TOR VERGATA
UNIVERSITY OF ROME

Conceptual design of a water-cooled first wall component for a tokamak machine

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Joint EPS-SIF International School on Energy 2021

Outline

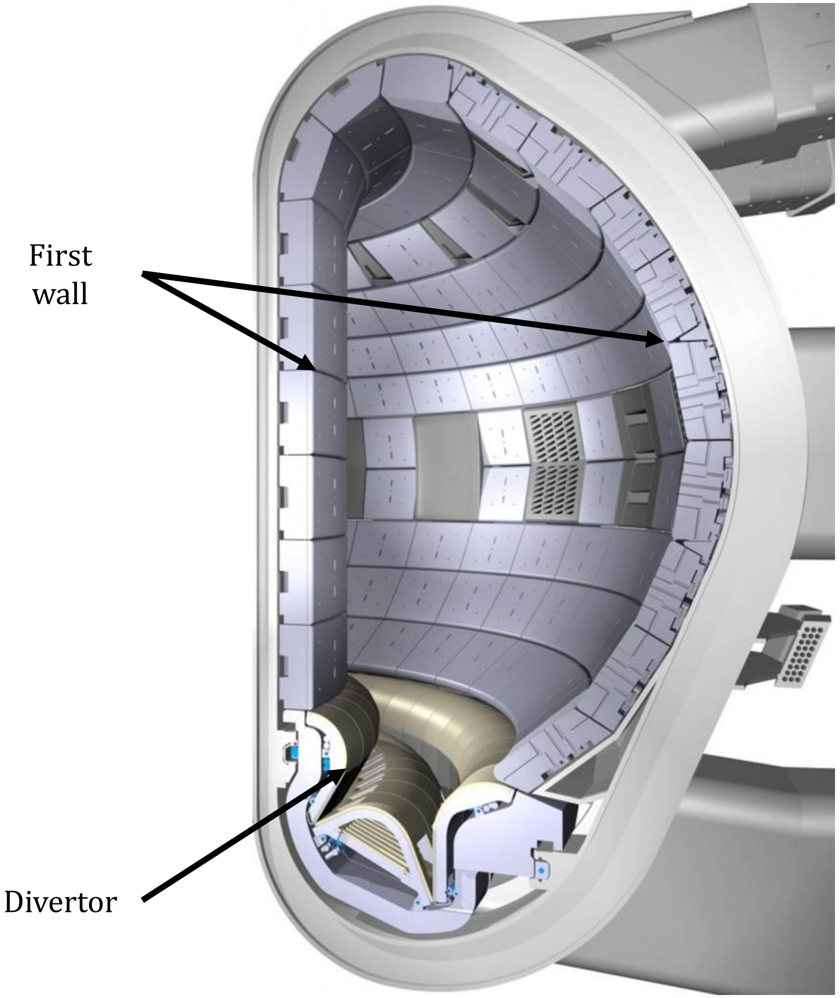
- Introduction
  - Plasma facing components
  - Design issues of the DEMO first wall
  - Divertor Tokamak Test facility

- Case study
  - Temperature field and HTC calculation
  - Analysis of internal stresses

- Conclusions and future outlooks

This work has been developed in collaboration with the laboratories of ENEA Frascati.

Plasma facing components



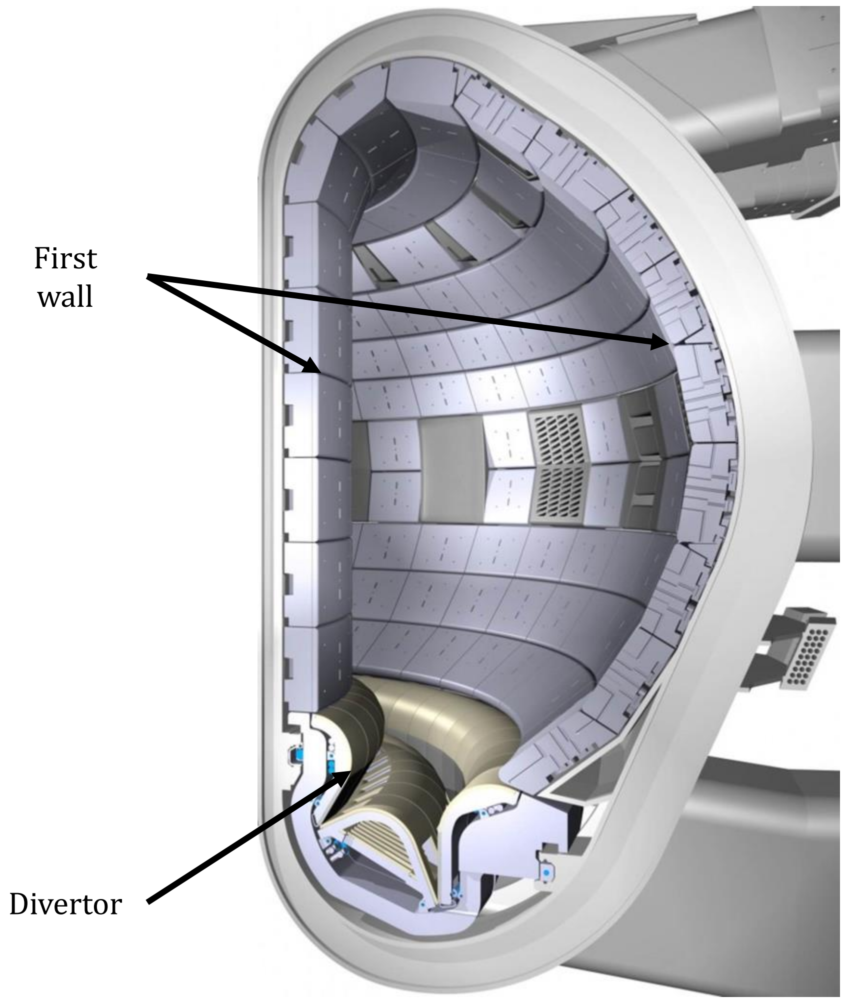
A cut-away of the ITER reaction chamber. [1]

PFCs can be divided in three categories:

- **Limiters:** put in discrete regions of the chamber where sometimes the plasma is in contact with the wall.
- **Divertor:** located at the bottom of the chamber. The divertor shall withstand a significant heat flux and dispose of the plasma particle waste.
- **First wall:** It can be defined as the component that covers the remaining plasma facing surfaces.

[1] ITER Organization website.

Plasma facing components



A cut-away of the ITER reaction chamber. [1]

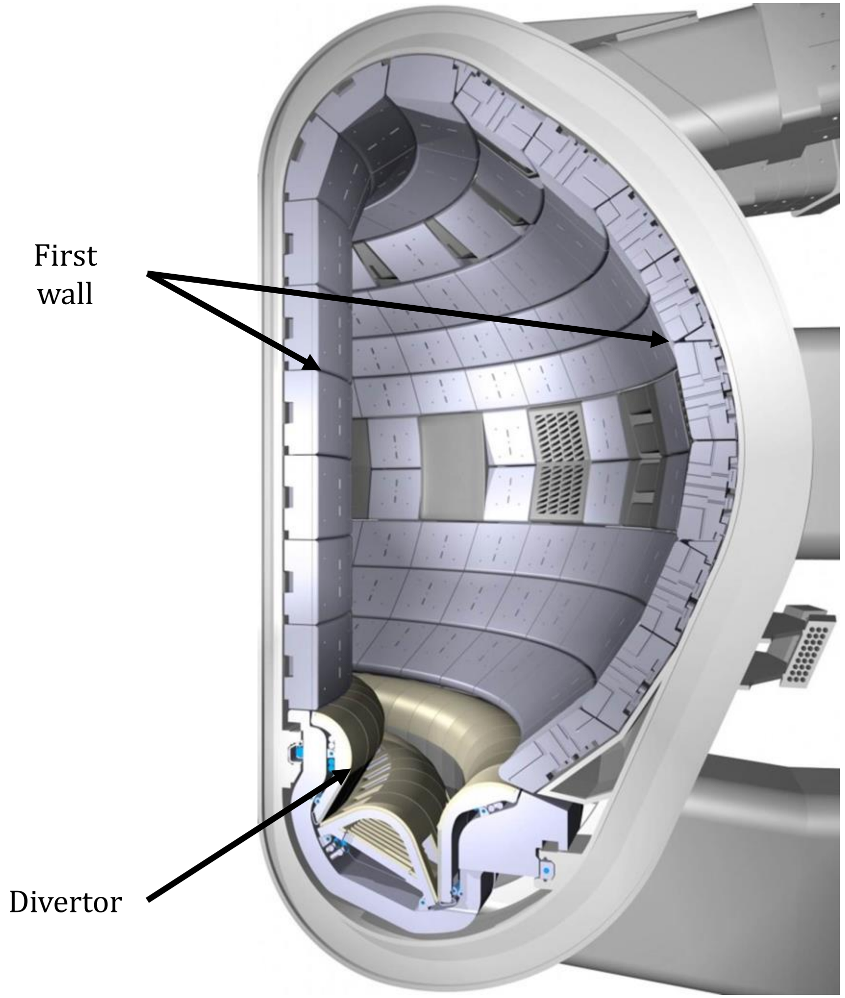
Photons

Charged particles

Neutrons

[1] ITER Organization website.

Plasma facing components



A cut-away of the ITER reaction chamber. [1]

Photons
Charged particles
Neutrons

1 MW/m^2

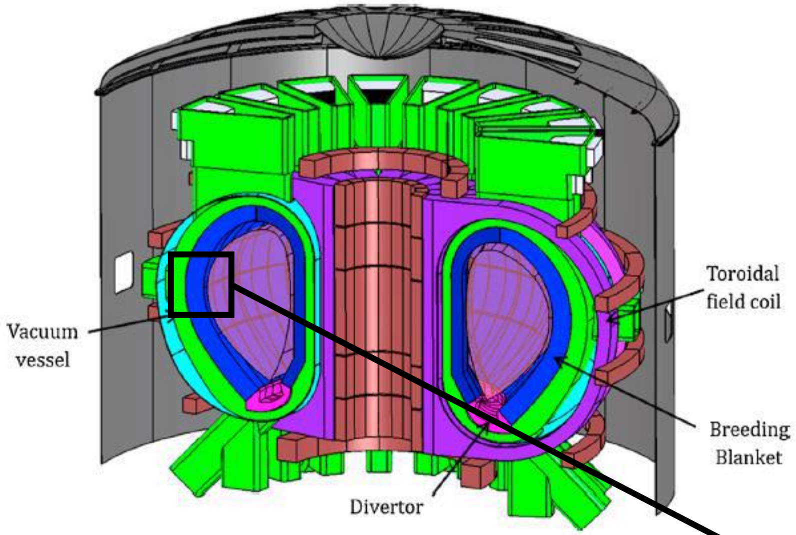
[1] ITER Organization website.

DEMOnstration fusion power plant

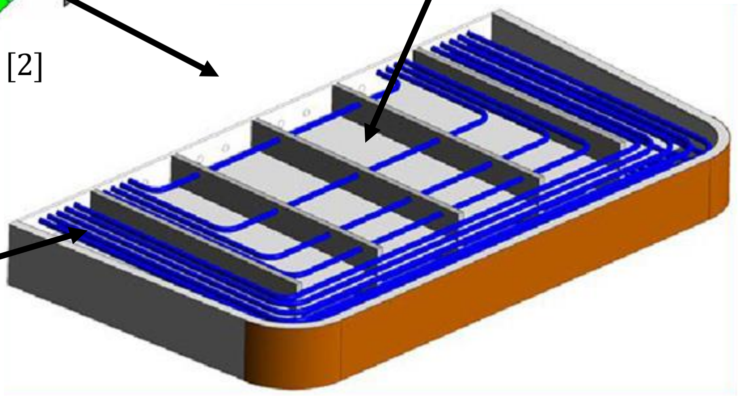
- The strategy to achieve energy production from nuclear fusion aims to realize a demostrative fusion reactor (DEMO).

- The purposes of DEMO are producing net electricity for the grid and ensuring the fuel self-sufficiency, also proving the economic feasibility of a fusion reactor.

- The breeding blanket has the dual function of breeding the tritium fuel and removing the heat by means of a coolant.



A view of the EU DEMO design. [2]



WCLL breeding unit. [3]

[2] A. Froio et al., Fusion Engineering and Design, 2018
[3] E. Martelli et al., Fusion Engineering and Design, 2018

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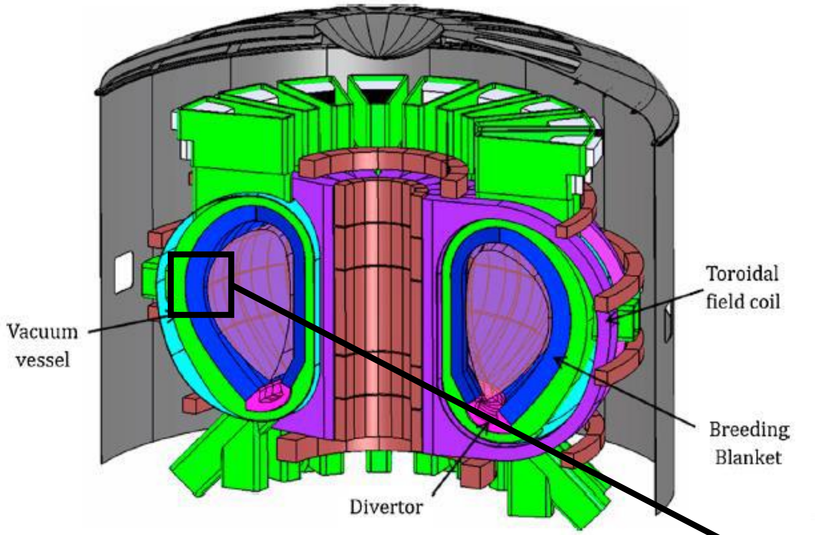
- In DEMO, the first wall is a protective layer which encases the breeding blanket.



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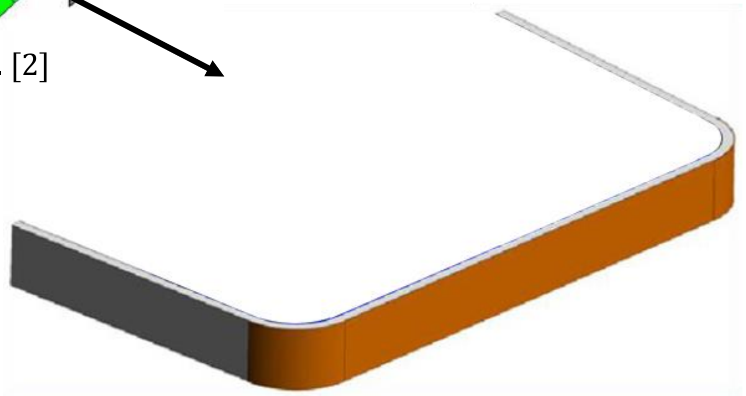


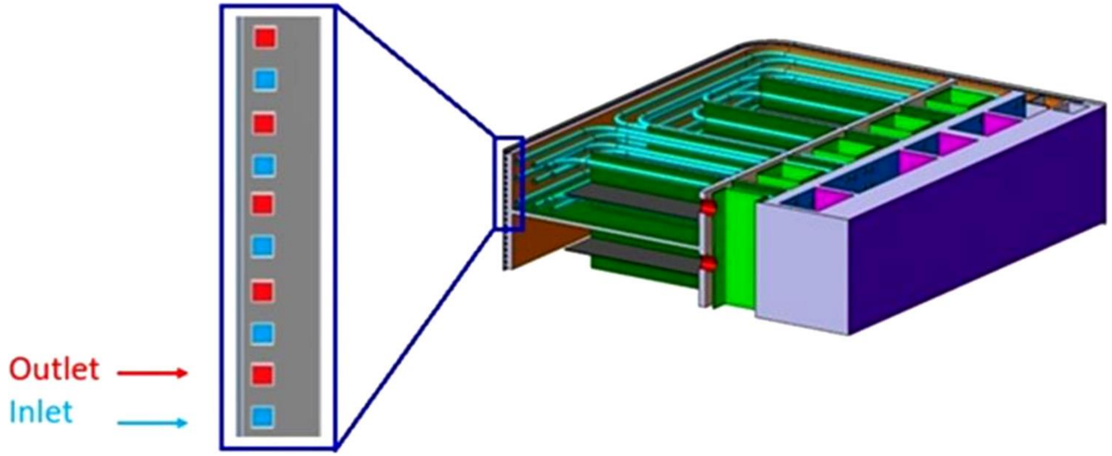
DEMO first wall.

[2] A. Froio et al., Fusion Engineering and Design, 2018
[3] E. Martelli et al., Fusion Engineering and Design, 2018

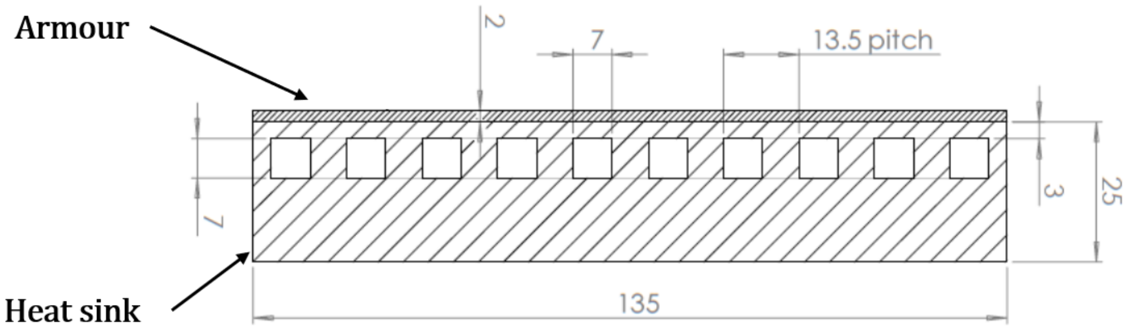
Layout of the DEMO first wall

- The DEMO FW is actively cooled. The coolant flows into square channels in a counter-current layout.

- The component consists of two main parts:
  - **Armour:** a thin tungsten protective layer necessary to protect the underlying region from the charged particles erosion.
  - **Heat sink:** neutron interact with the nuclei, leading to radioactivity, embrittlement and loss of strength; for DEMO the best solution is a RAFM steel (Eurofer).



Cut-away of a WCLL BB elementary cell. [4]



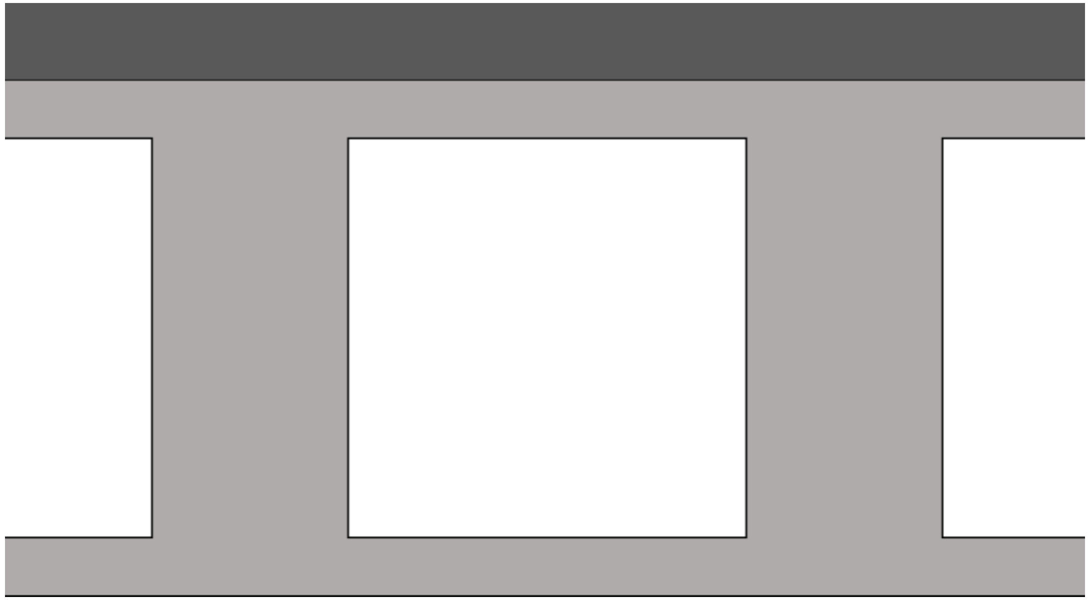
Internal layout of the DEMO FW. [5]

[4] F. Edemetti et al., Fusion Engineering and Design, 2020
[5] E. Martelli et al., Fusion Engineering and Design, 2018

Internal stresses

Two contributions to internal stresses:

- $\boldsymbol{\sigma}_{\Delta \boldsymbol{T}}$: Internal stresses due to the temperature gradients in materials.
- $\boldsymbol{\sigma}_{\Delta \boldsymbol{\alpha}}$: Internal stresses due to the mismatch of thermal expansion.

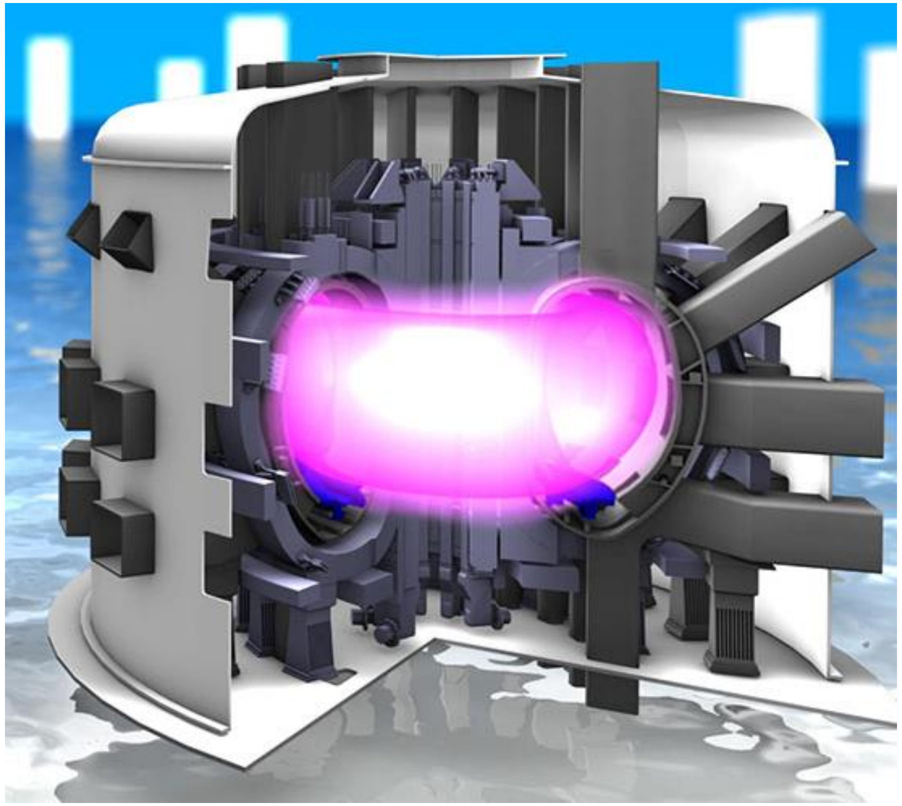


Divertor Tokamak Test facility

- DTT is an upcoming device that will be built in the ENEA Research Centre of Frascati, Italy.

- One of the DTT goals is to develop technological solutions to the power exhaust mission that can reliably be extrapolated to DEMO and future reactors. Proposed solutions can be tested in an integrated environment, thus from both physical and technological point of view.

- Designing and manufacturing a steel-based FW is one of the tasks.

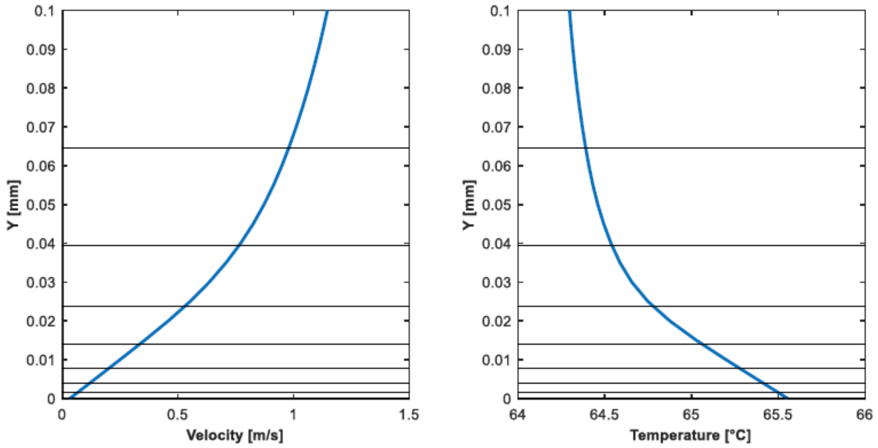


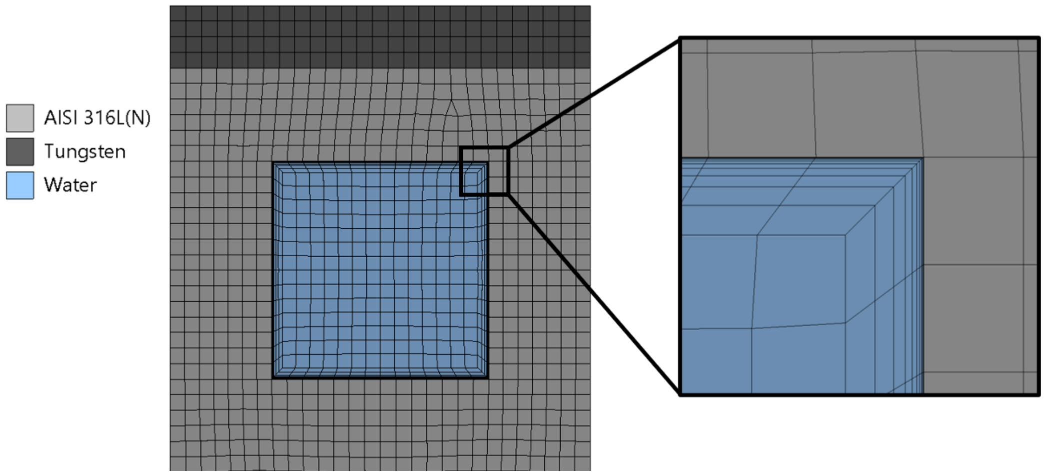
Divertor Tokamak Test facility. [6]

[6] ENEA website.

Temperature field

- Steady state CFD simulations are carried out using the software ANSYS CFX.
- The fluid mesh is realized refining the elements near the wall and ensuring $y^+ \leq 1$, thus the code is able to solve the viscous sublayer explicitly.

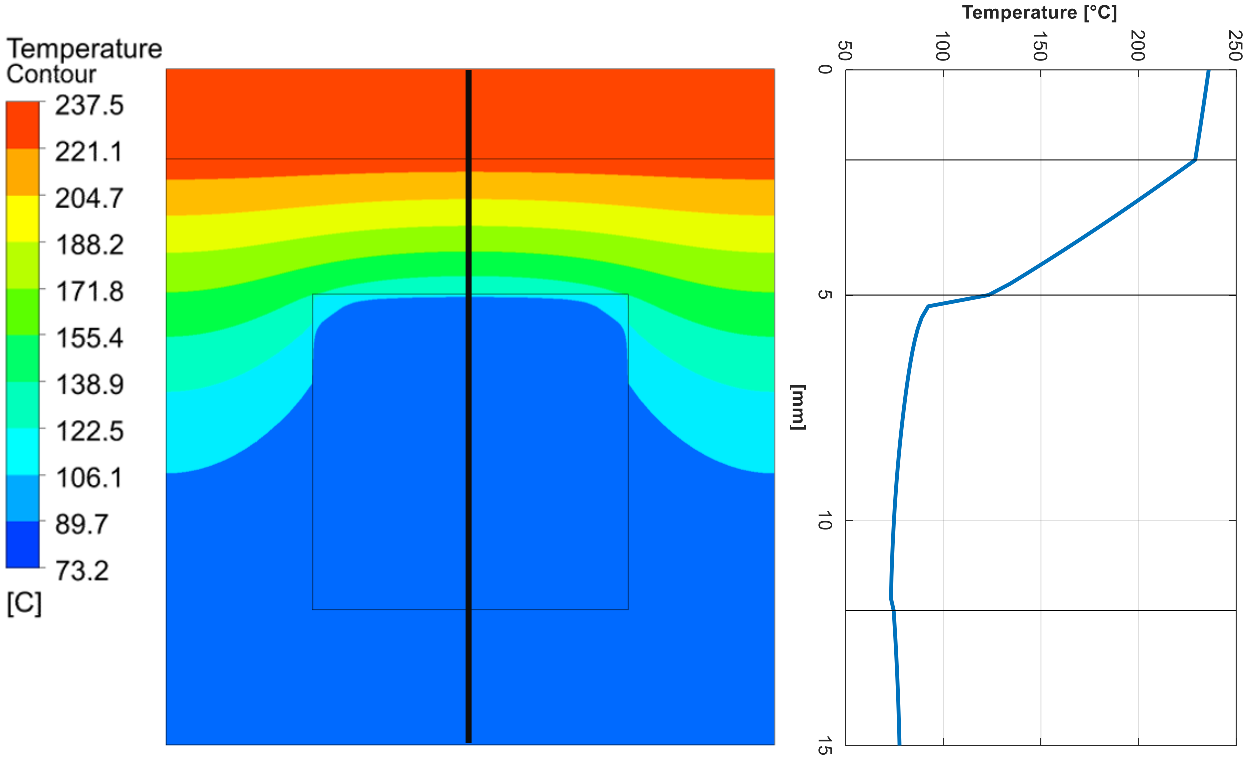




Temperature field

- Steady state CFD simulations are carried out using the software ANSYS CFX.
- The temperature gradient in steel is greater than in tungsten because steel has a smaller thermal conductivity.
- The temperature difference will generate significant stresses in the structural material.

	λ [W (mK)$^{-1}$]	CTE [K^{-1}]
Tungsten	173	4.5×10^{-6}
Steel	14	1.5×10^{-5}



$$\Delta T = \frac{q\ s}{\lambda}$$

HTC calculation

Thermo-mechanical simulations are carried out using the software ANSYS Mechanical.

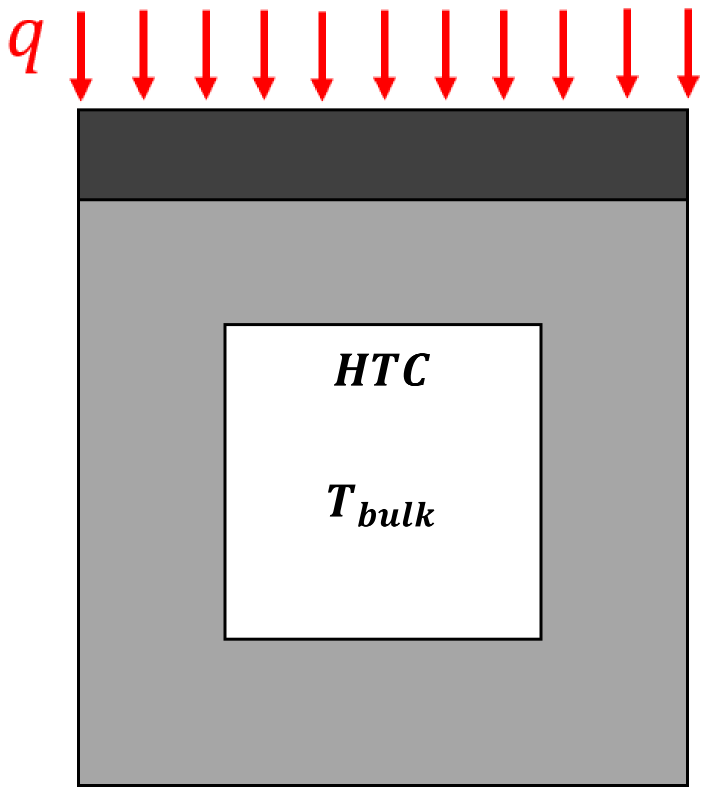
Boundary conditions of the thermo-mechanical simulations:

- Heat load q on the plasma facing surface of tungsten.
- Heat transfer conditions at the fluid wall.

$$HTC = \frac{q}{T_{wall} - T_{bulk}}$$

$$T_{bulk}(z) = T_{in} + \frac{\dot{Q}(z)}{\dot{m}\,\overline{c_p}}$$

No methods are found in literature to calculate the HTC for the case study layout.



$q = 0.5\ \mathrm{MW/m^2}$ for our case study.

HTC calculation

Dittus-Bolter Equation: $Nu = 0{,}023\ Re_D^{0.8}\ Pr^{0{,}4}$

Valid for a circular duct with a uniform thermal load on the surface, in the following ranges:

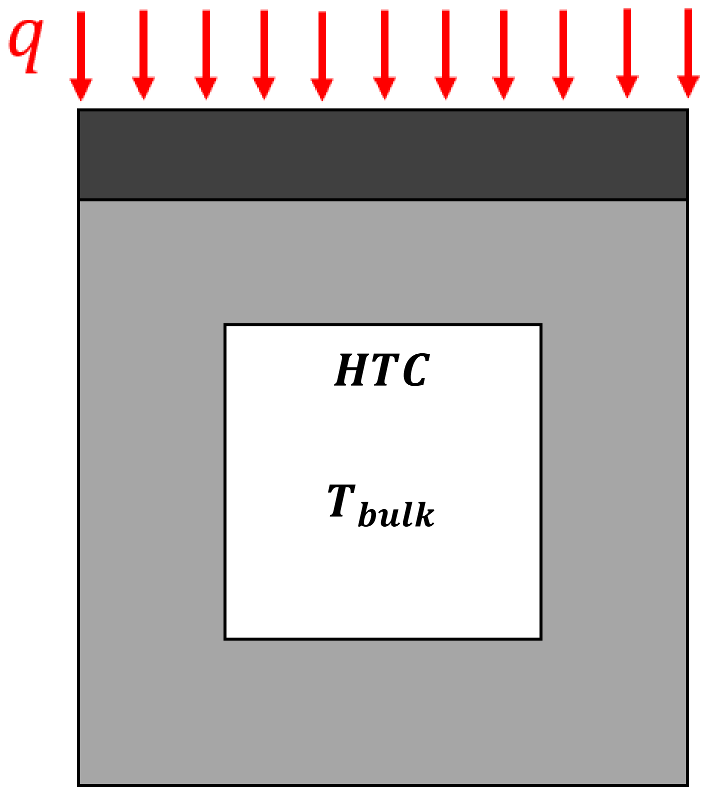
$$0.5 < Pr < 120 \text{ and } 6000 < Re_D < 10^7.$$

$$Re_D = \frac{\rho_b\ u\ D}{\mu_b}$$

$$Pr = \frac{Cp_b\ \ \mu_b}{\lambda_b}$$

$$HTC = \frac{Nu\ \lambda_b}{D}$$

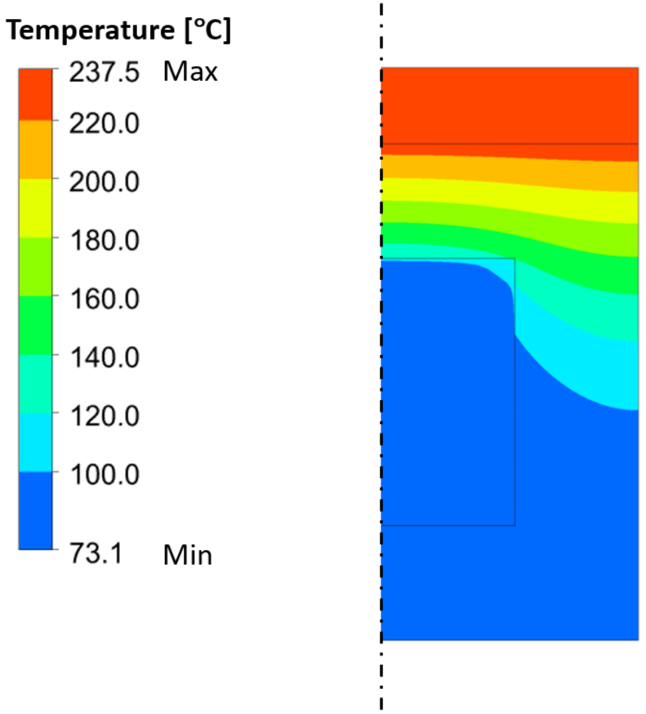
$$T_{wall} = T_{bulk} + \frac{q}{HTC}$$



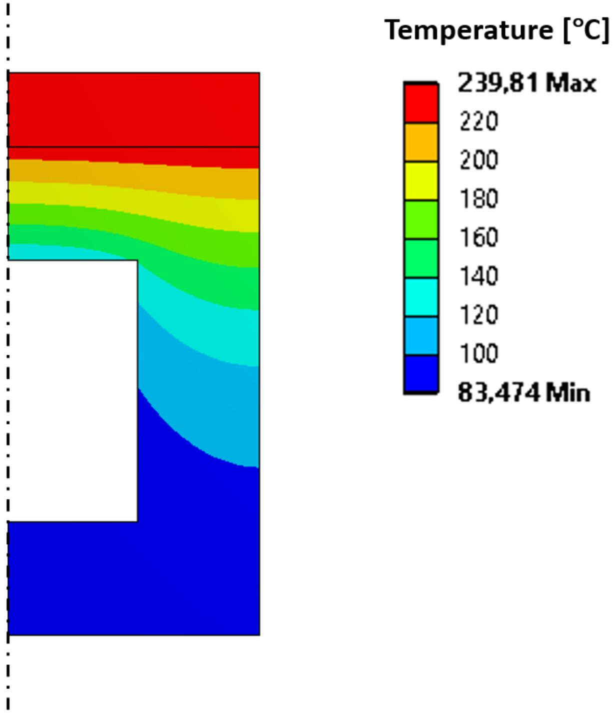
$q = 0.5\ \mathrm{MW/m^2}$ for our case study.

HTC calculation

Thermo-mechanical simulations based on the HTC calculation model proved to be a much faster and more flexible way to calculate the temperature field.



ANSYS CFX



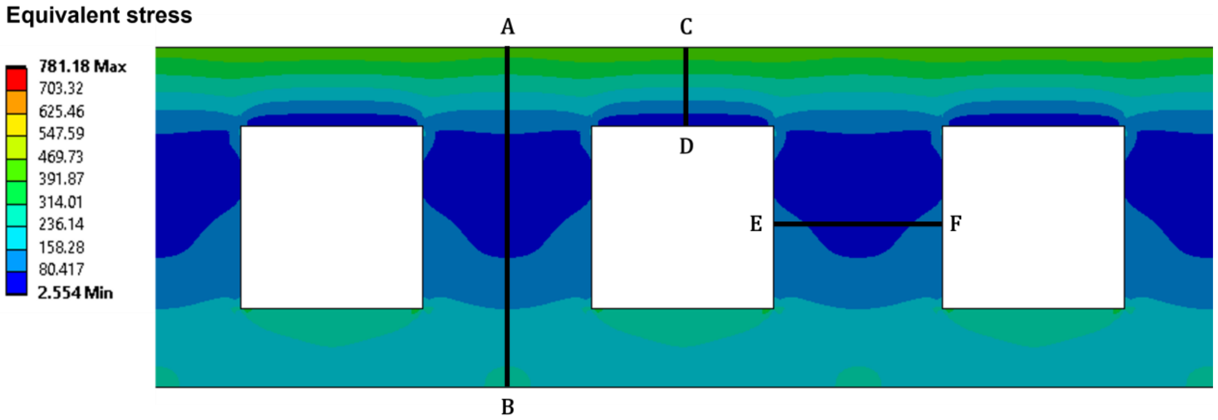
ANSYS Mechanical

Calculation of the internal stresses

- A preliminarily analysis of internal stresses has been carried out considering the SDC-IC limit criteria.

- SDC-IC is a code developed for experimental tokamak machines, like DTT.

- When considering the sole steel domain, membrane stresses are lower than the maximum allowable value.

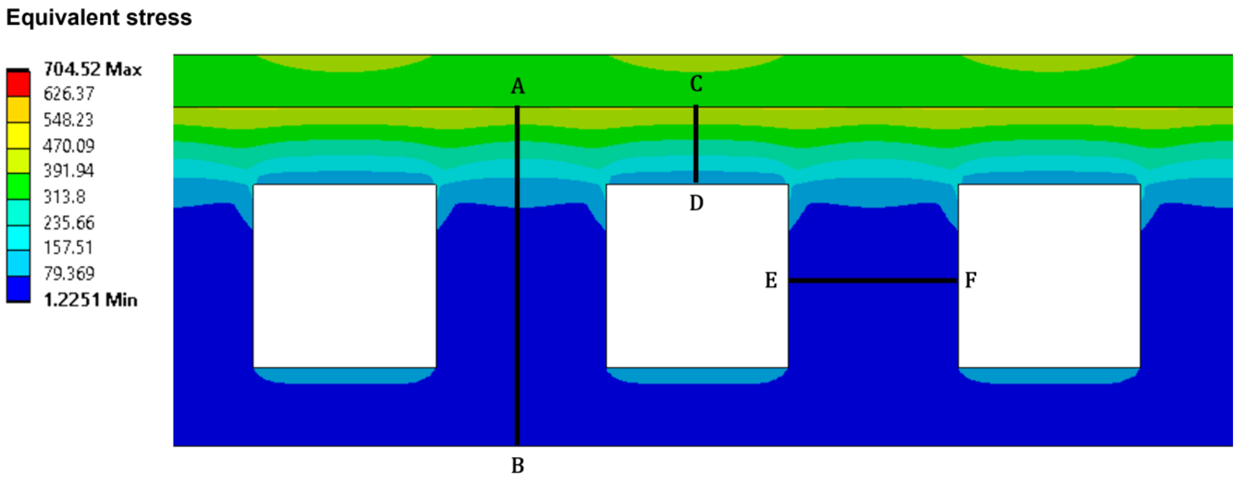


- Line CD: $\overline{P_m + Q_m} / S_e = 0.16$

- Line EF: $\overline{P_m + Q_m} / S_e = 0.60$

Calculation of the internal stresses

- A preliminarily analysis of internal stresses has been carried out considering the SDC-IC limit criteria.
- SDC-IC is a code developed for experimental tokamak machines, like DTT.
- When considering the sole steel domain, membrane stresses are lower than the maximum allowable value.
- The CTE mismatch is a source of additional stress. The limit criteria is not satisfied.



	λ [W (mK)$^{-1}$]	CTE [K^{-1}]
Tungsten	173	4.5×10^{-6}
Steel	14	1.5×10^{-5}

- Line CD: $\overline{P_m+Q_m}/S_e = 1.85$
- Line EF: $\overline{P_m+Q_m}/S_e = 0.70$

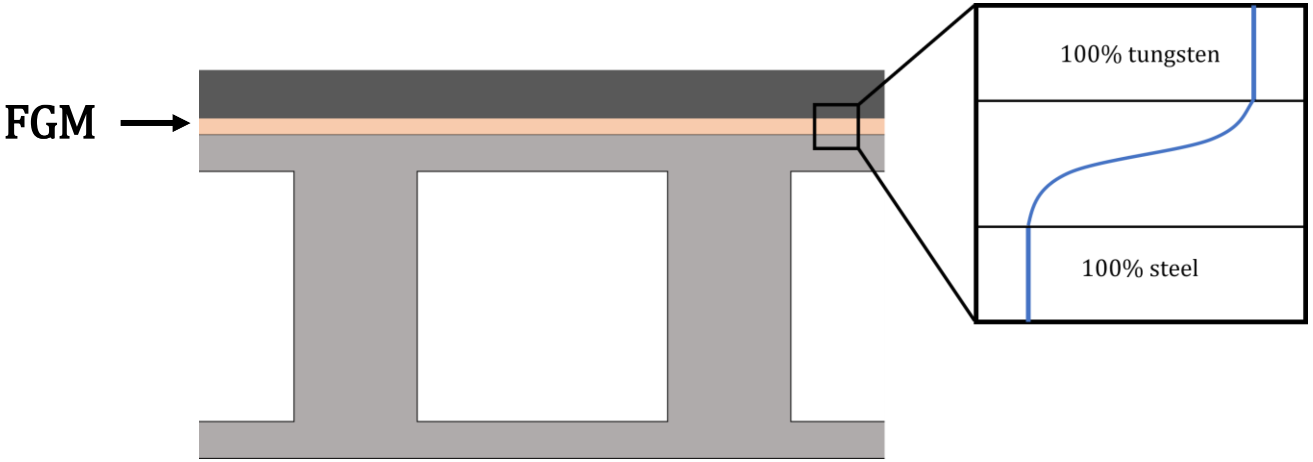
Conclusions and future outlooks

Conclusions:

- A method for the evaluation of stresses inside a FW component has been developed. The HTC evaluation model proved to perform calculations in a reduced computational time.
- The method will support the design of the FW components in DTT, with the purpose of reducing internal stresses.

Future outlooks:

- Engineering an interlayer to couple heat sink and armour. The material employed in the interlayer is a Functionally Graded Material (FGM).
- A well engineered FGM can reduce internal stresses at the interface.



Thank you for your attention!

I also want to thank the IVCs research group of ENEA Frascati
for giving me the opportunity of developing this work.