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Revised Divertor Design for the new European ’DEMO LAR’ reactor.

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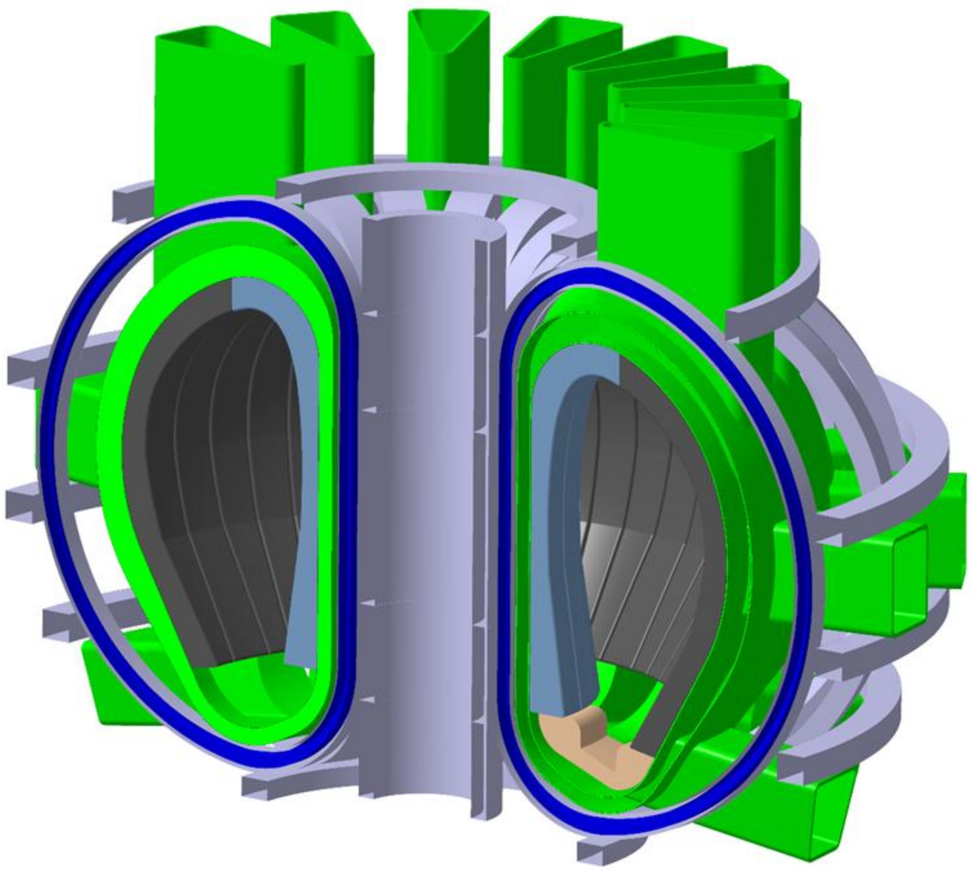
DEMO Low Aspect Ratio 2025*



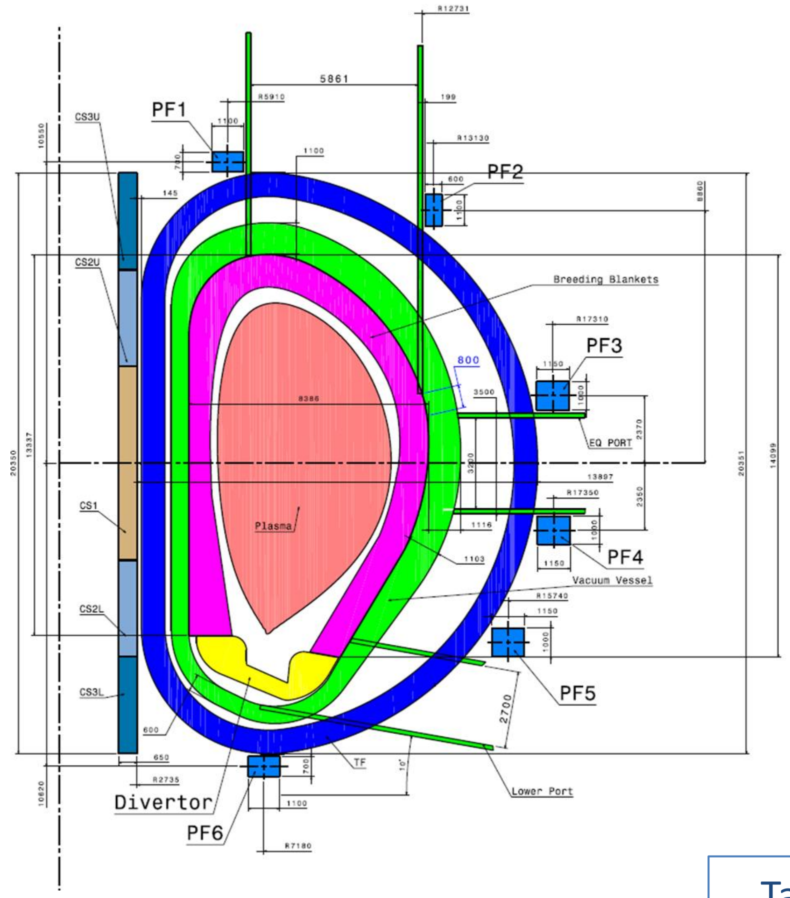
DEMO LAR - Full 3D (2S3RZQ)

*Proposal for a change of the aspect ratio of DEMO: High Level Architecture description to start impact analysis (Doc 1b) (2RVT5Y)

The new proposed design point at A=2.8, R_0=8.6m includes following enhancements with respect to G1 baseline:

- **Power Exhaust**: the power load to the divertor in case of reattachment decrease from ≈ 82 MW/m^2 (G1 case) down to ≈44 MW/m^2 (-46.5 %), which could be handled with sweeping/wobbling as an emergency manoeuvre. Qualitatively, lower heat load on the divertor implies easier and more robust access to divertor detachment.
- **Incorporation of margins in the design point**: The q95 safety factor increase from 3 (G1 case, close to known stability limits) up to 3.6 (+20%). This increase of q_{95} provides operational safety for the plasma scenario (it is less disruption prone at higher q_{95}). Together with this margin on the plasma stability, this value provides flexibility to recover performance (guaranteeing 350 MW electric and an acceptable pulse length) by lowering q95 to 3.3 in case of a 10% deterioration in confinement (which is inherently subject to high physics uncertainties).
- **Toroidal Field (TF) Simplification**: The new point enables a 10% reduction in the TF field at R_0, from 4.89T down to 4.39T, equivalent to a reduction at the TF inner leg from 10.7T to 10.4T (-3%) and aligns marginally with the panel's recommendation to simplify the TF design.
- **Remote maintenance**: It is difficult to quantify the ease of remote maintenance in the new point relative to G1 – as the previous point was effectively not maintainable (the BB volume increases of ≈ +7%). As a positive aspect, the relatively smaller size of the divertor with respect to the BB increases the margin for T-breeding and concurrently reduces power density, simplifying the design.

DEMO Low Aspect Ratio 2025 – Main Tokamak Parameters



Parameter	EU-DEMO G1 baseline [1]	Proposed point	Relative change
A	3.1	**2.8**	- 9.68 %
R_0 [m]	8.94	8.6	- 3.80 %
P_{fus} [MW]	1998	1651	- 17.3%
$P_{el,net}$ [MWe]	500 (424 if calculated with latest assumptions)	350	- 30.0 %(-17.3%)
q_{95} ($q_{95_{min}}$)	3.0 (3.0)	3.6 (3.3)	+ 20.0 %
τ_{pulse} [hr]	2.0	2.11	+ 5.50 %
$P_{sep}B_{T,0}/q_{95}AR_0$ [MW.T/m]	9.2	5.5	- 40.2 %
$\dot{q}_{div,outer}$ [MW/m^2]	82.85‡‡	44.35 (49.23)	- 46.5 %
$B_{T,0}$ [T]	4.89	4.39	- 10.2 %
$B_{T,TF_{max}}$ [T]	10.69	10.37	- 3.00 %
$V_{BB,out}$ [m^3]	19.6	21.0	+ 7.14 %

Table 1*: Relative changes of the main parameters between G1 baseline and the proposed point

(‡‡ Value above emergency reattachment sweeping maneuver, limited to 60-70MW/m2)

*Proposal for a change of the aspect ratio of DEMO: High Level Architecture description to start impact analysis (Doc 1b) (2RVT5Y)

DEMO Low Aspect Ratio 2025 -Plant requirements 1of 2

New IE Object	Nr.	New UID	Subject	Keyword	New description
Stakeholders Requirement	01.00	**DLAR-SHRd-01**	Operation	Electrical power	The DEMO-LAR plant shall produce net electrical power (target: 300 to 500 MWe) from D-T fusion reaction for a sufficient flat top duration (target: ≥ 2 hours) in a reproducible way
Plant requirement	01.01	DLAR-PRd-01.01		Architecture	The DEMO-LAR plant shall adopt a tokamak architecture
Plant requirement	01.02	DLAR-PRd-01.02		Electrical power	The DEMO-LAR plant shall reliably deliver averaged net electrical power in the range of 300-500 MWe to the grid
Plant requirement	01.03	DLAR-PRd-01.03		Duty cycle	The DEMO-LAR Plant shall reliably generate a plasma duty cycle with the flat top of at least 2h with a completion cycle time much less than 1 hour
Plant requirement	01.04	DLAR-PRd-01.04		Plant lifetime	The major non-replaceable (or extremely difficult to replace) components of the DEMO-LAR Plant shall be designed for a primary lifetime threshold of 7 full power years
Plant requirement	01.05	DLAR-PRd-01.05		Operational phases	The staged construction and operation of the DEMO-LAR Plant shall permit to perform the subsequent two operation phases defined by the level of damages generated at the outboard mid-plane of the first wall made of Eurofer up to 20 dpa (phase 1) and 50 dpa (phase 2)
Plant requirement	01.06	DLAR-PRd-01.06		Power exhaust	The exhaust concept of the DEMO-LAR plant allows affordable lifetime of all types of components installed in the vacuum vessel
Plant requirement	01.07	DLAR-PRd-01.07		Assembly & maintenance	The design of the DEMO-LAR plant systems, structures and components shall consider assembly and/or maintenance strategy of the delivered systems and manufactured components

*Table 1: Plant requirements propagated from DLAR-SHRd-01- Status of Plant Requirements Gate 2a DEMO-LAR (EFDA_D_2SP7U4)**

DEMO Low Aspect Ratio 2025 -Plant requirements 1of 2

New IE Object	Nr.	New UID	Subject	Keyword	New description
Plant requirement	01.08	DLAR-PRd-01.08		Diagnostics	The DEMO-LAR plant shall be equipped with the relevant set of diagnostics to provide data of plasma performance and behavior to allow plasma controllability and safe operation
Plant requirement	01.09	DLAR-PRd-01.09		Energy storage	The DEMO-LAR Plant design shall integrate energy storage to assure preferably continuous power output, and /or soften transients in case of loss of plasma control
Plant requirement	01.10	DLAR-PRd-01.10		Grid connection	Operation of the DEMO-LAR plant shall demonstrate its capability to be connected to the grid by producing a predictable electrical power output
Plant requirement	01.11	DLAR-PRd-01.11		Recirculating Power	The DEMO-LAR plant shall demonstrate that the energy conversion is selected to minimize recirculating power. This recirculating power shall be reduced throughout its lifecycle to a level representative of a future commercial fusion power plant
Stakeholders Requirement	02.00	**DLAR-SHRd-02**	Operation	Tritium self sufficiency	The DEMO-LAR plant shall be self sufficient in terms of breeding tritium to guarantee its planned operational life
Plant requirement	02.01	DLAR-PRd-02.01		Tritium breeding	In plasma operation phase the DEMO-LAR Plant shall breed sufficient tritium to fuel its plasma without requiring supply from external sources throughout its planned operational schedule (including all planned maintenance, stand-by)
Plant requirement	02.02	DLAR-PRd-02.02		Tritium Breeding Ratio	The design and technology of the first wall of the DEMO-LAR plant shall be designed to provide a tritium breeding ratio (TBR) with adequate margin to guarantee reliable tritium operation

*Table 1: Plant requirements propagated from DLAR-SHRd-01- Status of Plant Requirements Gate 2a DEMO-LAR (EFDA_D_2SP7U4)**

DEMO LAR divertor 2025 long & short-leg divertor – Physics & Engineering Improvements

Aspect	Long-Leg Divertor	Short-Leg Divertor
Heat Flux Management	Superior flux expansion reduces peak heat loads; better surface area distribution.	Limited flux expansion leads to higher localized heat loads.
Magnetic Geometry	Extended connection length enables advanced shaping (e.g., Super-X), improving exhaust control.	Compact geometry restricts shaping flexibility and connection length.
Detachment Control	Easier to achieve and sustain detachment; detachment front is more stable and controllable.	Detachment onset is harder to control; more sensitive to upstream conditions.
Neutral Trapping	Enhanced neutral trapping improves recycling and detachment efficiency.	Lower neutral trapping efficiency; detachment relies more on impurity seeding.
Impurity Seeding Efficiency	Requires less impurity concentration for effective detachment.	Higher impurity levels needed to achieve similar cooling effects.
Recombination Effects	Recombination sinks more prominent in deeply detached regimes; helps reduce ion flux.	Recombination less effective; detachment relies more on radiative cooling.
Thermal-Hydraulic Behaviour	Easier to implement efficient cooling strategies due to extended geometry.	Compact design challenges cooling; double-circuit systems help mitigate.
Operational Margin	Wider margin for safe operation under high power loads; better resilience to plasma variations.	Narrower margin; more sensitive to plasma and impurity fluctuations.
Engineering Integration	Requires more space and complex coil arrangements; higher integration challenges.	Easier to integrate into compact reactor designs; better for early-stage DEMO layouts.

In summary long-leg divertors offer significant physics advantages, especially in handling power exhaust and maintaining detachment. However, short-leg designs remain attractive for their compactness and engineering feasibility as:

- Reduction of divertor cassette size;
- Reduction of VV size;
- Reduction of TF coil size;
- Reduction of lower port size;
- Reduction of divertor targets size and consequent cost saving;
- Simplification of design of divertor cassette;
- Reduction of activation waste stemming from divertor;

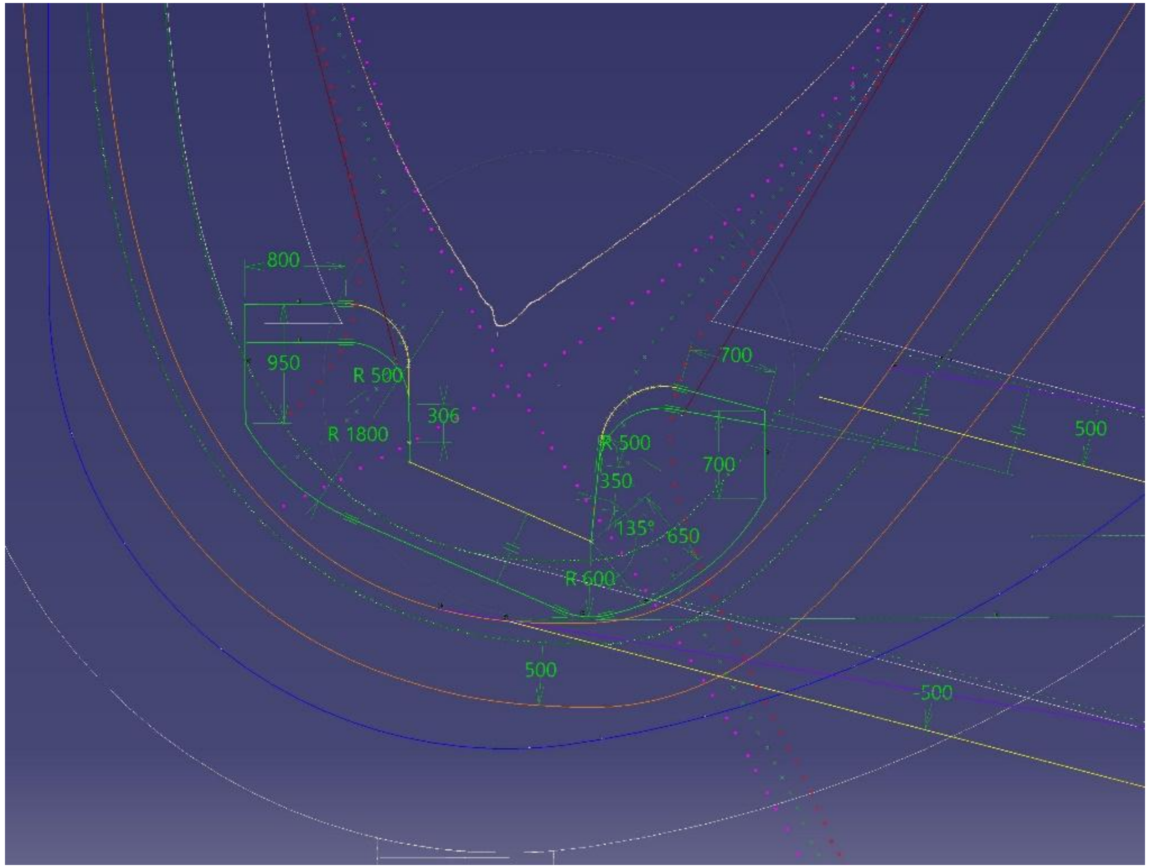
DEMO LAR divertor 2025 - Main Divertor Parameters

	Design	Comments
Grazing angle	2°	
Strike point sweeping	sinusoidal movement of 20 cm peak-to-peak at 1Hz	
Inner leg	Short leg: 0.9m Long leg: 1m	
Outer leg	Short leg: 0.9m Long leg: 1.2m	
$\dot{q}_{div,outer}$	44.35 (49.23) [MW/m^2]	
Peak heat flux density in normal operation	Length of flat top: 2h -Number of Cycles: 6600 -Heat flux: 10 MW/m2	Once the first SOLPS runs will be available the detached HF will be updated and is it expected to be lower.
Peak heat flux density in slows transients	TBD	Once ramp up scenarios simulations will be performed, the HF transients will be updated (in DT or He cases, as previous studies)
Surface thermal power (by core radiation)	TBD	
Surface heat flux density (by core radiation)	TBD	
Strike point position	Reference plasma profiles	
Divertor Poloidal profile	reference CAD 2D profiles	
Lower port inclination	As from reference CAD – 10° respect to horizontal direction	
Number of modules	3 cassette per sector	

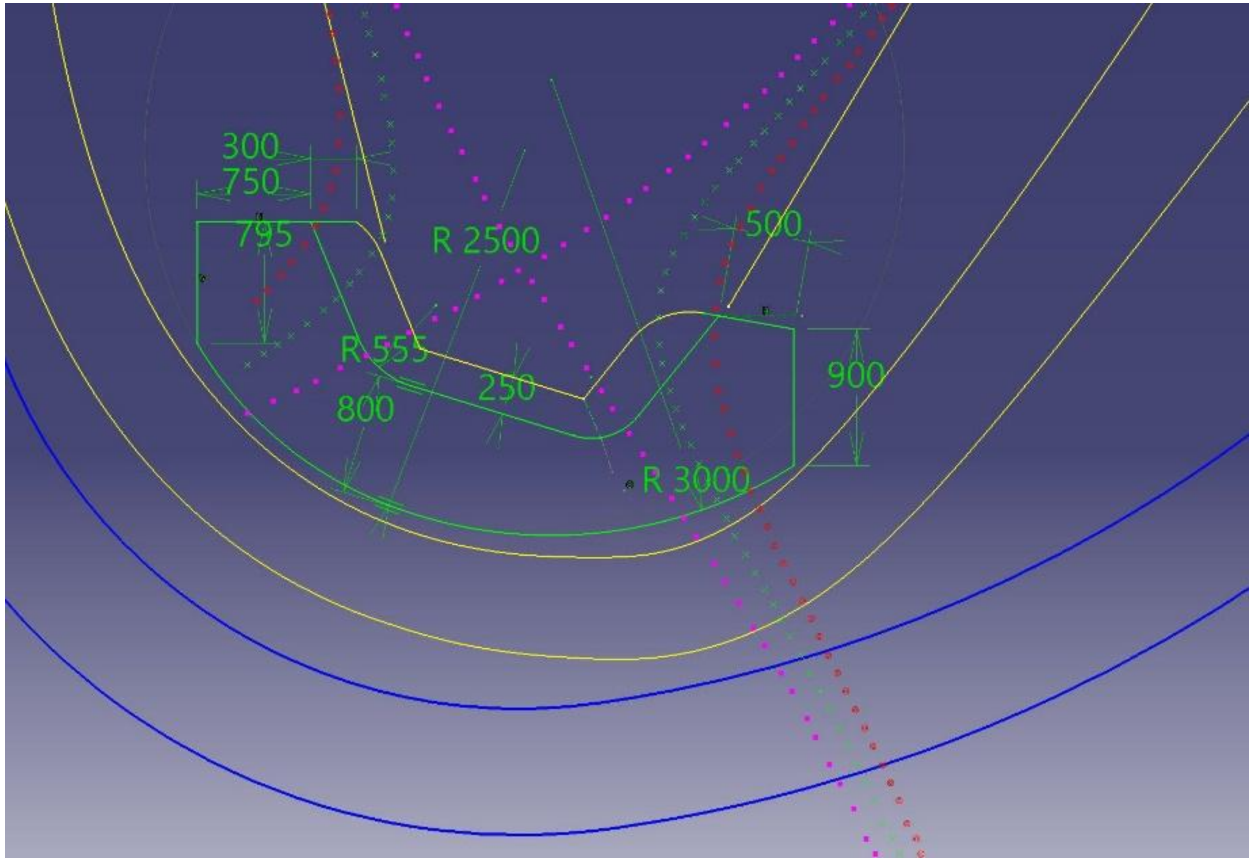
Table 3: Divertor input data*

*Ref: DEMO Low Aspect Ratio: Input data document for Work Packages (2RZK7F)

DEMO DIV LAR 2025 – Long/short leg – Plasma Profile*



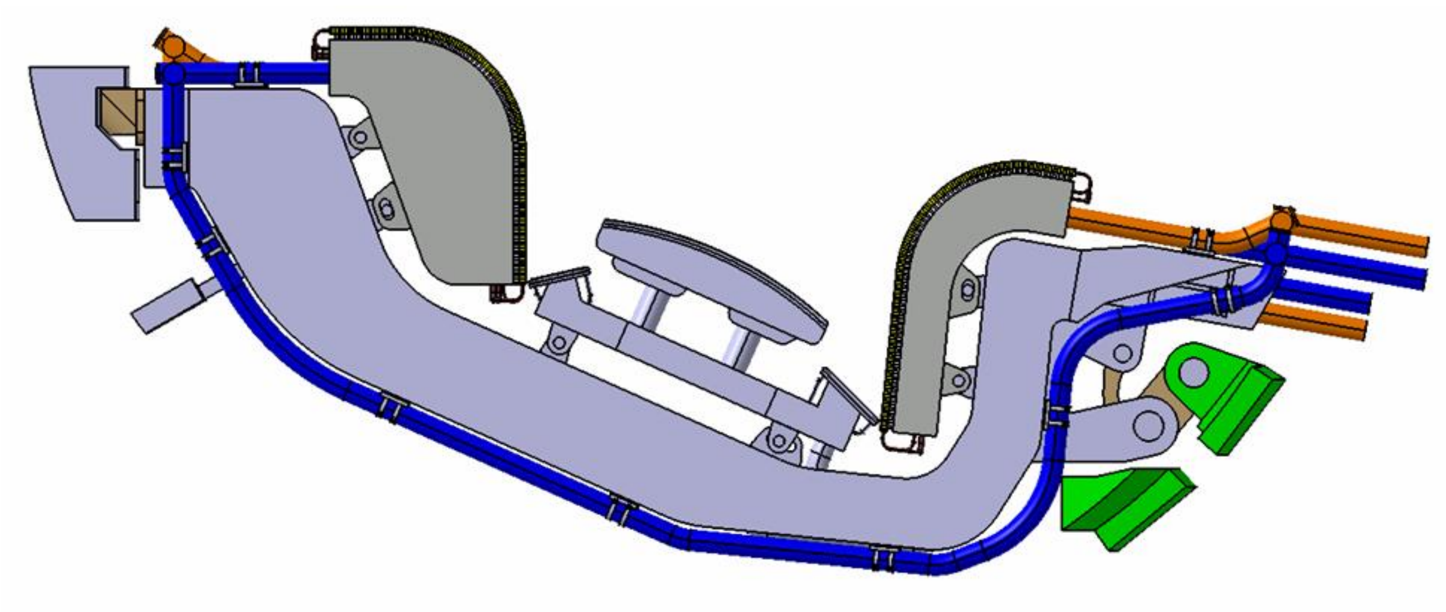
Long leg option



Short leg option

*Divertor poloidal profiles for A2.8 R8.6m (2RUHZZ)

DEMO LAR divertor 2025 –long leg option – CAD MODEL



- two cooling systems with low pressure and low temperature for PFC (7.5 MPa, 130°C) and high pressure and high temperature for cassette, reflector plates and shielding liners (15.5 MPa, 295°C).

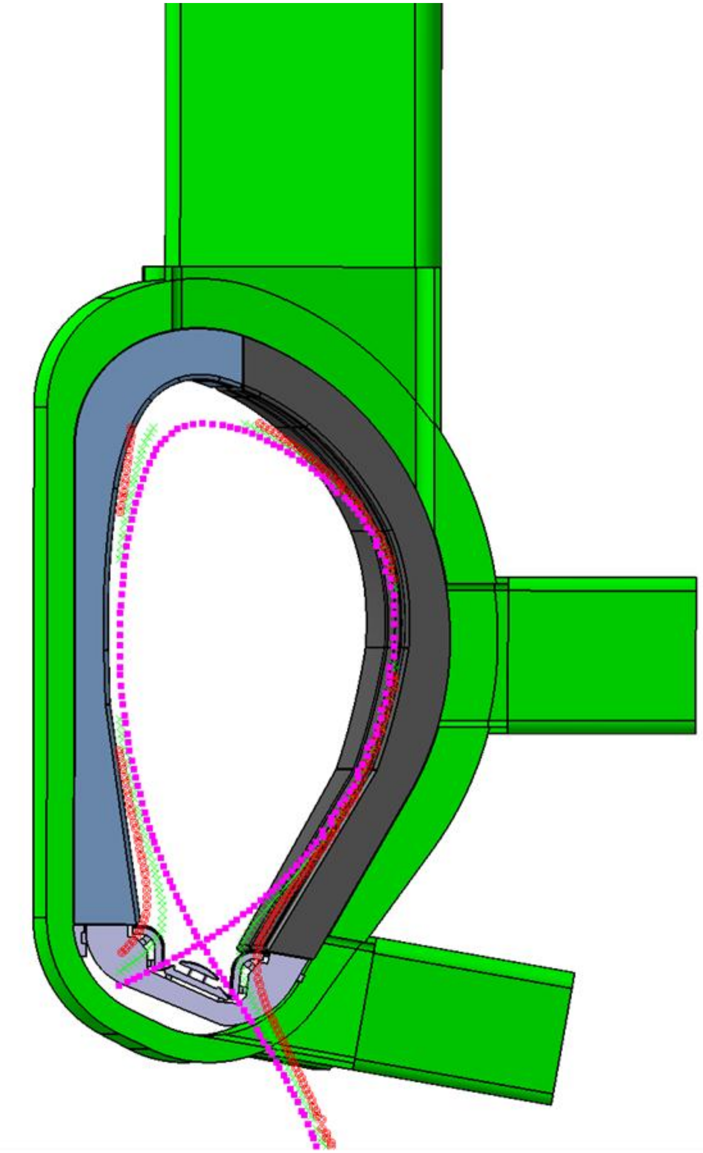
- main manifolds are blue for inlet and orange for outlet.

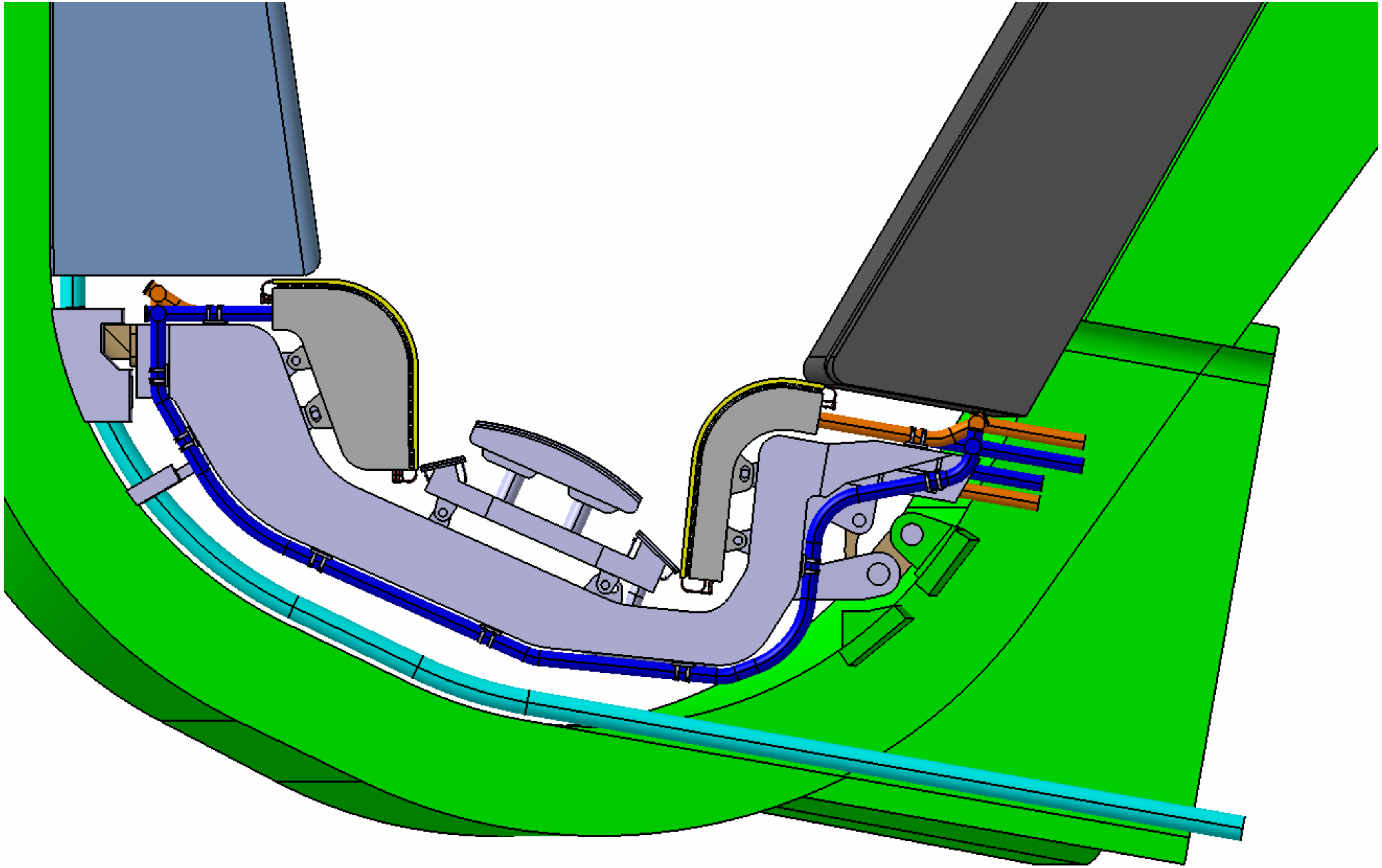
- For the VTs support part (or back plate) we should consider two options (AISI 316 Ti as reference and CuCrZr as alternative);

- The material for the Shielding liner/reflector plates support block structure is EUROFER.

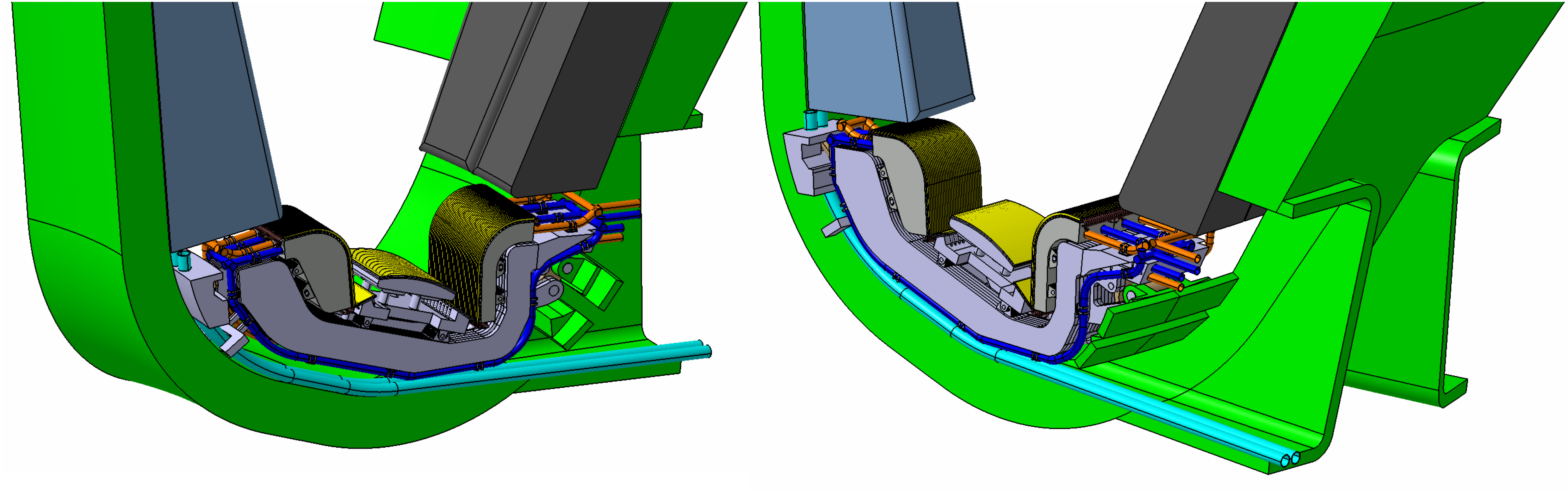
-The Shielding liner/reflector plates are protected with a plasma spray layer of tungsten (about 2 mm).

DEMO LAR divertor 2025 –long leg option – CAD MODEL

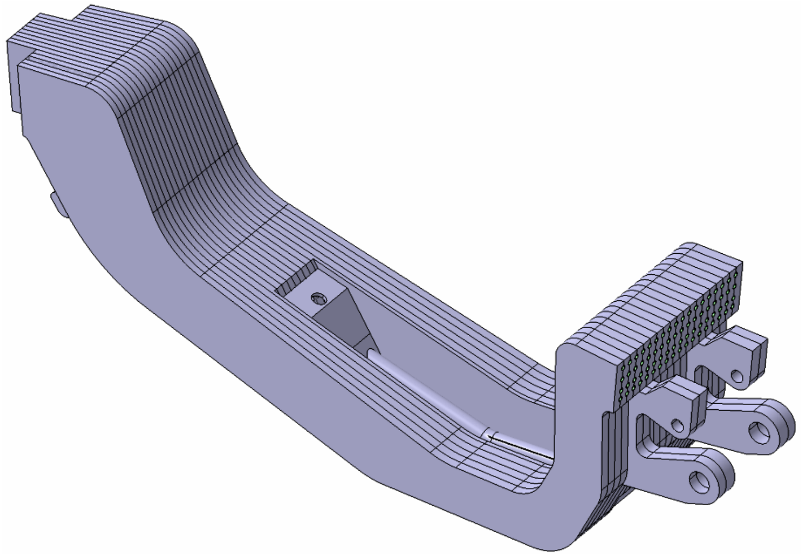


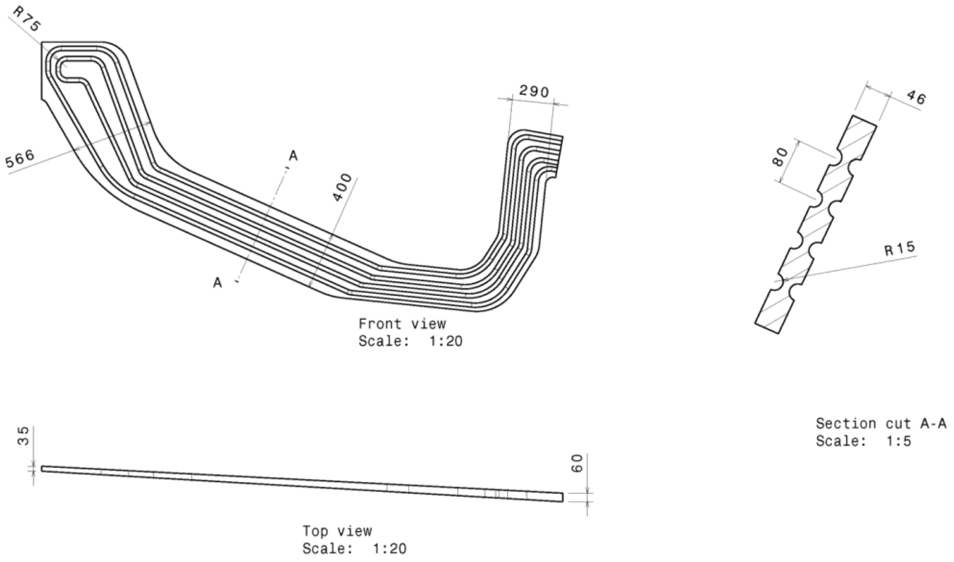


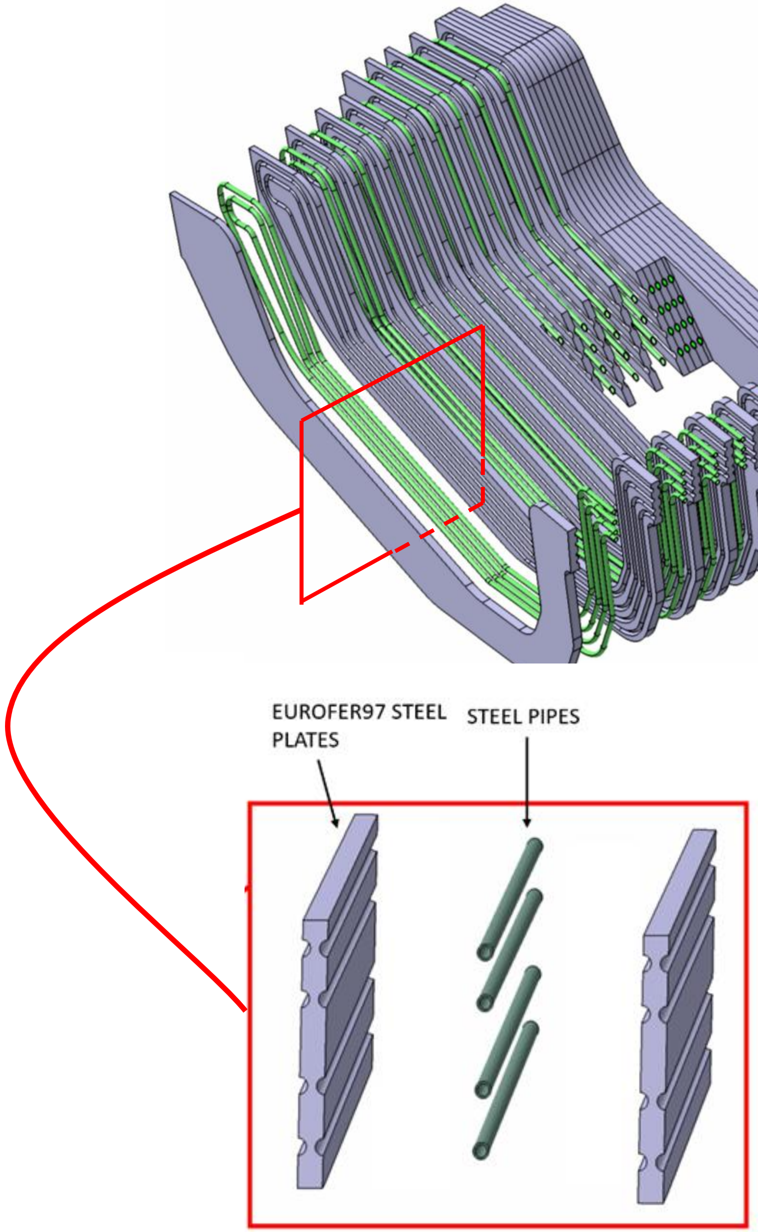
DEMO LAR divertor 2025 –long leg option – CAD MODEL



DEMO LAR divertor 2025 –long leg option -Cassette Manufactory detail



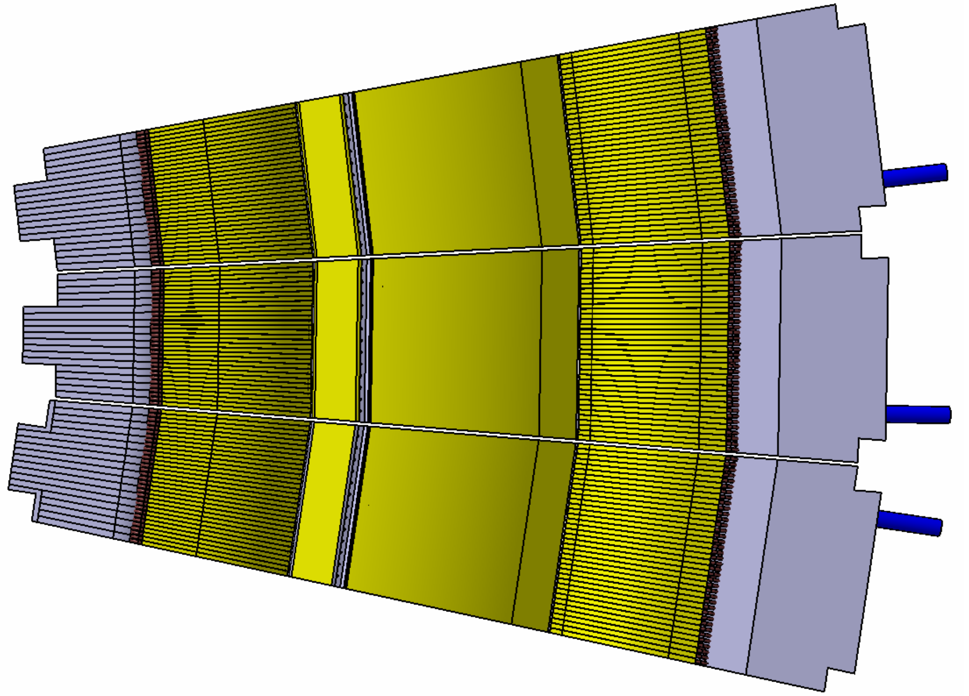


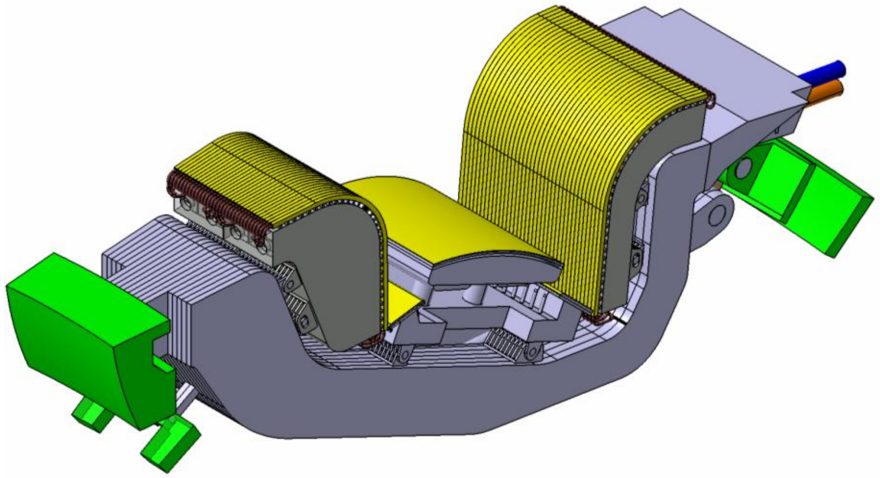


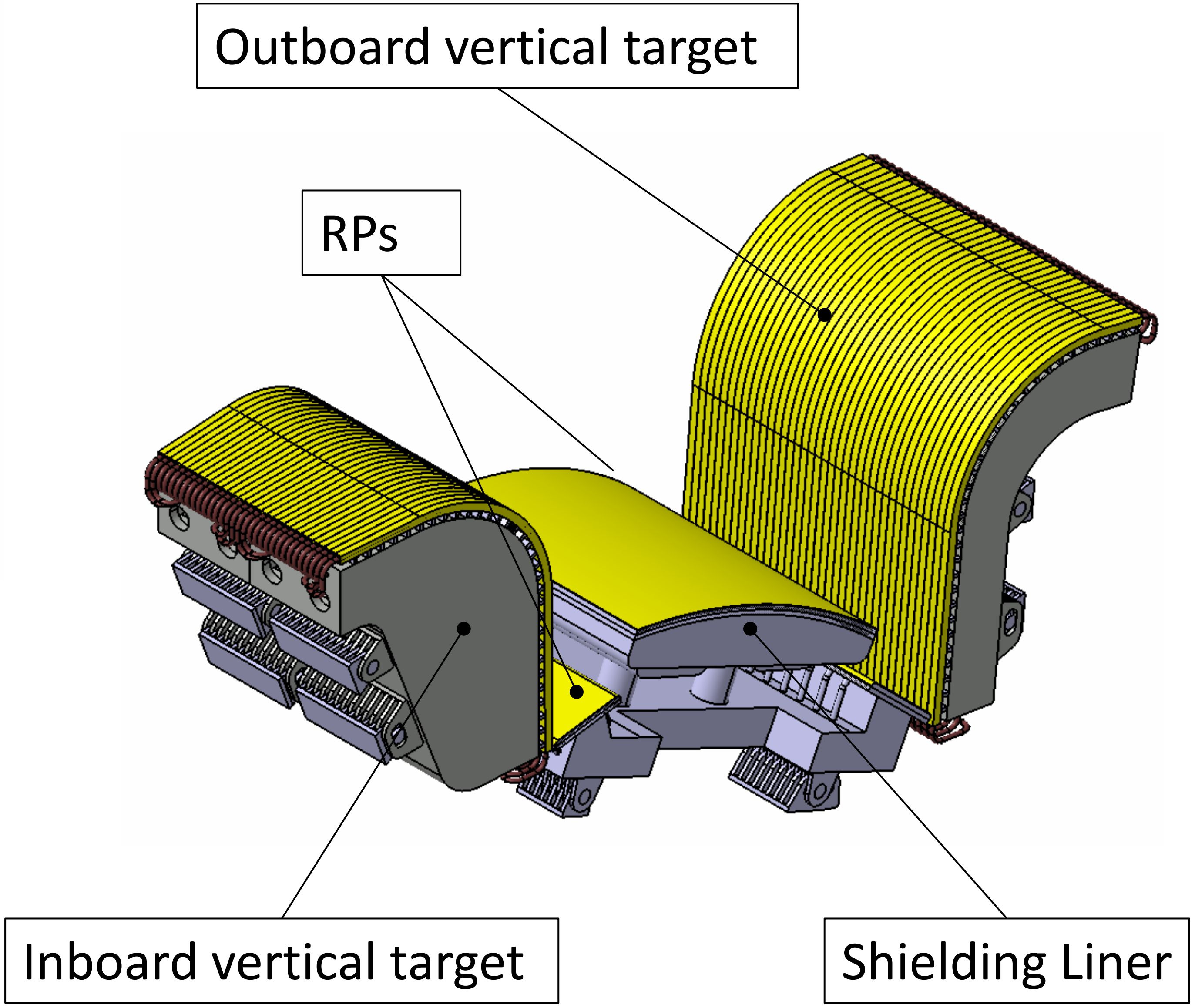
WELDING OPTIONS:

- HIP
- BRAZING
- LASER
- A COMBINATION OF DIFFERENT WELDINGS

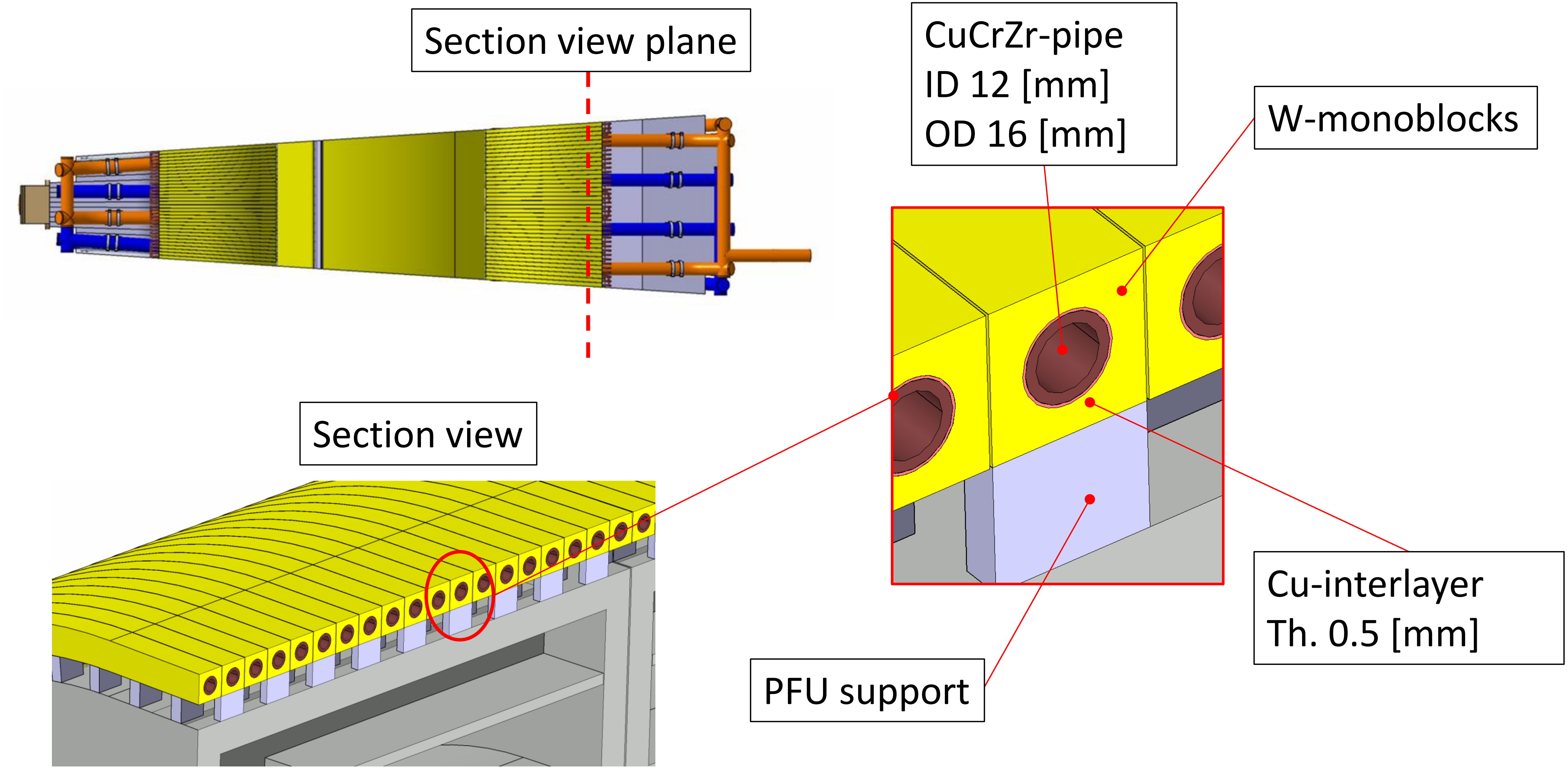
DEMO LAR divertor 2025 –long leg option –PFCs detail



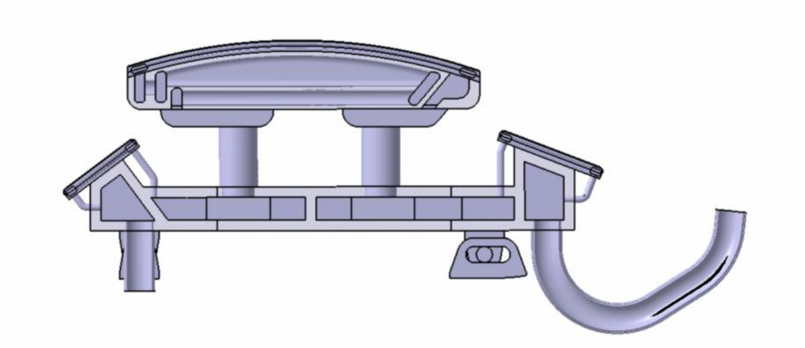


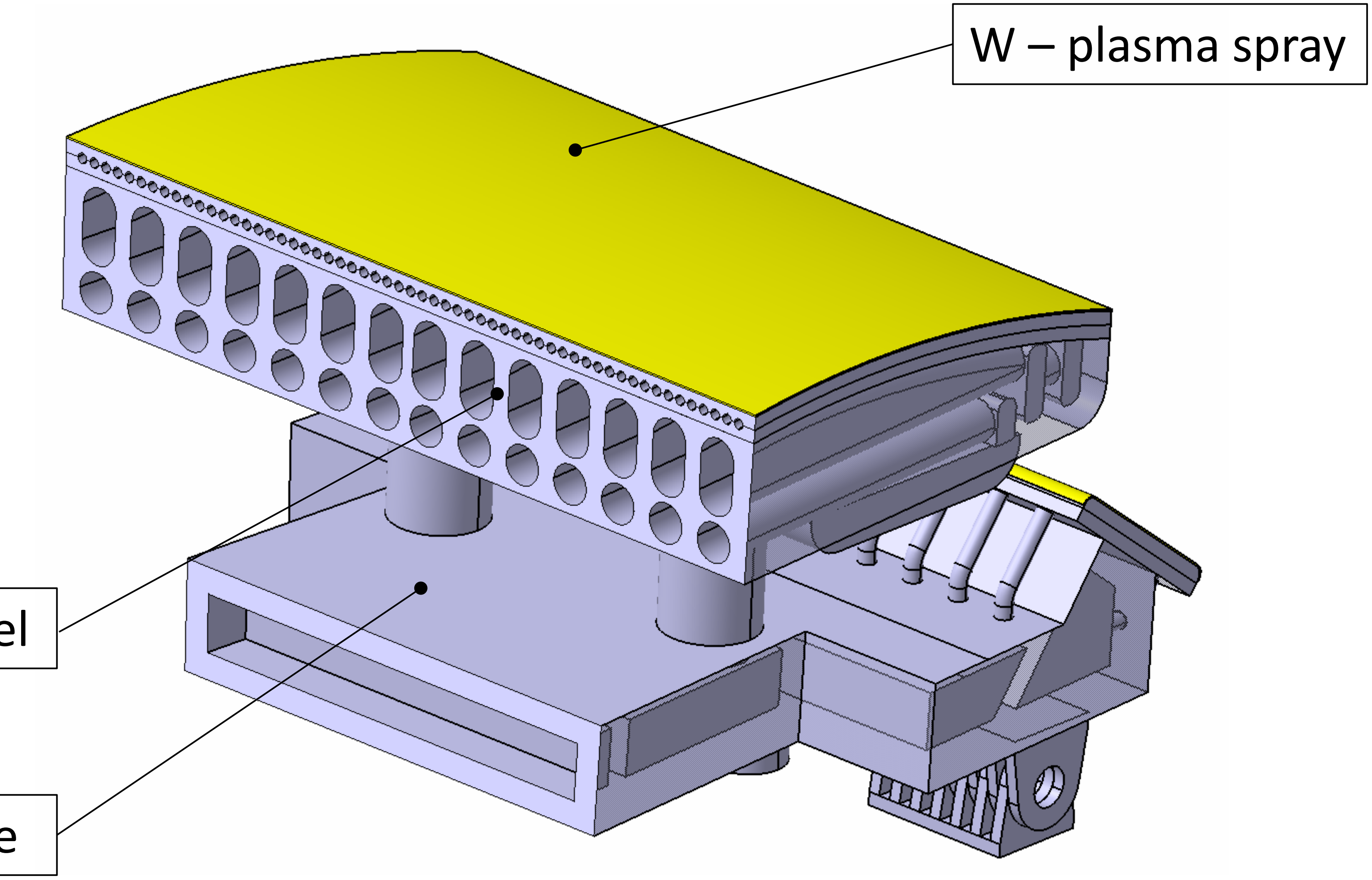


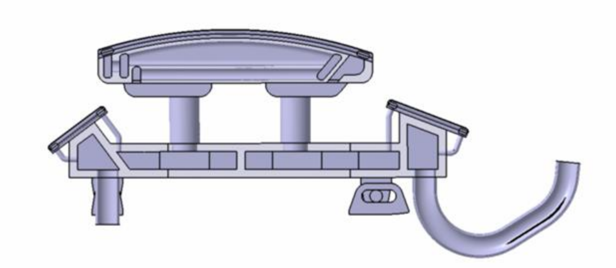
DEMO LAR divertor 2025 –long leg option –PFCs detail

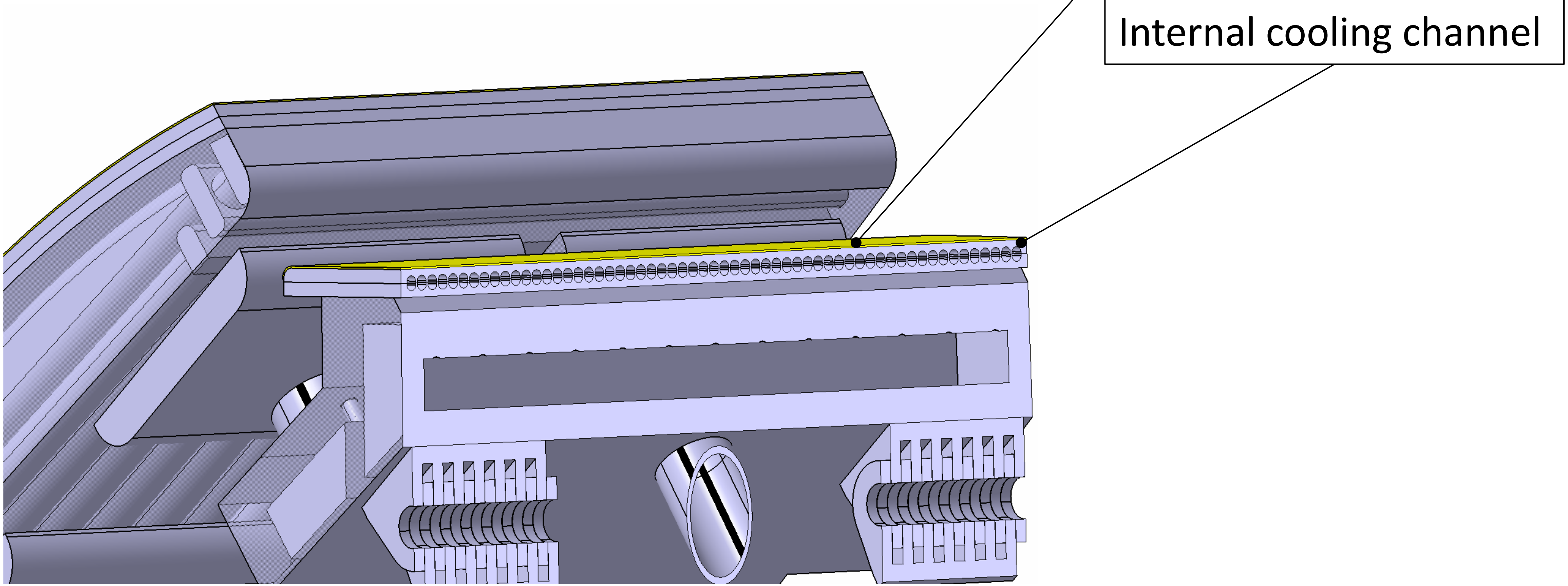


DEMO LAR divertor 2025 –long leg option –SL Manufactory detail



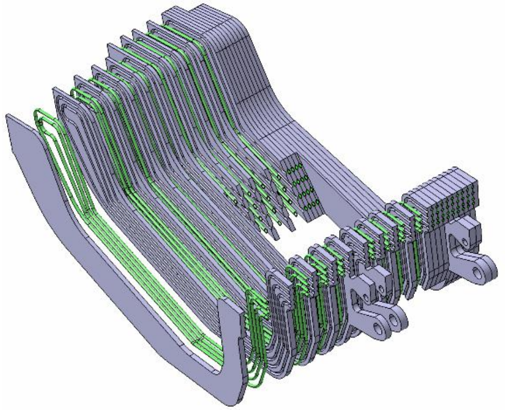


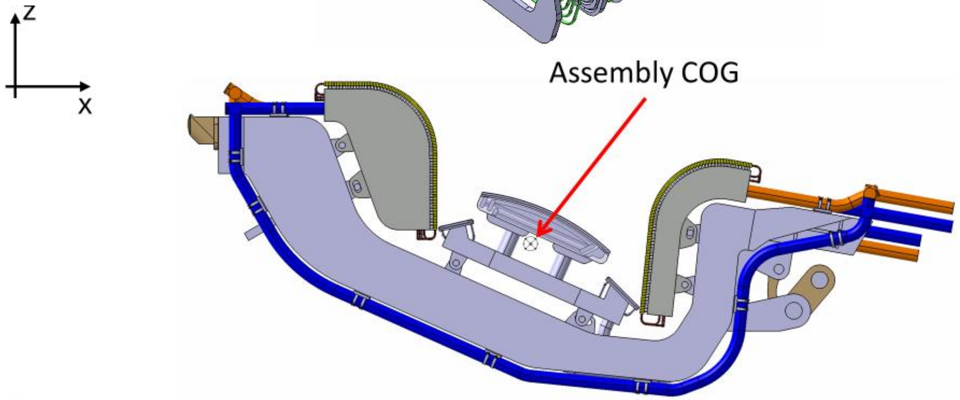



W – plasma spray
Internal cooling channel

DEMO LAR 2025 – Divertor Long Leg - DIV-Remote Maintenance Interface

DEMO DIV LAR 2025 Cassette with -circular cooling channels



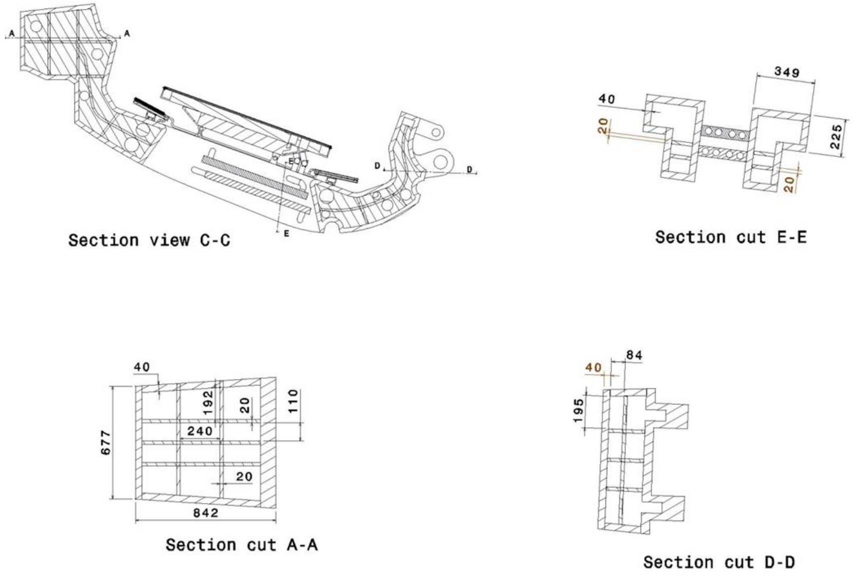


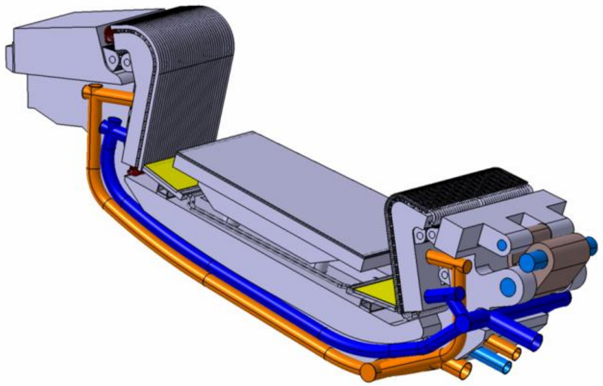
Assembly COG coordinates (respect to the tokamak CS):

(7233 mm; 0 mm; -7201 mm)

The total weight of the divertor assembly, without cooling water is:
17.5 tons

DEMO DIV 2024 Cassette with Box Structure





Divertor Assembly without cooling water(installation and RH)	Total Mass [Kg]	7917

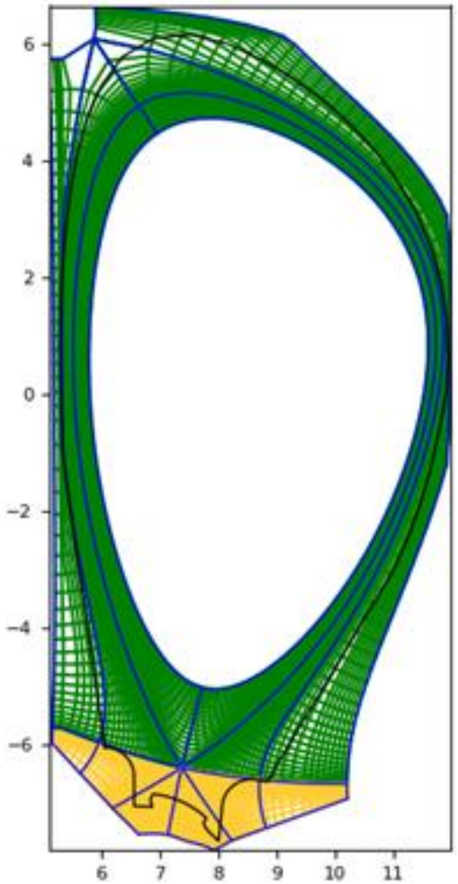


Fig-2 SOLEDGE3X grid and first wall shape

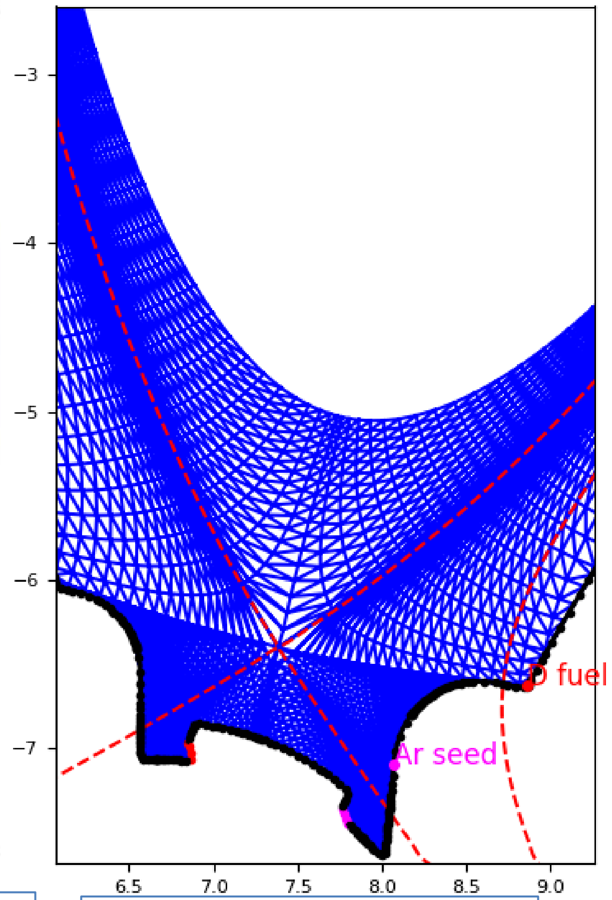


Fig-3 Eirene grid, puffing and pumping location

-**SOLEDGE3X** and **SOLPS-ITER** was employed in 2D mode, and therefore all the input and output quantities discussed here assume axisymmetric conditions, including the divertor and the first wall.

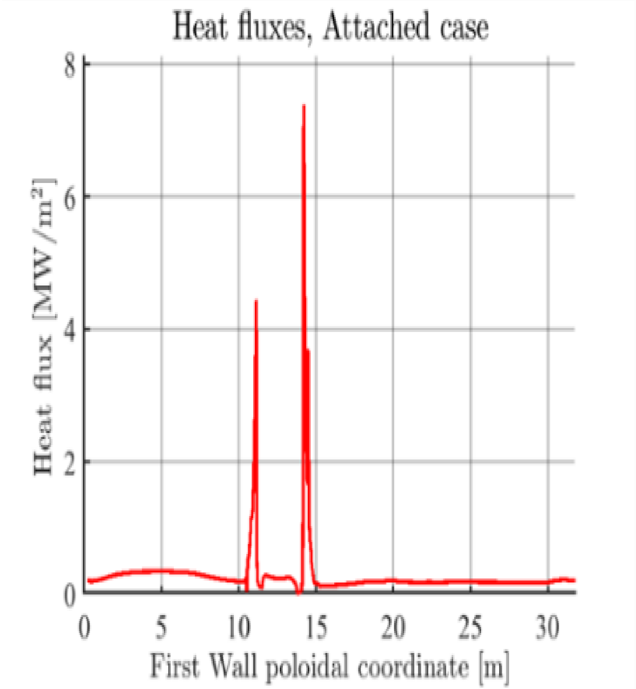
-The neutral particle modelling was performed using **EIRENE**, coupled to SOLEDGE3X.

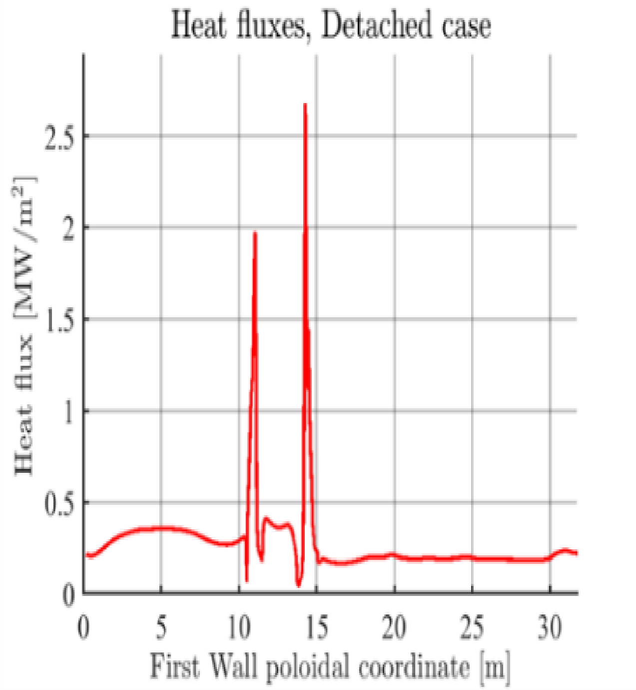
-Pumping is modeled through the surfaces highlighted in red and magenta in Figure 3, which represent the openings toward the sub-divertor region, where a **pumping speed of 100 m^3/s is imposed**.

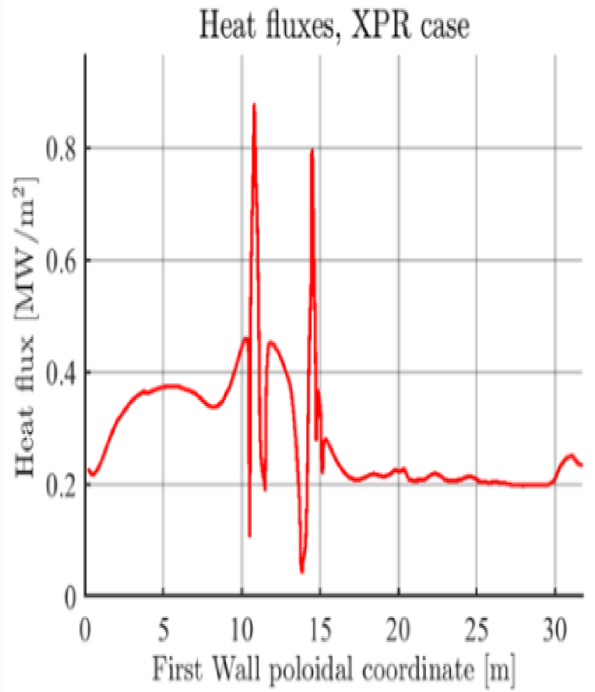
-The fueling rate was adjusted to achieve a separatrix **electron density of ne,sep = $n_{e,sep}$ = 3.8 × 10^{19} m^{-3}**

- the transport parameters used are the "reference" ones (see F. Subba et al 2021 Nucl. Fusion 61 106013) and produce a lambda_q of about 3mm.

The heat flux calculated by SOLEDGE, which includes both neutral charge, ion charge, and radiation from the plasma edge and the SOL, for the argon simulation described above is always less than 10 MW in both the cases with and without argon, where there is partial reattachment. **The flux does not exceed 10 MW/m2** even when there is partial loss of detachment. The flux at the dome exceeds 0.5 MW/m2 and must be added to the flux from the core. The sum of the two contributions **on the DOME is between 0.5 and 1 MW/m2**.



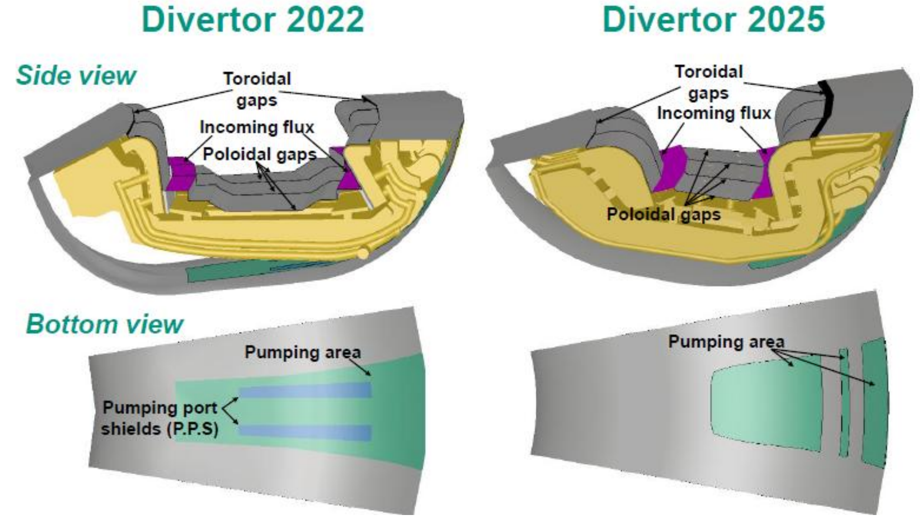


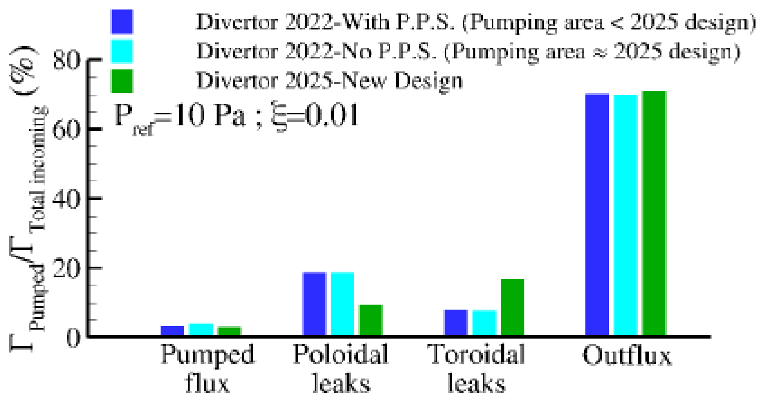


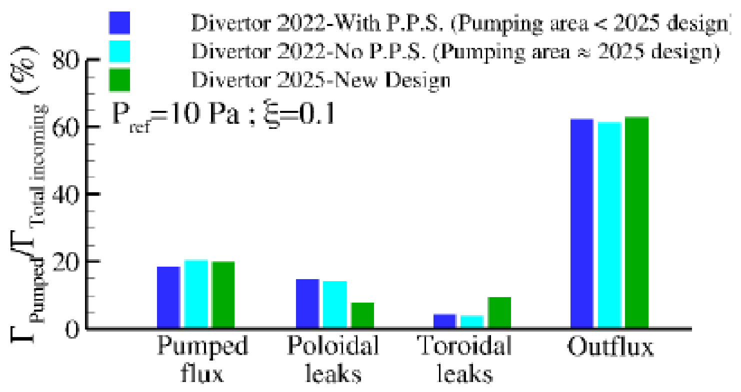
Luca Balbinot- DIV-DEMO.S.2-T003 - D001 Simulation (using SOLPS-ITER or SOLEDGE3X) on the DEMO Divertor 2025 long leg option with umbrella dome configuration.

DEMO LAR divertor 2025 – Divertor Neutral Gas Flow and Optimizing of Divertors*

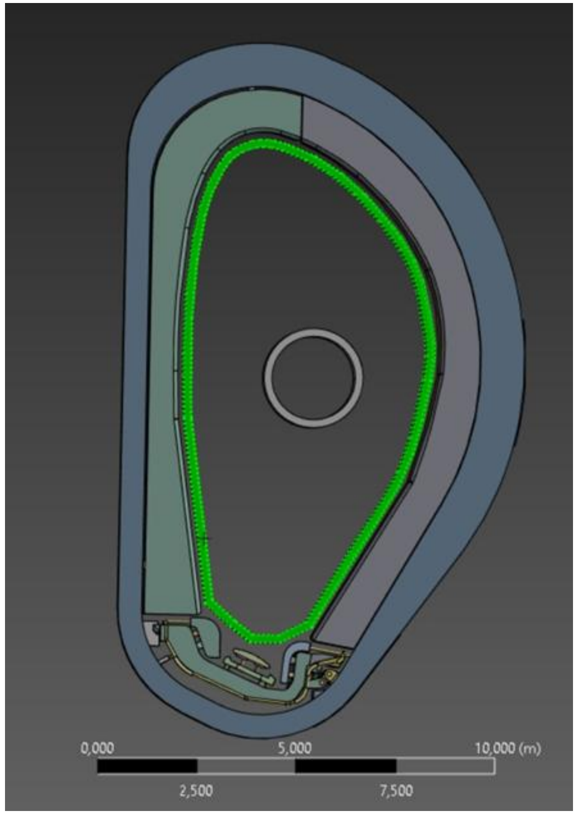
- 3D DIVGAS simulations of a full divertor sector reveal that outflux (back flux to the vacuum vessel via divertor neutral entry gaps) through entry gaps consistently exceeds 60% of the total incoming flux.
- Based on the limitations imposed by the foreseen DEMO pumping technology, the pumped flux is expected to remain well below 20% of the incoming flux.
- The new divertor design, under identical inlet conditions, exhibits similar pumped flux and outflux levels. While it improves performance regarding poloidal gaps, increased toroidal leakage suggests room for further optimization.

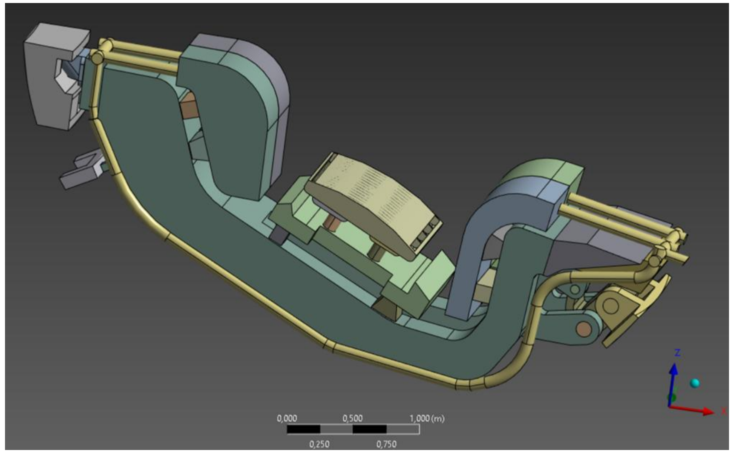






* See Christos. Tantos - DIVGAS: A Robust and Reliable Workflow for Modelling Divertor Neutral Gas Flow and Optimizing Divertors in Next-Generation Fusion Reactors – Applications to DTT and EU-DEMO Divertors. Today Poster Session.





Model for evaluating the transient EM loads associated to eddy currents

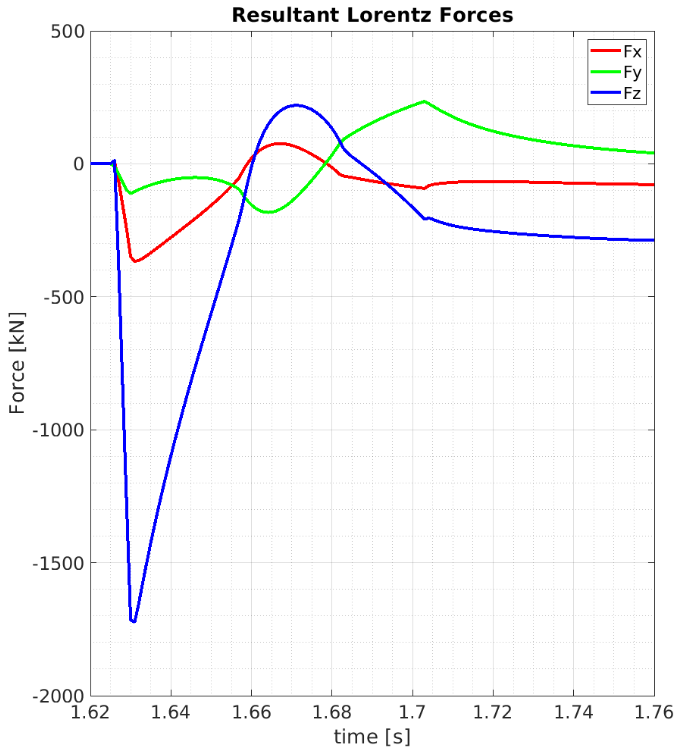
- A transient 3D Magneto-Quasi-Static (MQS) problem is solved
- A section of 22.5° of the tokamak is studied
- Numerical FEM model implemented in Ansys EMAG

Components	Material
Vessel	AISI 316 L(N) IG
Blanket	EUROFER97
Divertor cassette	EUROFER97
Cassette support to VV (inward)	AISI 316 L(N) IG
Cassette support to VV (Wishbone)	Ti-6Al-4V
Vertical targets, pipes, manifolds, and supports of cooling system	AISI 316 SS

Plasma disruption events under study for DEMO LAR divertor;

1. VDE DOWN SLOW;
2. VDE DOWN FAST;
3. MD;

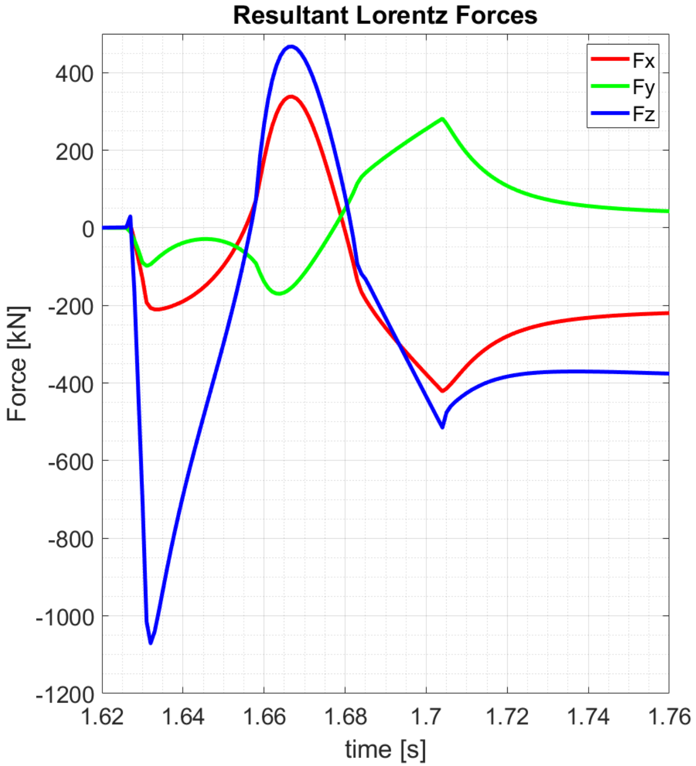
Transient EM loads on the Whole Divertor (VDE_down_74 ms)



Peak values for each component

Fx [MN]	Time [s]	Fy [MN]	Time [s]	Fz [MN]	Time [s]
-0.37	1.631	0.23	1.703	-1.72	1.63

DEMO LAR - long leg option 2025

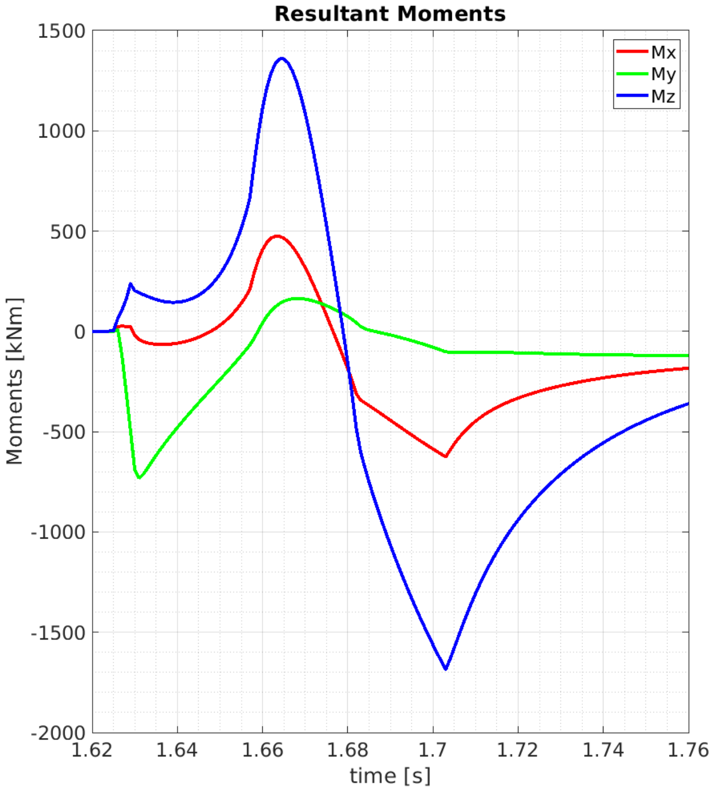


Peak values for each component

Fx [MN]	Time [s]	Fy [MN]	Time [s]	Fz [MN]	Time [s]
-0.42	1.704	0.28	1.704	-1.07	1.632

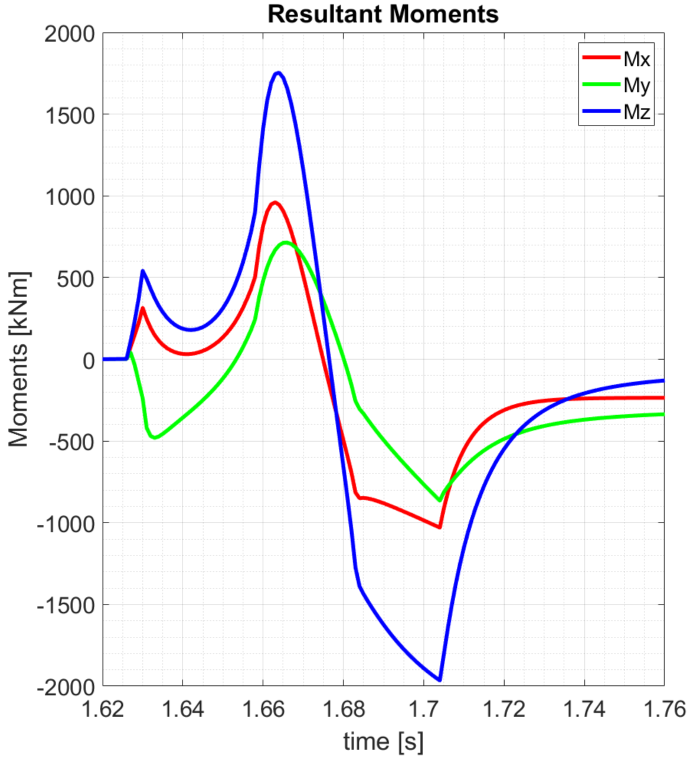
old model (EM model 2024)

Transient EM loads on the Whole Divertor (VDE_down_74 ms)



Moments related to the geometric mass center of the object (here, an external one)

X=7.2026m
Y=-0.9564m
Z=-7.0994m



Moments related to the geometric mass center of the cassette (here, an external one)

X= **7.3983m**
Y=**-0.9700m**
Z=**-6.5798m**

Peak values for each component

Mx [kNm]	Time [s]	My [kNm]	Time [s]	Mz [kNm]	Time [s]
-626.06	1.703	-731.70	1.631	-1686.4	1.703

DEMO LAR - long leg option 2025

Peak values for each component

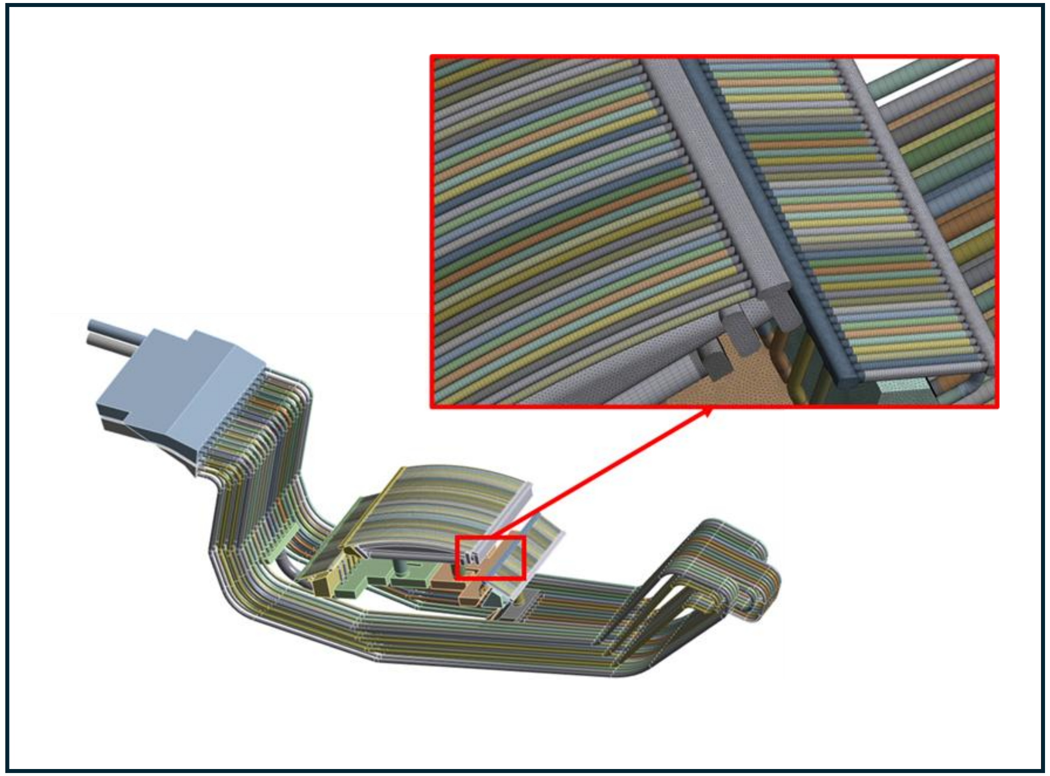
Mx [kNm]	Time [s]	My [kNm]	Time [s]	Mz [kNm]	Time [s]
-1030.12	1.704	-865.57	1.704	-1965.42	1.704

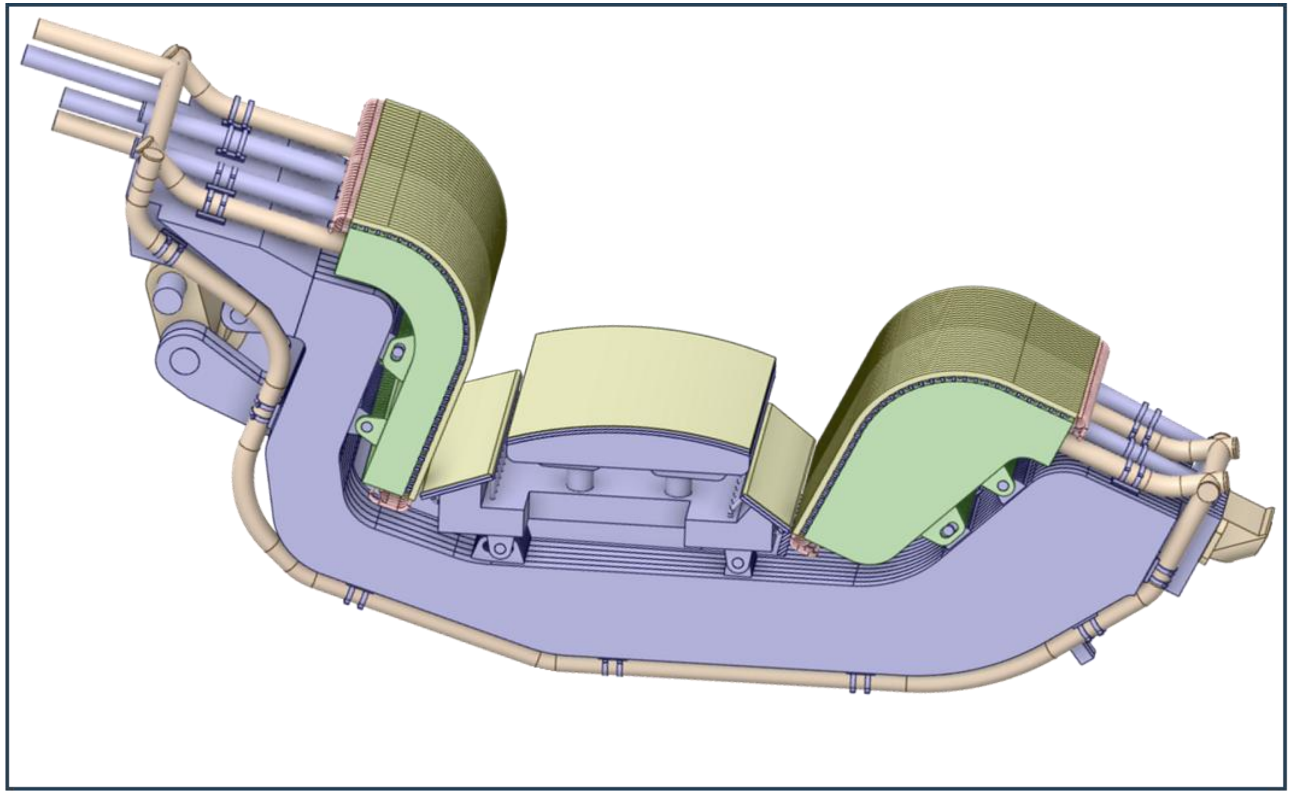
old model (EM model 2024)

DEMO LAR divertor 2025 – long leg option – Thermo-Hydraulic Analyses

In the context of the Work Package Divertor (WP-DIV) of the EUROfusion action, the University of Palermo (UNIPA) has investigated the thermal-hydraulic performances of the **DEMO LAR Divertor** cooling system.

Two cooling circuits exists: one for the Plasma Facing Components (PFC) and one for the Cassette Body (CB), including Liner and Reflector Plates (RPs).



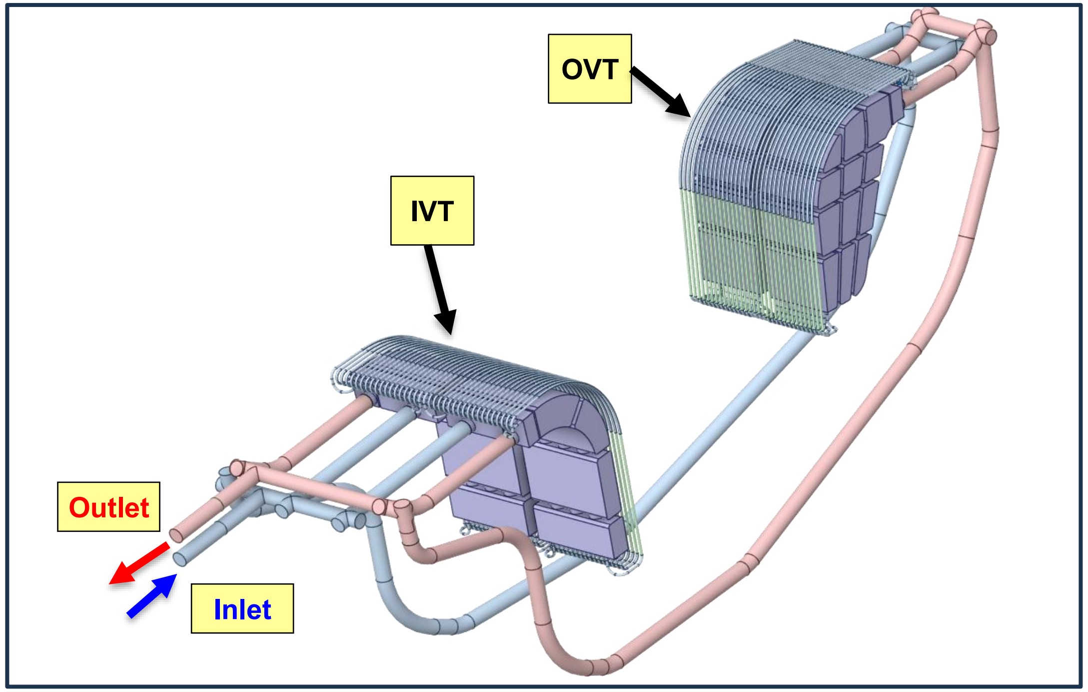


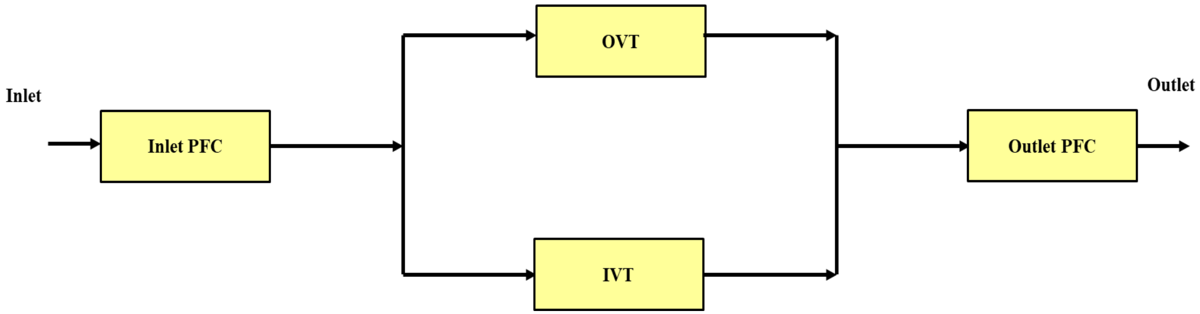
The two circuits' fluid-dynamic performances have been assessed following a theoretical-numerical approach based on the **Finite Volume Method** and adopting the **ANSYS-CFX 2023 R2** commercial **Computational Fluid-Dynamic** (CFD) code.

Hybrid structured/unstructured meshes with approximately 48 and 50 million volumes were generated for PFC and CB circuits respectively and 3D steady-state isothermal CFD analyses have been performed.

DEMO LAR divertor 2025 – long leg option – PFC cooling circuit

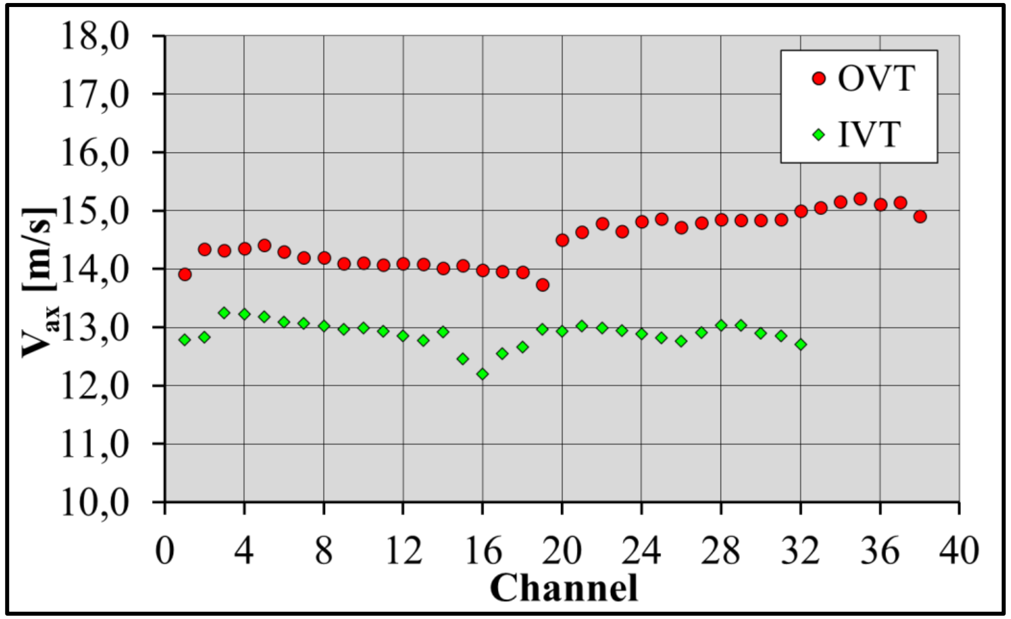
Analysis Set-up	
Analysis Type	Steady State / Isothermal
Material Library	Water
Turbulence Model	k-ω SST
Boundary Layer Modelling	Automatic Wall Functions
Wall Absolute Roughness	2-15 μm
PFU treatment	OVST
Inlet BC (Temperature/Pressure)	**133 °C / 7.5 MPa**
Outlet BC (Mass Flow Rate)	**93.30 kg/s**

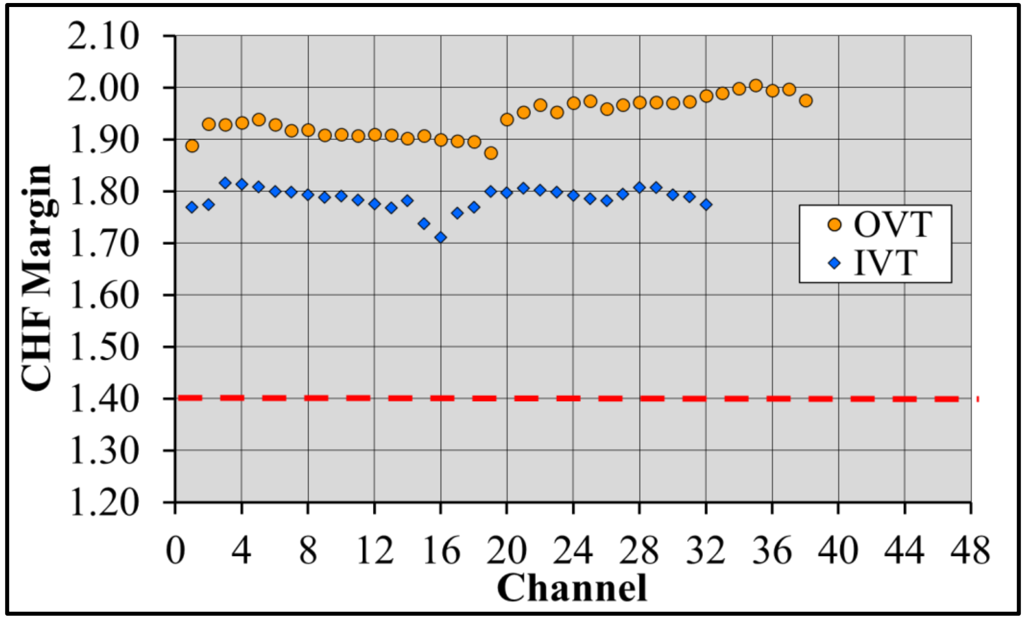




Mass Flow Rate Distribution		
Sections	**G [kg/s]**	**G/G_{Tot} [%]**
OVT Branch	53.35	57.2%
IVT Branch	39.95	42.8%
Total	93.30	-

DEMO LAR divertor 2025 – long leg option – PFC cooling circuit



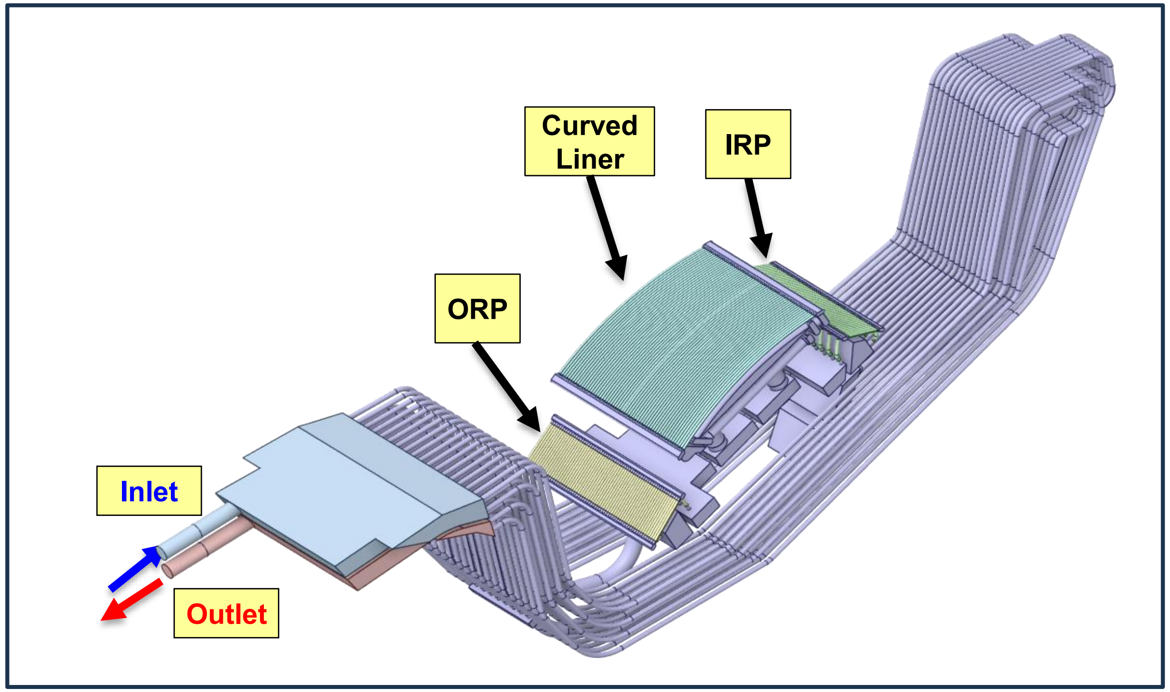


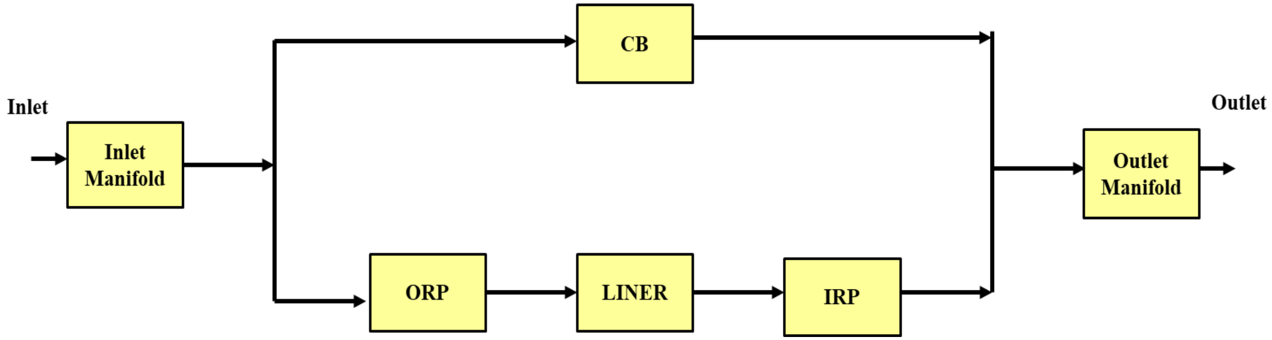
Main results:

- The **total pressure drop** is **1.22 MPa** (below the prescribed limit of 1.4 MPa).
- High velocities (~ 22 m/s) observed at Inlet and Outlet manifolds.
- The **mass flow rate distribution** between IVT and OVT is respectively of 42.8% and 57.2%.
- **Flow velocity distributions among VTs channels** are quite **uniform** (~ 13 m/s) .
- Considering a maximum heat flux of 20 MW/m^2**, CHF margins are sufficiently high for VTs channels**, between 1.7 and 2 (the threshold value is 1.40).

DEMO LAR divertor 2025 – long leg option – CB cooling circuit

Analysis Set-up	
Analysis Type	Steady State / Isothermal
Material Library	Water IAPWS
Turbulence Model	k-ω SST
Boundary Layer Modelling	Automatic Wall Functions
Wall Absolute Roughness	15 μm
Inlet BC (Temperature/Pressure)	**311.5 °C / 15.5 Mpa**
Outlet BC (Mass Flow Rate)	**15.96 kg/s**

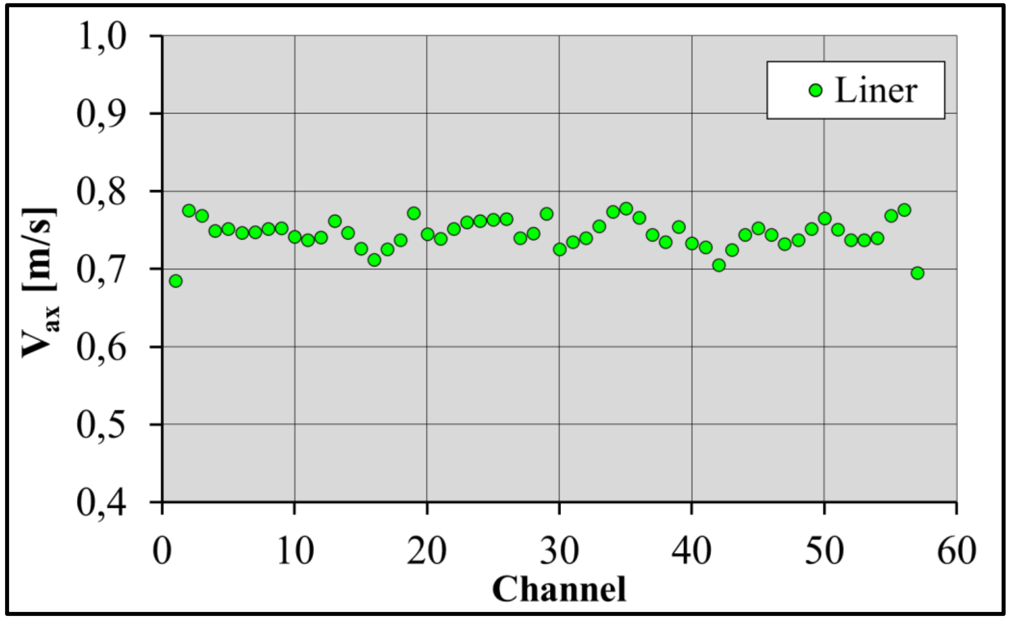


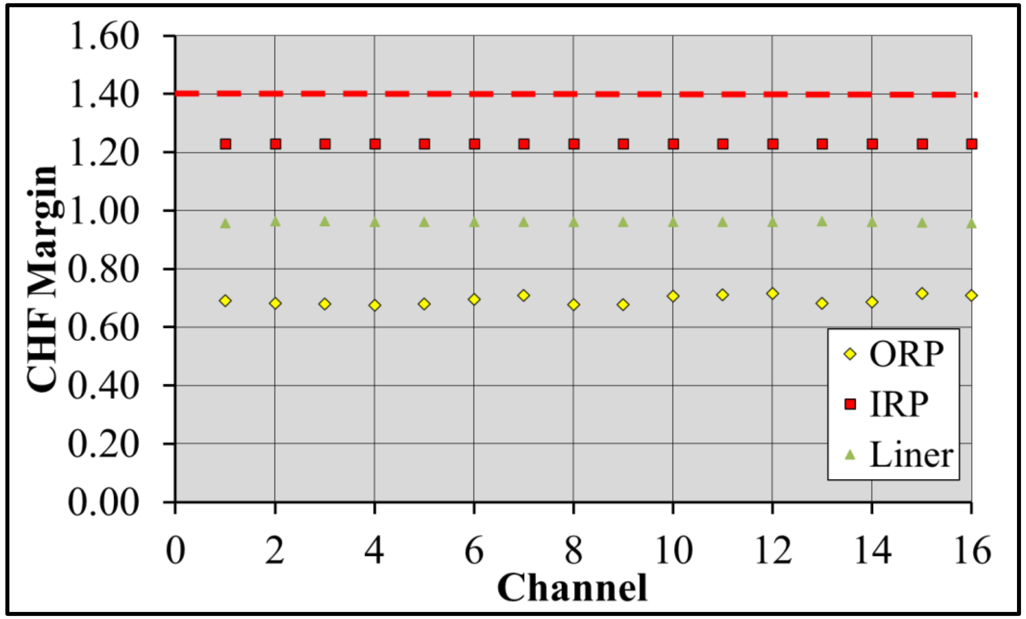


Mass Flow Rate Distribution		
Sections	**G [kg/s]**	**G/G_{Tot} [%]**
CB Branch	12.59	78.9%
Liner Branch	**3.37**	**21.1%**
Total	15.96	-

Very low mass flow rate through the Liner

DEMO LAR divertor 2025 – long leg option – CB cooling circuit





Main results:

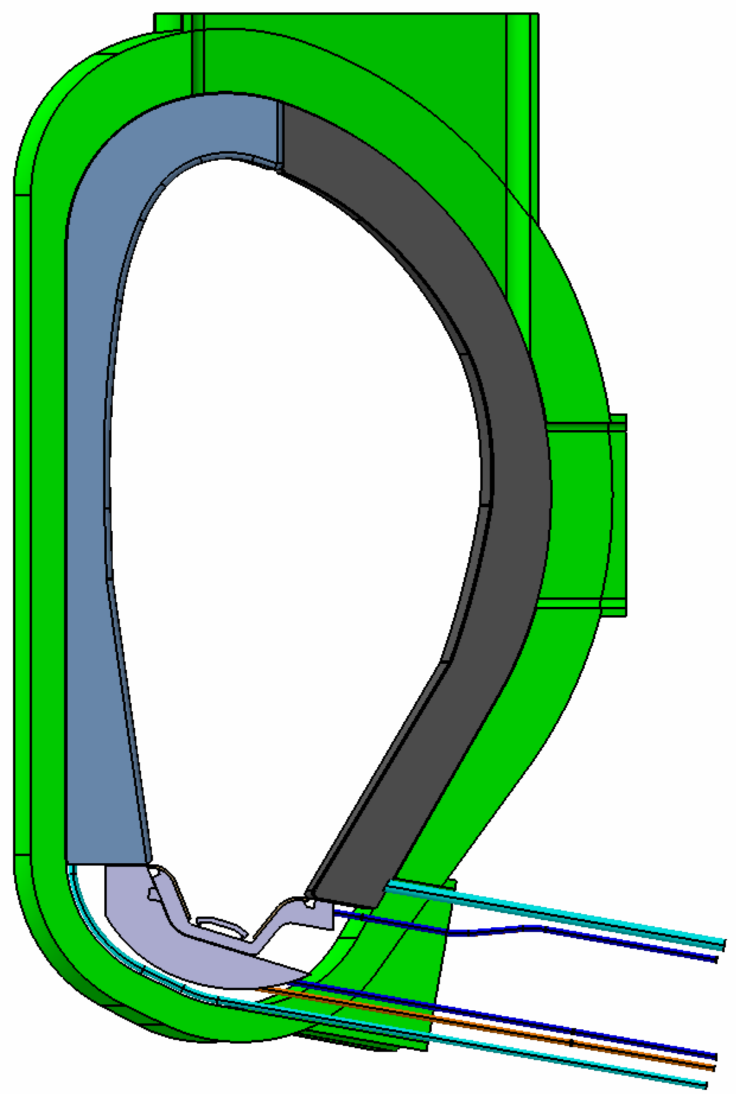
- The **total pressure drop** is **0.025 Mpa** due to the very low mass flow rate through Liner and RPs.
- **Rather low mass flow rate** (**3.37 kg/s**) goes through the Liner, while the 78.9% flows though the CB branch.
- **Flow velocity distributions among FW Liner channels** are **uniform**, instead **high non-uniformities** can be observed among **RPs channels**.
- **CHF margins are unduly low for Liner** (~ **0.9**) **and RPs** (~ **0.6 - 1.2**), significantly lower than the threshold value (1.40).

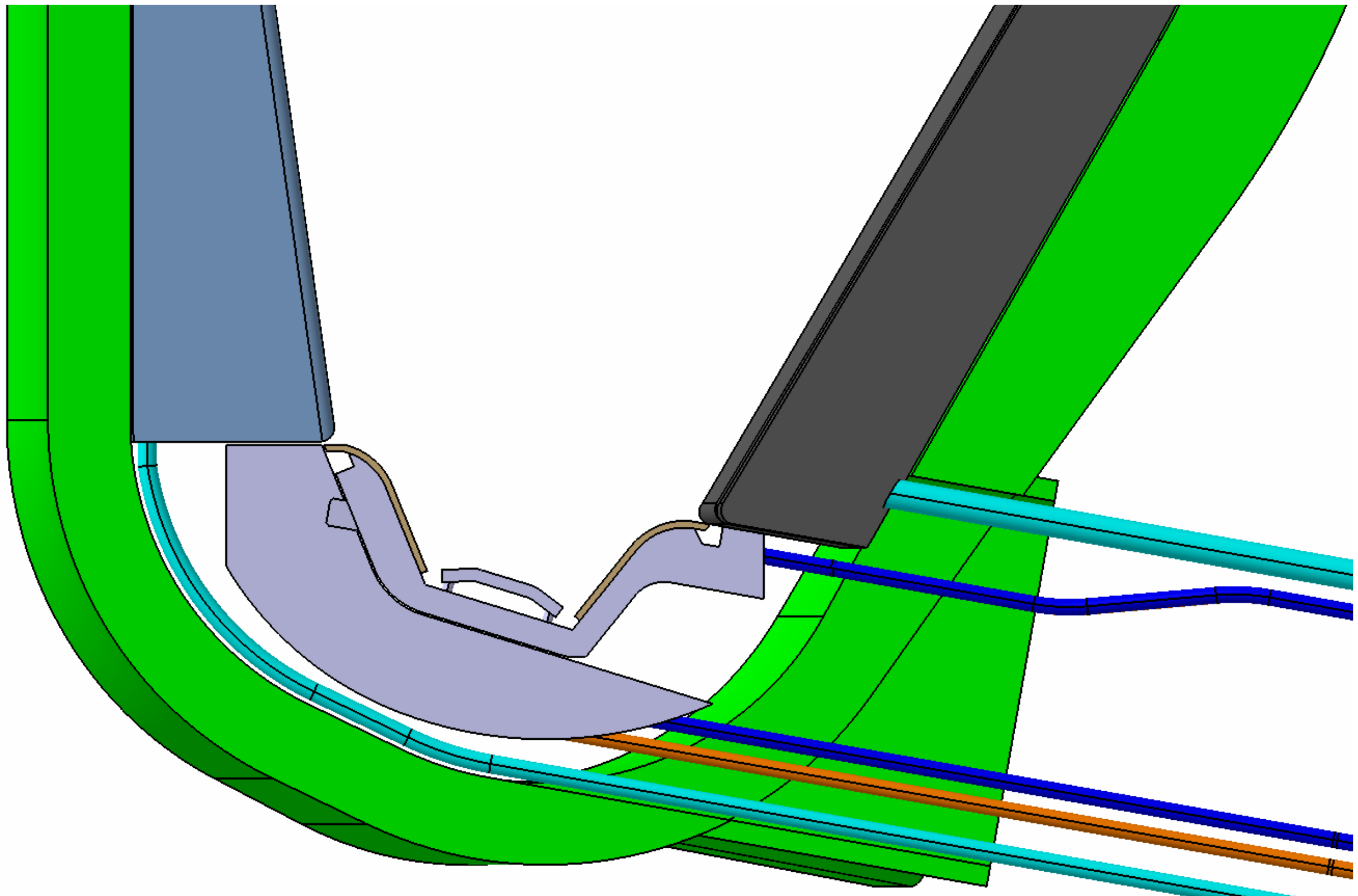
DEMO LAR divertor 2025 –short leg option

- Reduced cassette and port size;
- Lower cost and activation waste;
- Simplified assembly.

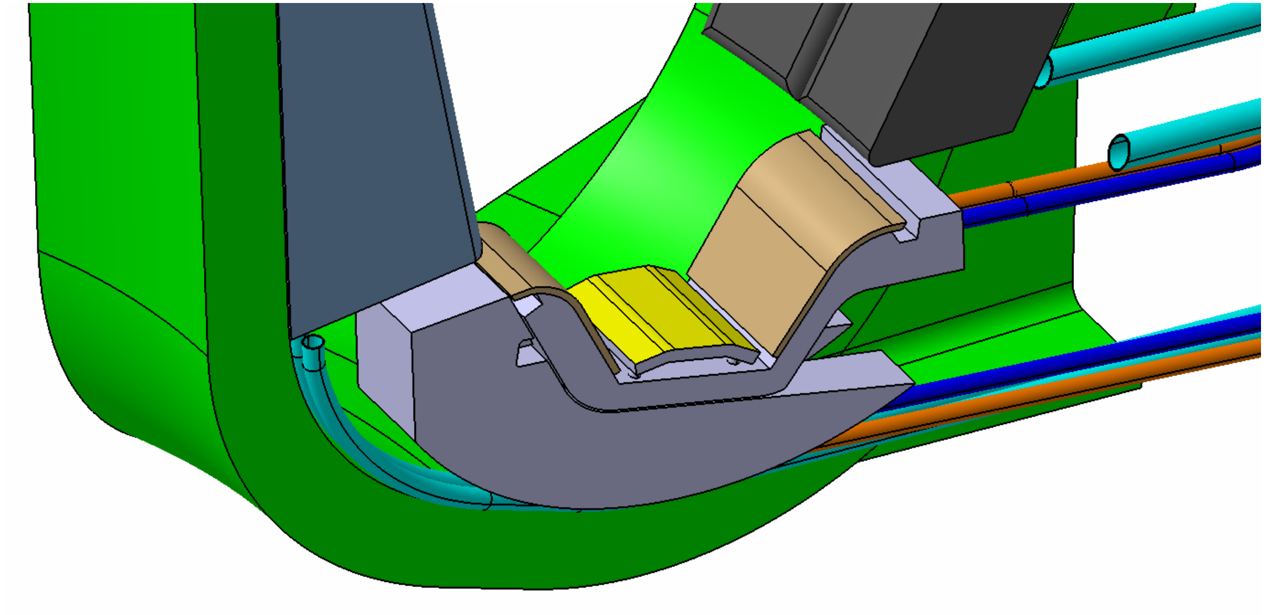
However, it faces challenges in heat flux management and detachment control.

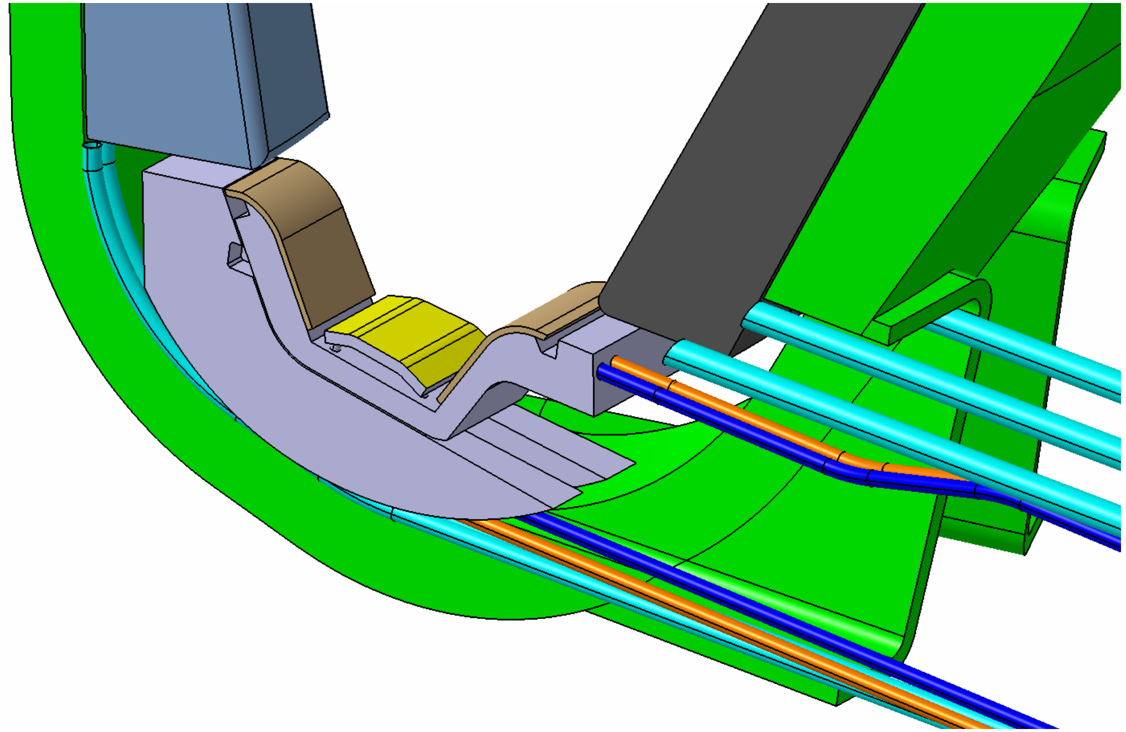
DEMO LAR divertor 2025 –short leg option



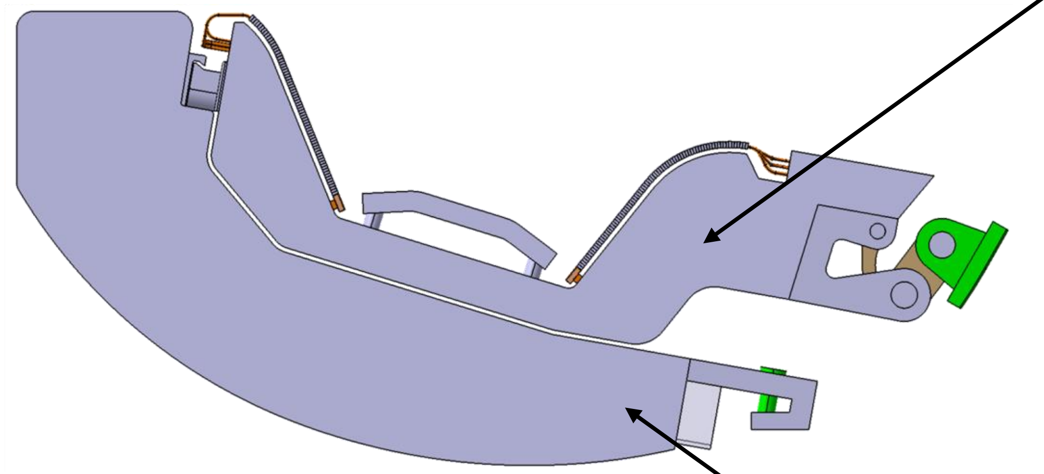


DEMO LAR divertor 2025 –short leg option





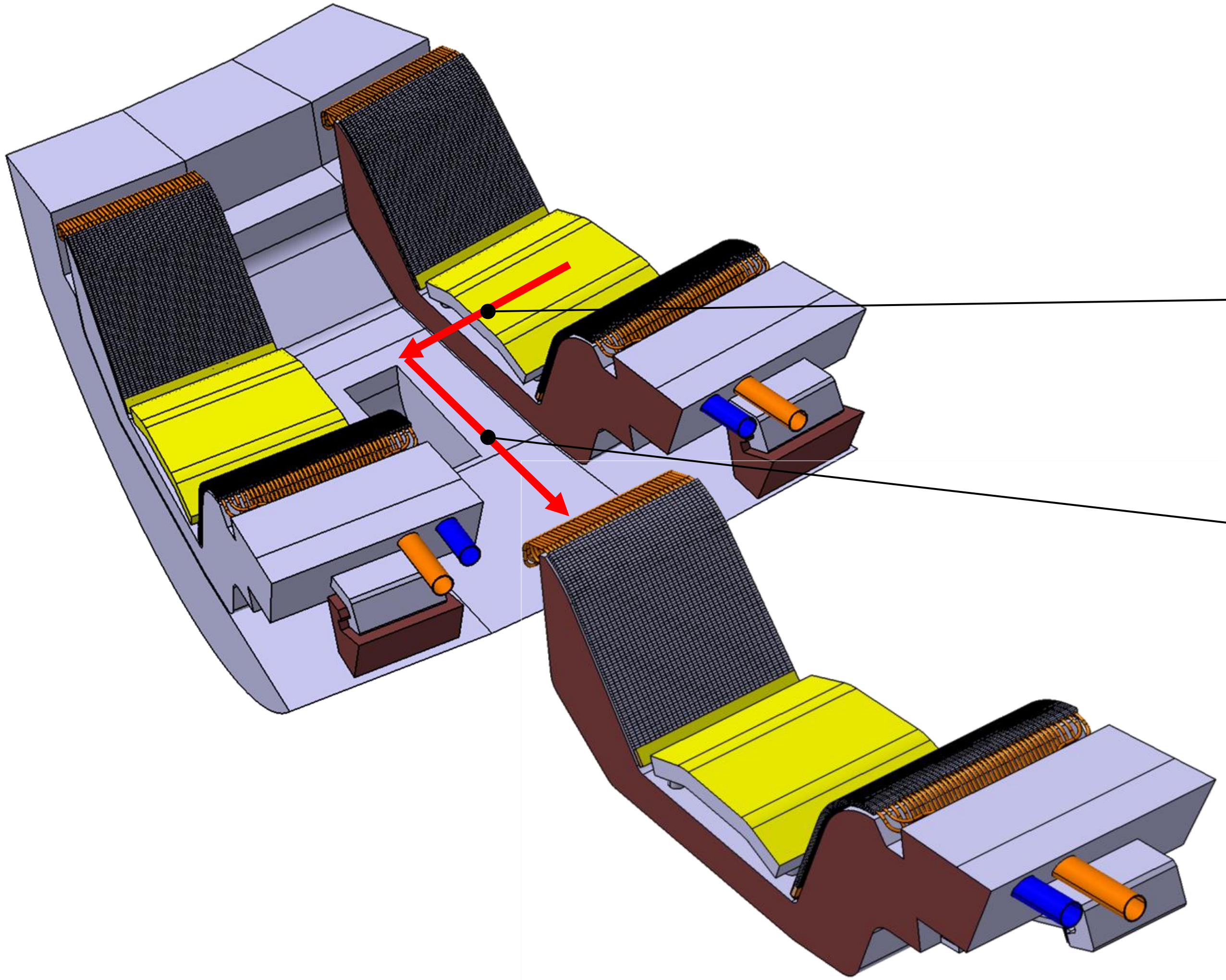
DEMO LAR divertor 2025 –short leg option



<u>Upper Cassette:</u> <u>CB made in AISI 316.</u>
It support all the PFC components, and it is cooled at low temperature and pressure.. **It can be extracted from the VV independently** respect to the Lower CB. **It is fixed to the VV on the outboard.**

<u>Lower Cassette:</u> <u>CB made in EUROFER97.</u>
It supports the Upper CB, and it is fixed to the VV.
Since the cooling scheme is the PWR (high temperature and pressure) the frequency of maintenance is lower than the Upper CB.

Upper CB extraction procedure.

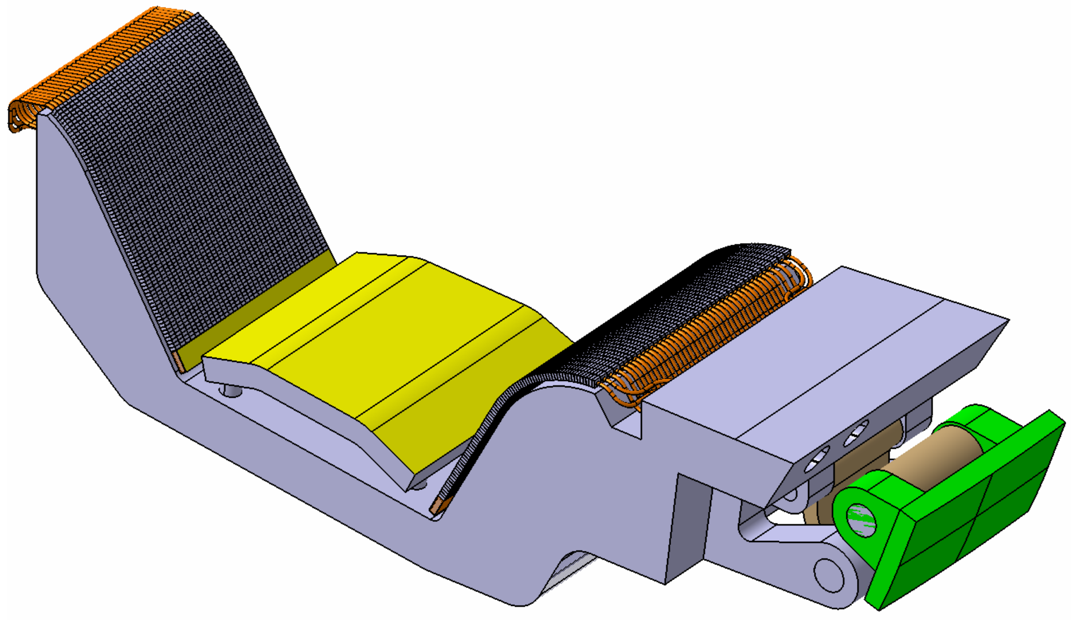


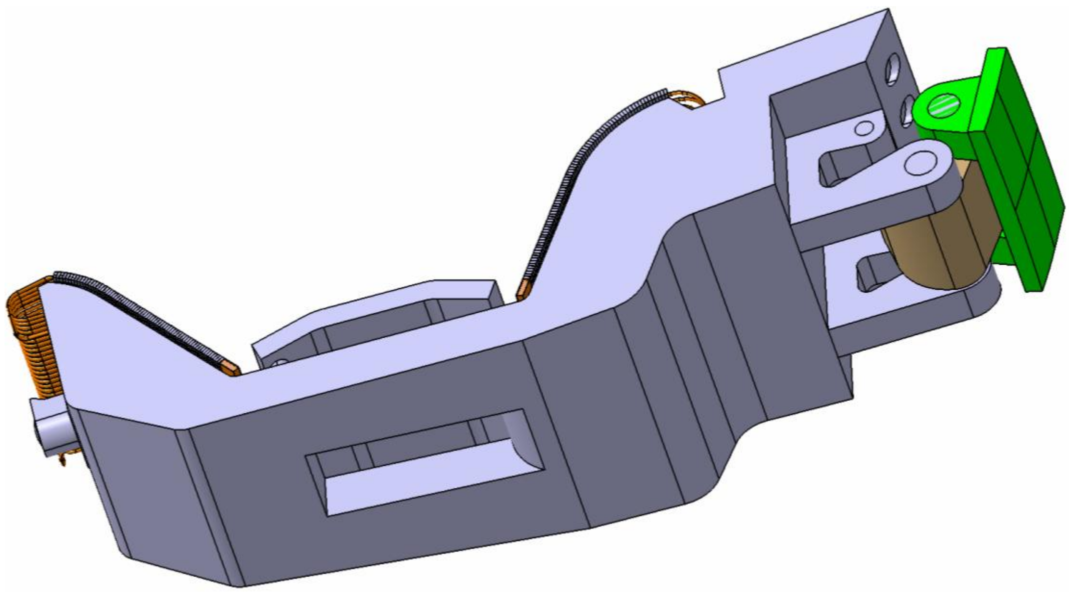
1. Extraction of the central upper CB.

2. Toroidal translation of the first lateral Upper CB to reach the central position.

3. Radial extraction from the lower port.

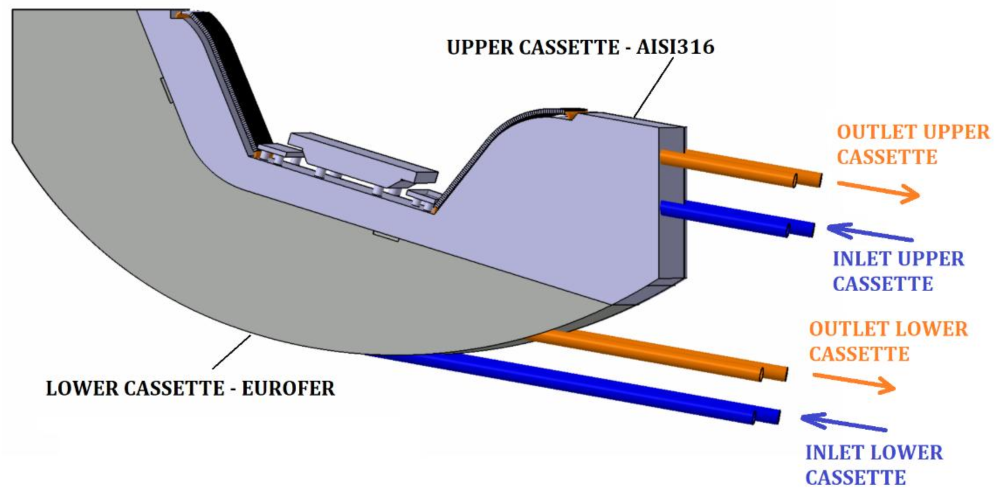
4. Step 2. and 3. for the second lateral upper CB.

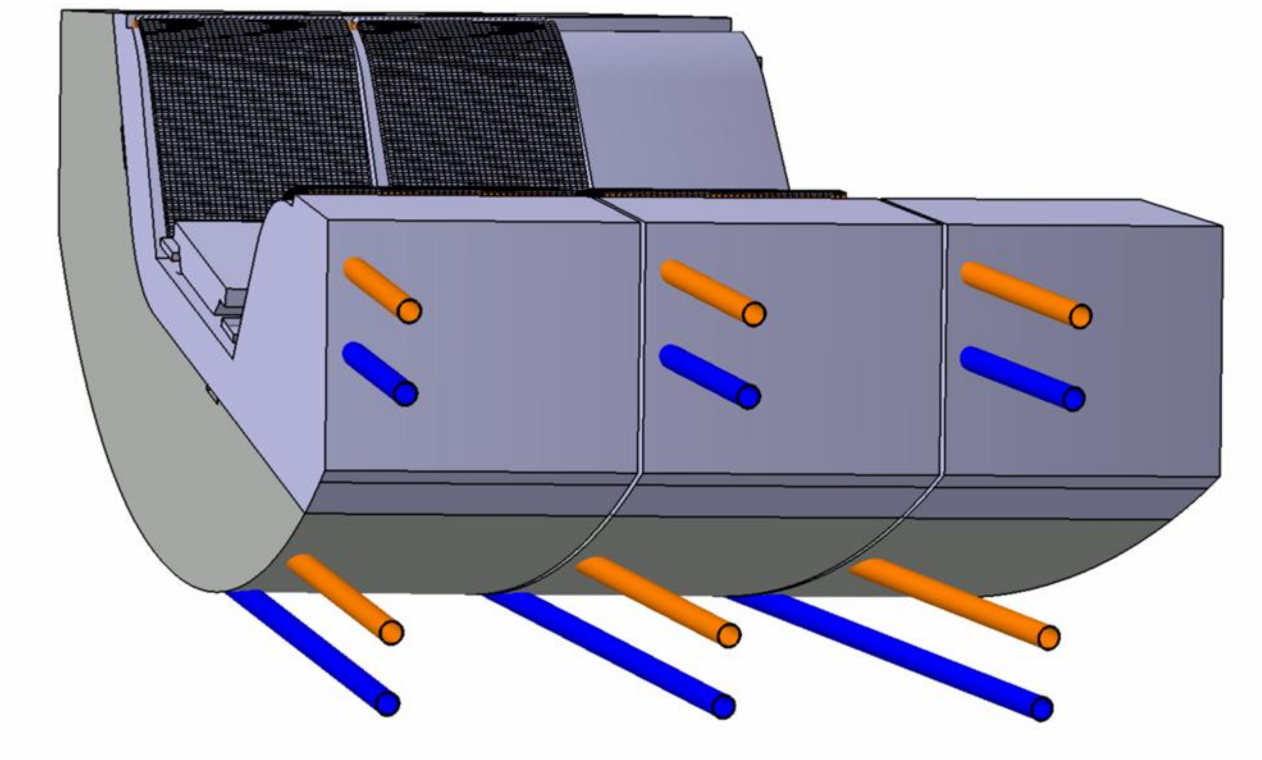




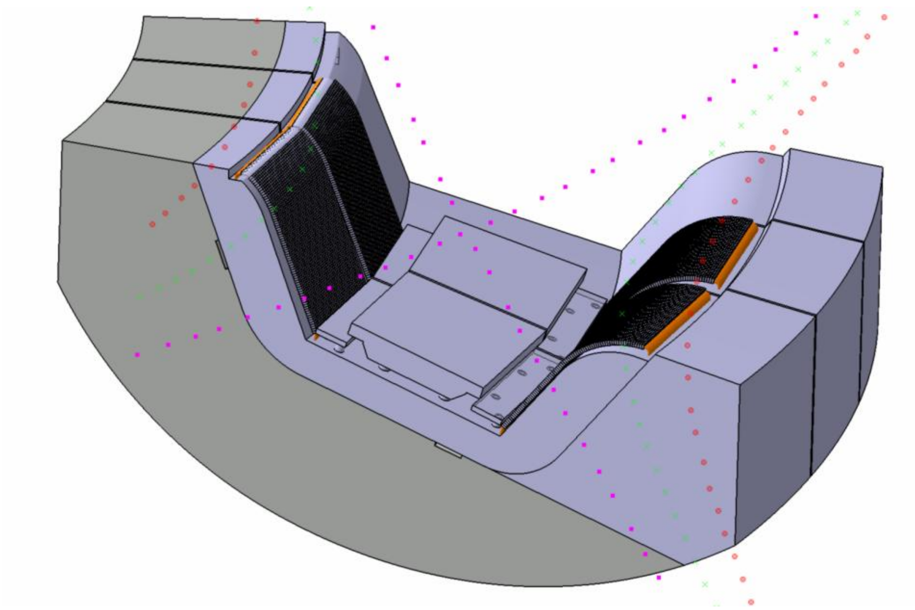
The baseline for attachment system is the Wishbone, but different option are under investigation, one of these is the Spring Box solution.

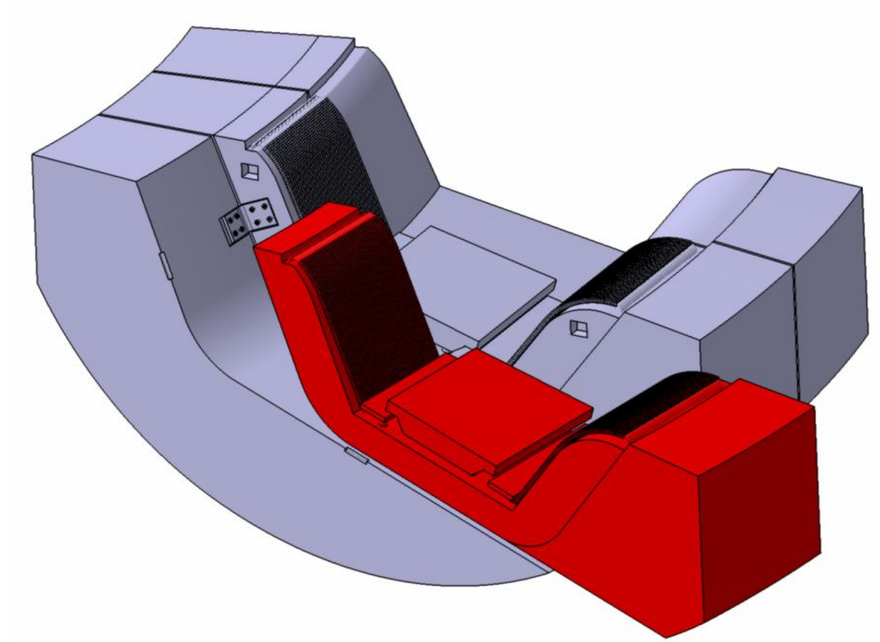
DEMO short leg (or Open Divertor) – Cooling Tubes/materials

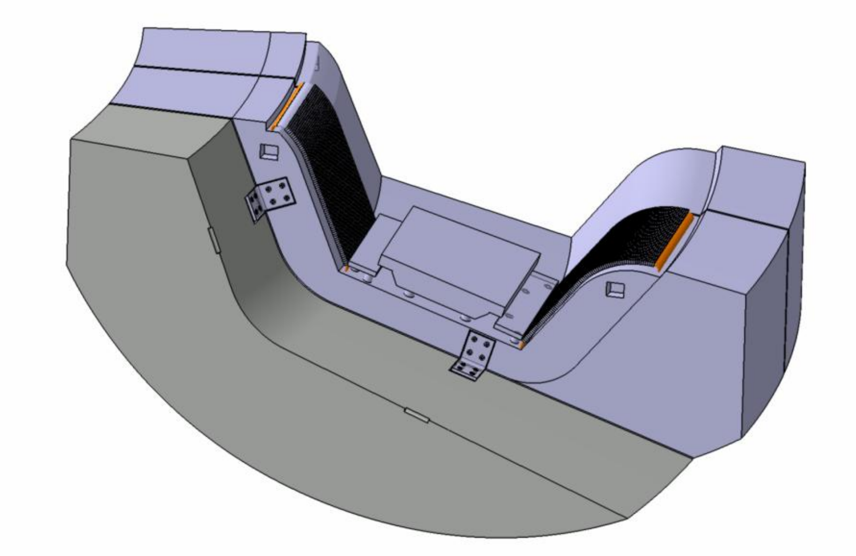


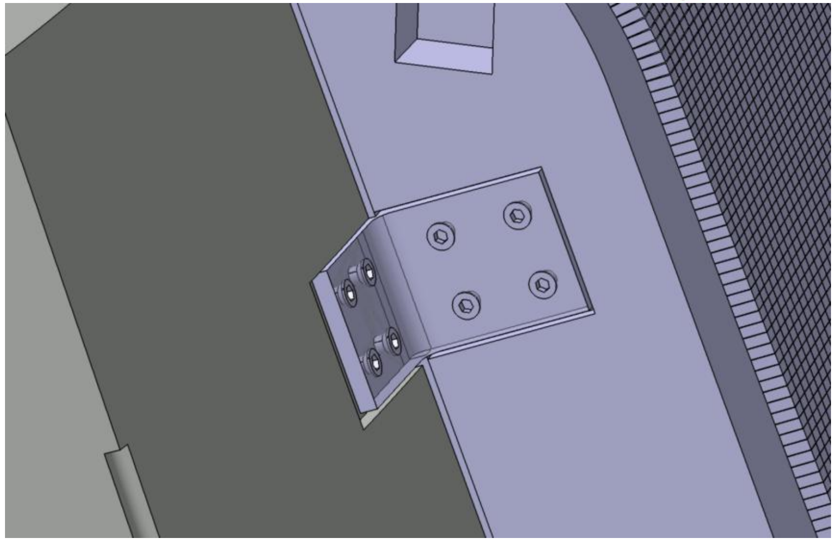


DEMO short leg (or Open Divertor) – Assembly procedure









Conclusion

- Starting from DEMO LAR configuration model, Plant/Divertor requirements and plasma/PFC profile for long Leg and short leg configuration, Divertor assembly CAD models have been prepared.
- For the Long leg option, chosen as baseline, a detailed CAD models for the main Divertor components have been prepared. Also, the progress status of main analyses have been presented.
- The first thermal-loads analyses (using SOLEDGE3X and SOLPS-ITER) results show that the flux on PFC does not exceed 10 MW/m^2 even when there is partial loss of detachment. The flux at the dome is between 0.5 and 1 MW/m^2.
- The first DIVGAS Flow 3D simulations results, in particular the Neutral Gas Flow for the LAR long leg configuration, exhibits similar pumped flux and outflux levels of 2024 divertor configuration, it improves performance regarding poloidal gaps but increased toroidal leakage suggests room for further optimization.
- The first Hydraulic Analyses results with two cooling systems (one for PFCs and one for CB/RPs/SL) do not show major issues. The only minor issue is the low mass flow rate in the Liner Branch that must be increase to avoid high temperature in the liner.
- EM, Neutronic and Structural Analyses are under execution.

EUROfusion

Thank you for attention

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