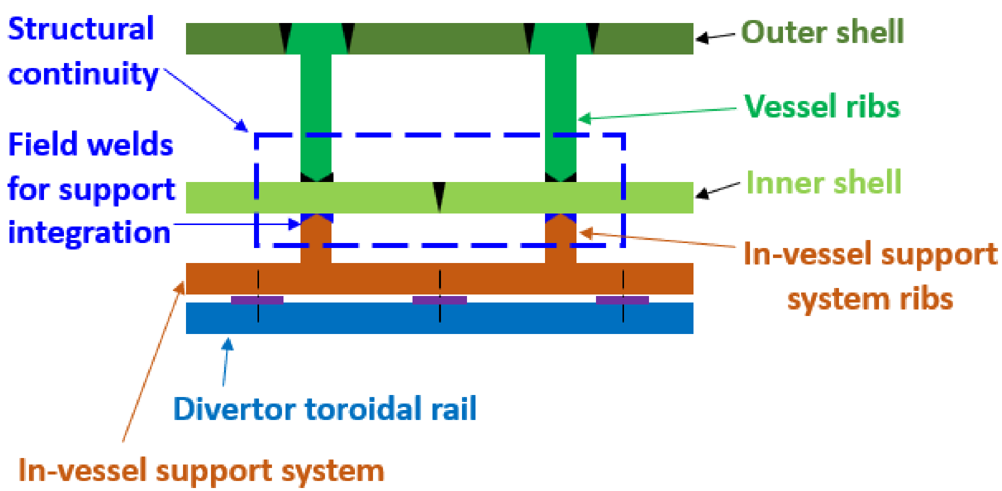



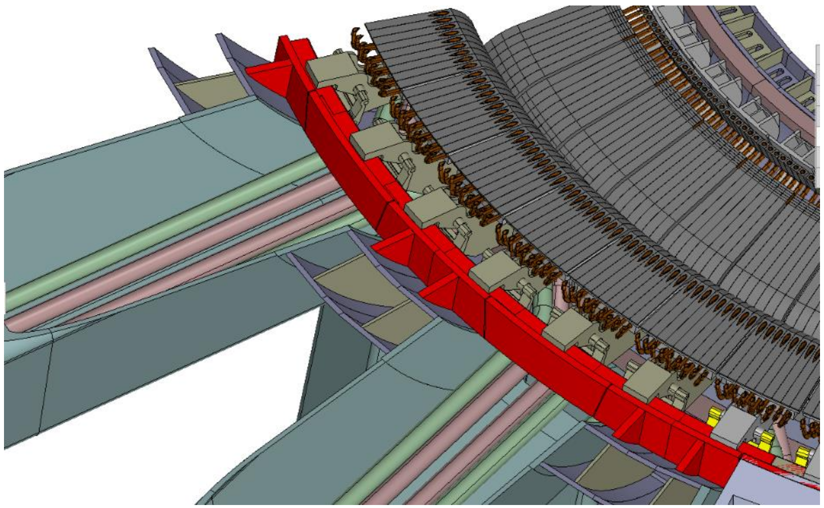

Schematic of outer VV - divertor interface

# Conceptual design of an ITER-like solution for DTT: VV – in-vessel support system connection

Two problems are being studied regarding the in-vessel support system connection to the VV:

- ❑ Attachment position of the **in-vessel support system ribs**. Two possible solutions will be furtherly analysed:
  - ➢ ***Positioning the ribs in correspondence of the vessel ribs***, to guarantee structural continuity and realise a rigid transfer of loads from the in-vessel component to the vessel structure (like in the figure)
  - ➢ Positioning the ribs in the middle of the vessel ribs
- ❑ Type of welds



# Conceptual design of an ITER-like solution for DTT: VV – in-vessel support system connection

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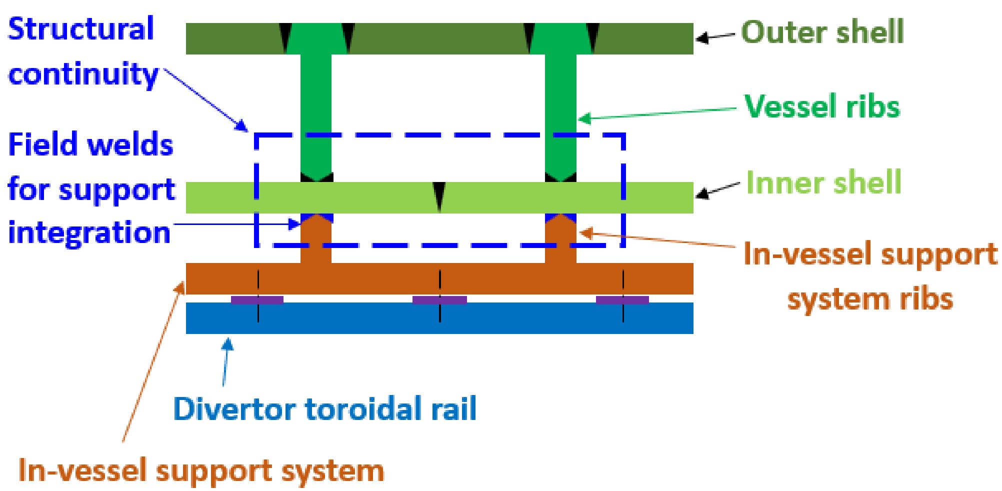
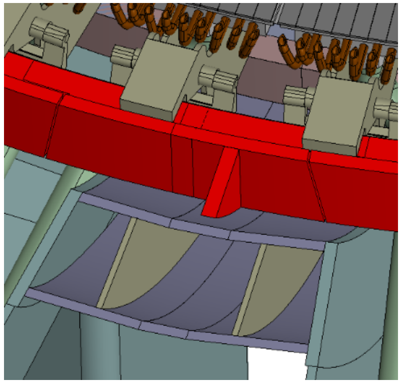
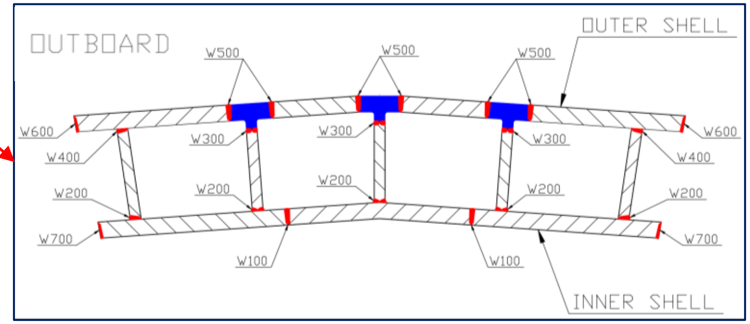
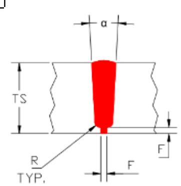
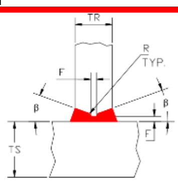
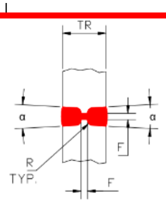
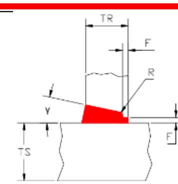
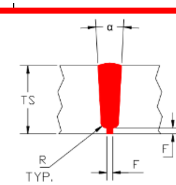
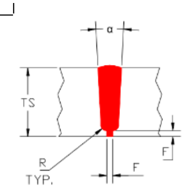
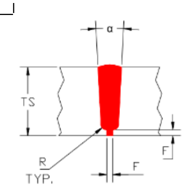


# Identification of welded joints types and NDT

Several possible types of welded joints are used for VV inner welds. The joints for support integration will be T-joints, therefore W-200 or W-400. It is important to ensure a 100% extension of the Non Destructive Testing




| Detail | | | | Weld process | | Non destructive testing | |
|---|---|---|---|---|---|---|---|
| Ref. | Weld joint sketch | Type of joint [RCC-MRx RD3800] | Edge preparation | Weld mode | Process number | Type | Extent |
| W100 |  | I.2 butt welding, full penetration, two sides accessible, gaseous back protection | single-U groove | 001 manual | 141 (TIG) root layer | VT | 100% |
| | | | | | | LT | 100% |
| | | | | | 131 (MIG) overlay layers | VT | 100% |
| | | | | | | RT | 100% |
| | | | | | | ET | 100% |
| W200 |  | III.1 T, full penetration, two sides accessible, back welding | double-J groove | 001 manual | 141 (TIG) root layer | VT | 100% |
| | | | | | 131 (MIG) overlay layers | VT | 100% |
| | | | | | | UT | 100% |
| | | | | | | ET | 100% |
| W300 |  | I.1 butt welding, full penetration, two sides accessible, back welding | double-U groove | 001 manual | 141 (TIG) root layer | VT | 100% |
| | | | | | 131 (MIG) overlay layers | VT | 100% |
| | | | | | | RT | 100% |
| | | | | | | ET | 100% |
| W400 |  | III.2 T, full penetration, back side inacessible, gaseous back protection | J-groove | 001 manual | 141 (TIG) root layer | VT | 100% |
| | | | | | 131 (MIG) overlay layers | VT | 100% |
| | | | | | | UT | 100% |
| | | | | | | ET | 100% |
| W500 |  | II.1 butt welding, full penetration, back side inaccessible, gaseous protection | single-U groove | 001 manual | 141 (TIG) root layer | VT | 100% |
| | | | | | 131 (MIG) overlay layers | VT | 100% |
| | | | | | | UT | 100% |
| | | | | | | ET | 100% |
| W600 |  | I.2 butt welding, full penetration, two sides accessible, gaseous back protection | single-U groove | 002 automatic | 141 (TIG) root layer | VT | 100% |
| | | | | | 131 (MIG) overlay layers | VT | 100% |
| | | | | | | RT | 100% |
| | | | | | | ET | 100% |
| W700 |  | II.1 butt welding, full penetration, back side inaccessible, gaseous protection | single-U groove | 002 automatic | 141 (TIG) root layer | VT | 100% |
| | | | | | 131 (MIG) overlay layers | VT | 100% |
| | | | | | | UT | 100% |
| | | | | | | ET | 100% |

# Verification of welded joints

Verification parameters for VV welded joints structural analyses [ITER SDC-IC, RCC-MRx]:

- **Joint coefficient $\boldsymbol{n}$**: it takes in account of the type of joint and the scope of the checks made; if multiplied by the allowable stresses in the weld, it gives the allowable stresses of the welded joint.
- **Weld fatigue strength reduction factor $\boldsymbol{f}$**

For all the VV welded joints it is required that: $n \geq 0{,}85$, $f \leq 1{,}25$

**Table 8-3 Joint coefficient n**

| Examinations | Types of welded joints | | | |
|---|---|---|---|---|
| Volumetric examinations: radiography or ultrasonic examinations<br>Surface examinations: liquid penetrant or magnetic particle examinations | I.1, I.2, I.3, III.1 | II.1, III.2 | II.2, III.3 | IV, V, VI, VII |
| Volumetric examinations + surface examinations after welding (both sides) | 1 | N/A | N/A | N/A |
| 100% Volumetric examination + Surface examination (after penetration pass and front side after welding) | 1 | 1 | N/A | N/A |
| (*)Surface examinations during welding + surface examinations after welding (one side) | 0.85 | 0.85 | 0.5 | 0.5 |
| (*)Surface examinations after first pass + surface examinations after welding (one side) | 0.7 | 0.7 | 0.5 | 0.5 |
| Surface examinations after welding (one side) | 0.5 | 0.5 | 0.5 | 0.5 |

**Table 8-4 Fatigue strength reduction factor f**

| Examinations | Types of welded joints | | | |
|---|---|---|---|---|
| Volumetric examinations: radiography or ultrasonic examinations<br>Surface examinations: liquid penetrant or magnetic particle examinations | I.1, I.2, I.3, III.1 | II.1, III.2 | II.2, III.3 | IV, V, VI, VII |
| Volumetric examinations or surface examinations during welding (between passes) | 1 | 1 | N/A | N/A |
| Surface examinations after welding (both sides) | 1 | N/A | N/A | N/A |
| Other examinations | 2 | 2 | 4 | 4 |

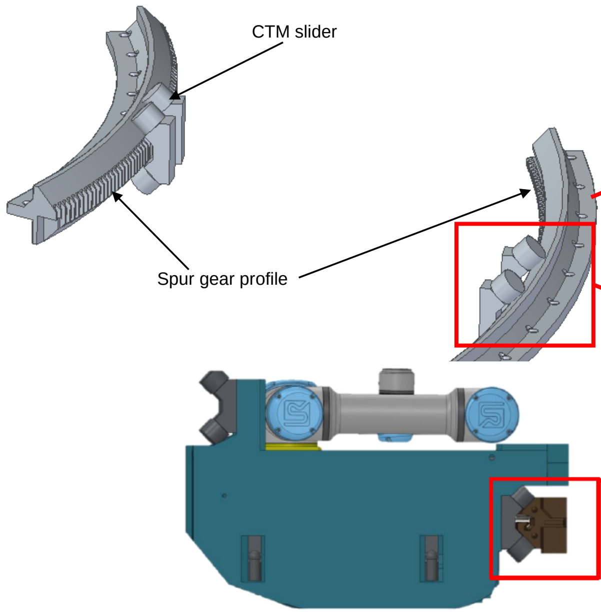
# Conceptual design of an ITER-like solution for DTT: CTM interface

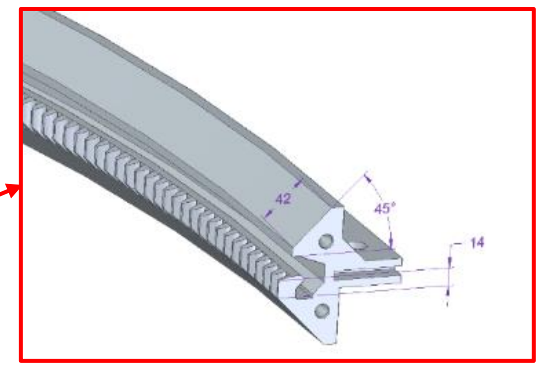
First concepts have been conceived concerning:

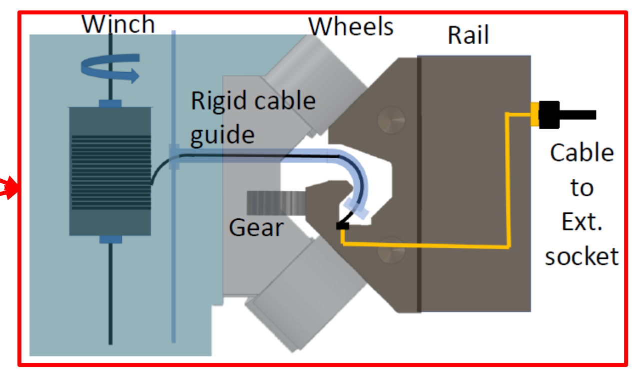
- The interface with the divertor
- The interface with the CTM

First concept solution from RHS ENI-CREATE for **CTM interface**, including ITER-like inboard and outboard toroidal rails equipped with:

- Rack for CTM toroidal movement
- Inclined surfaces for CTM wheels rotation

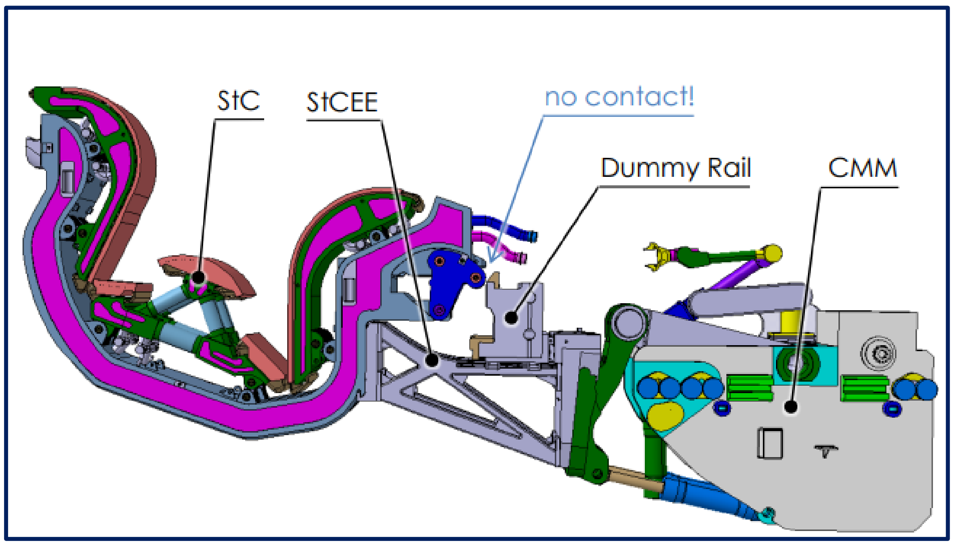


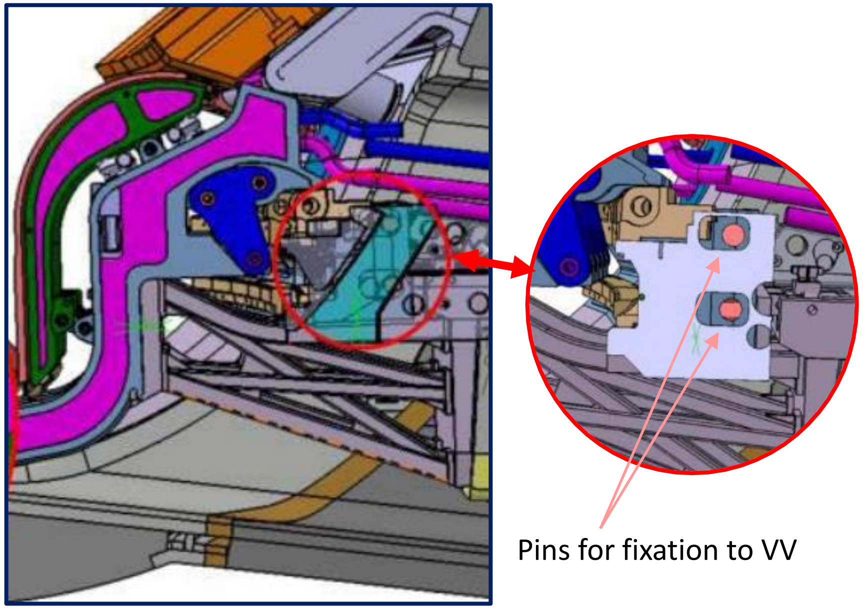



# VV – Central Cassette interface

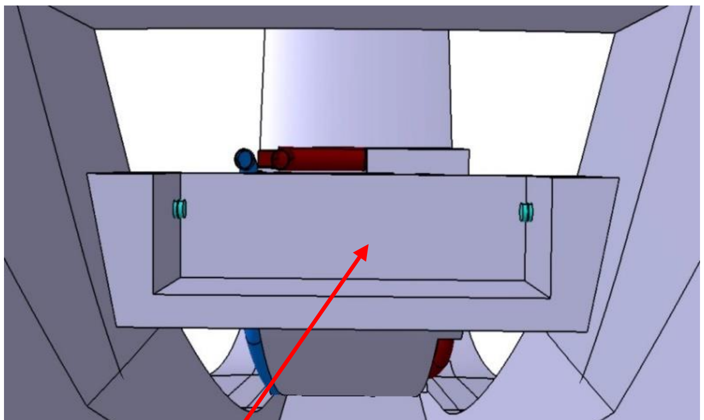
- ❑ Additional requirement:
  - ➢ The VV – Central Cassette interface (for RH sectors) needs to be removed with the cassette to leave the entrance in the VV from port #4 free for lateral and standard cassettes handling
- ❑ ITER Solution: Central Cassette Outer Rail (CCOR) also called "Dummy Rail"
  - ➢ Module of the Outboard Rail fixed to the lateral walls of the port #4 duct by means of 4 pins (2 for each side), in order to be removable with the cassette

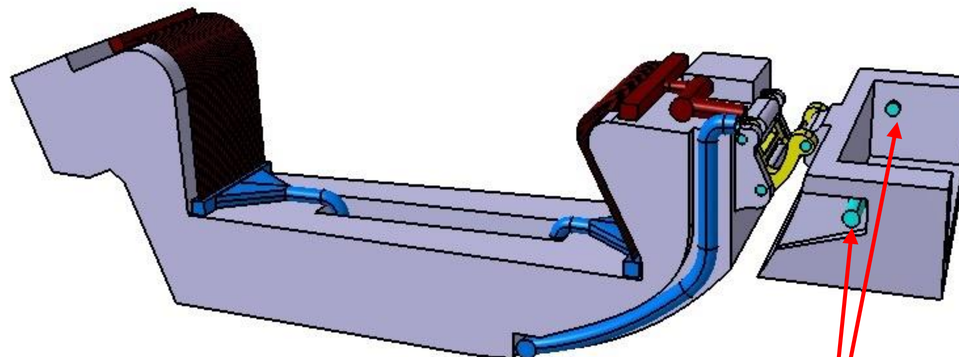


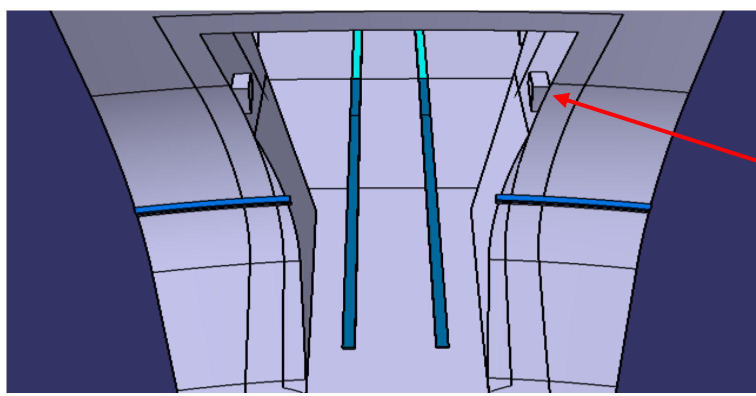
# VV – Central Cassette interface

- Proposal of an ITER-like solution whose concept design has been already developed for DEMO. Dimensional compatibility and the method of cassette gripping need to be studied





Rear opening to allow pins removal by CMM Manipulator



Pins for fixation

Trapezoidal protrusions to couple with CCOR corresponding slots

# Next developments

- Update of disruptive loads
- Detailed design and implementation of the interfaces with CTM and divertor. Two ways are under consideration:
  - Couple the two interfaces in a single rail
  - Decouple the two interfaces in two separate rails
- Detailed design and implementation of the Central Cassette interface
- Mechanical, electrical, and vacuum compatibility verification of the designed solutions
- Verification of interfaces through an integrated structural analysis (also including the VV)
- Cinematic simulation of the Remote Handling procedures to verify the compatibility of the designed solutions with the surrounding components during each RH stage