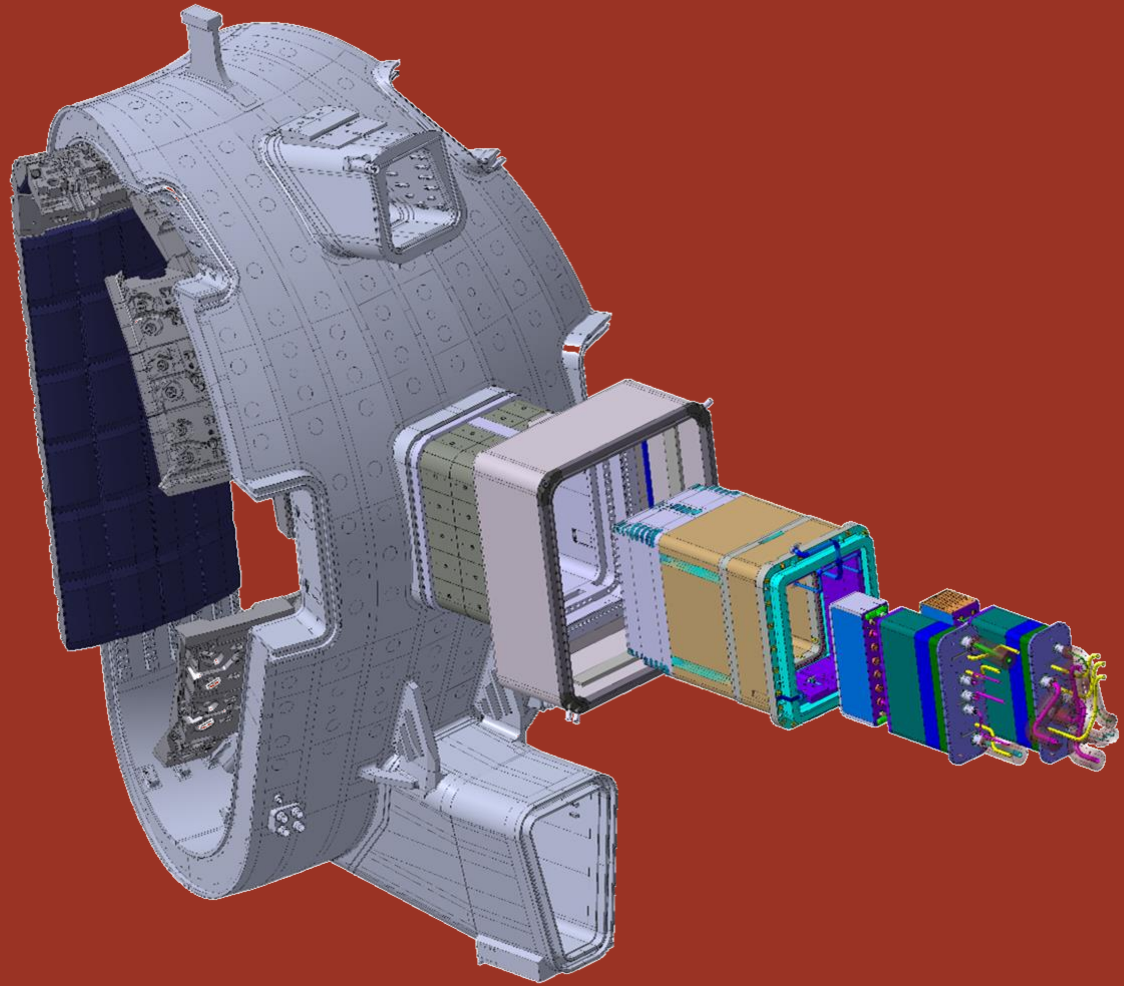
An integral methodological framework for the thermo-mechanical analysis and structural integrity assessment of the European TBM Sets



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F. Rueda[1], J. Vallory[2], R. Forte[3], F. Fantini[2], I. Ricapito[2], Y. Poitevin[2]

1 ESTEYCO

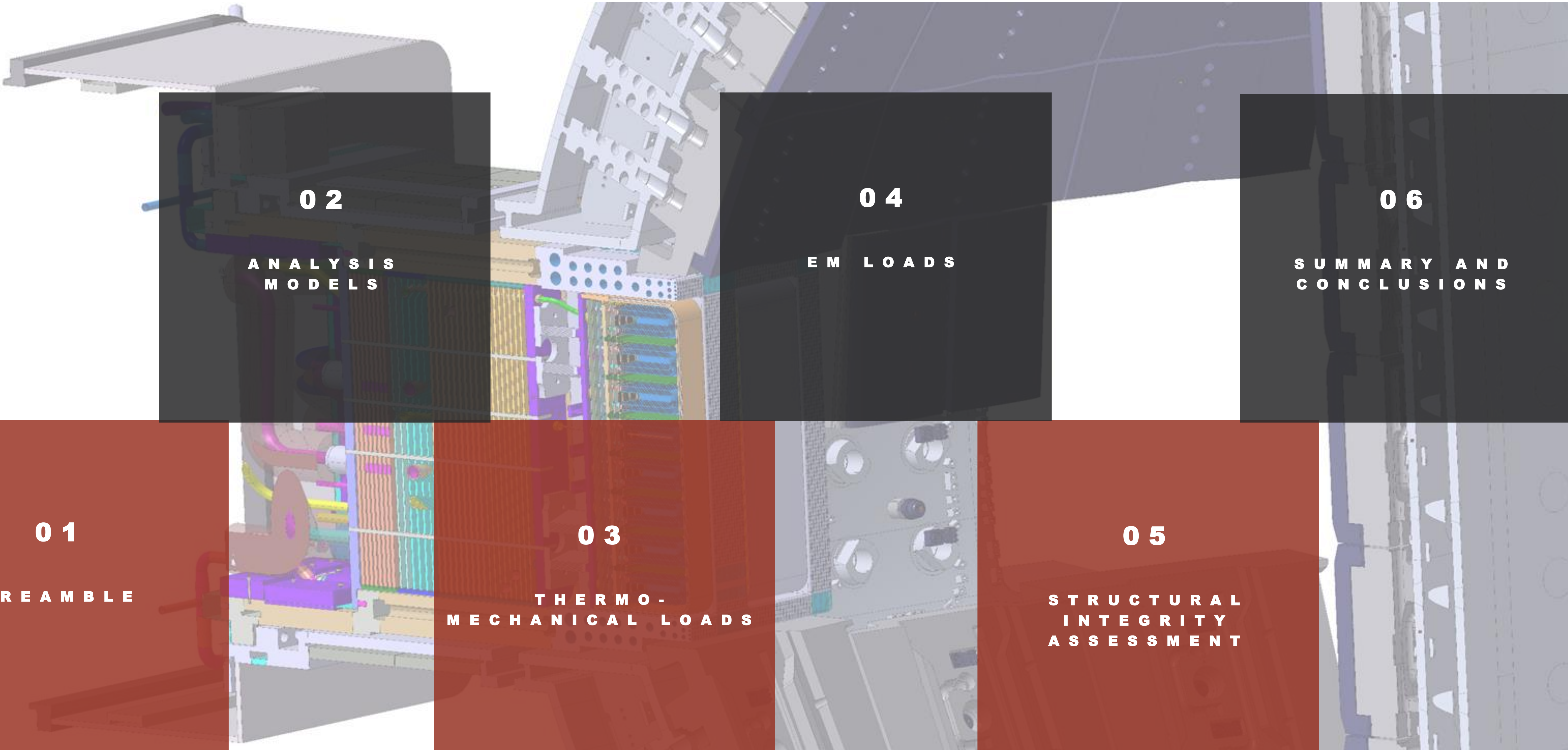
2 FUSION FOR ENERGY

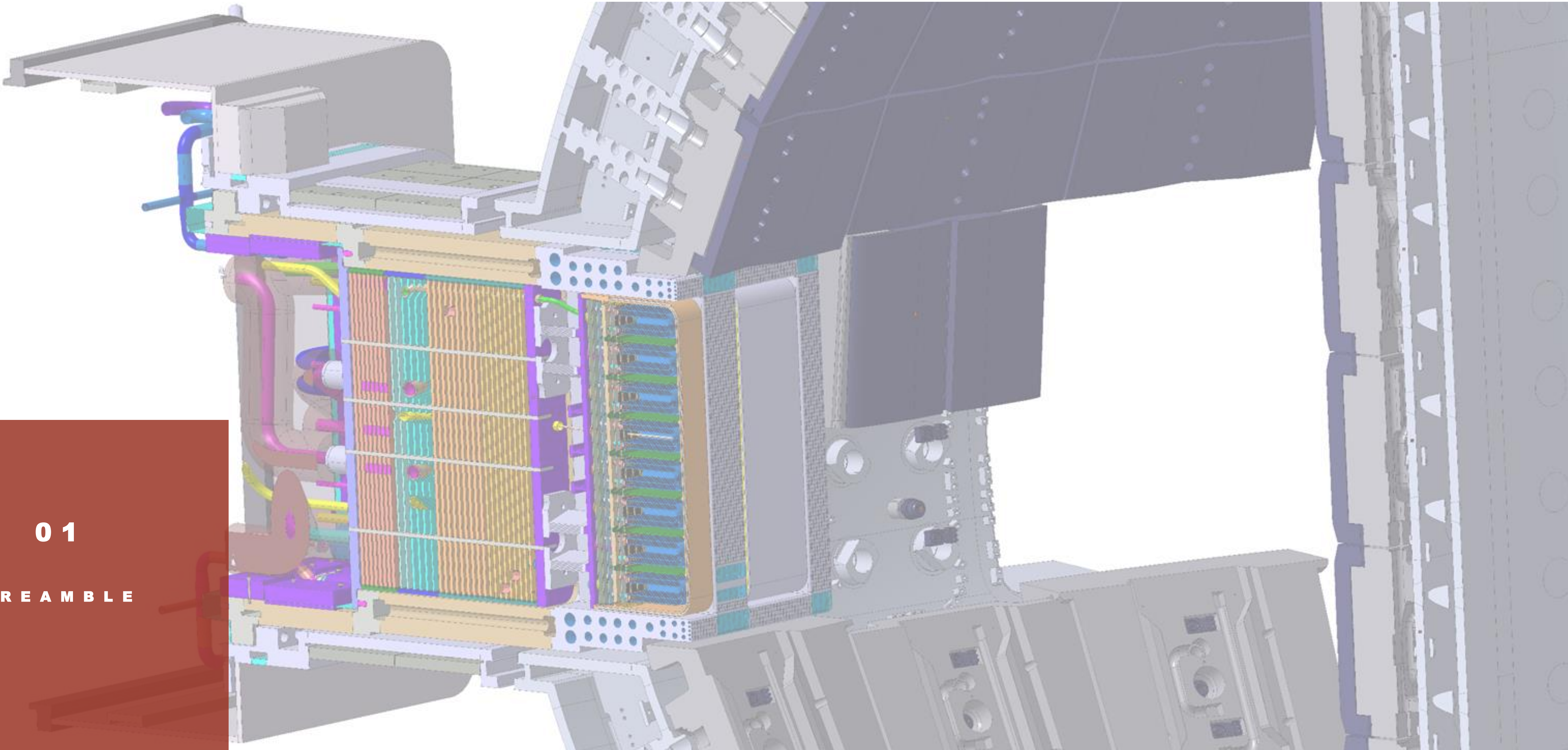
3 *ATG Science & Engineering*

15th International Symposium on Fusion Nuclear Technologies

13th September 2023 – Las Palmas de Gran Canaria, Spain

ESTEYCO



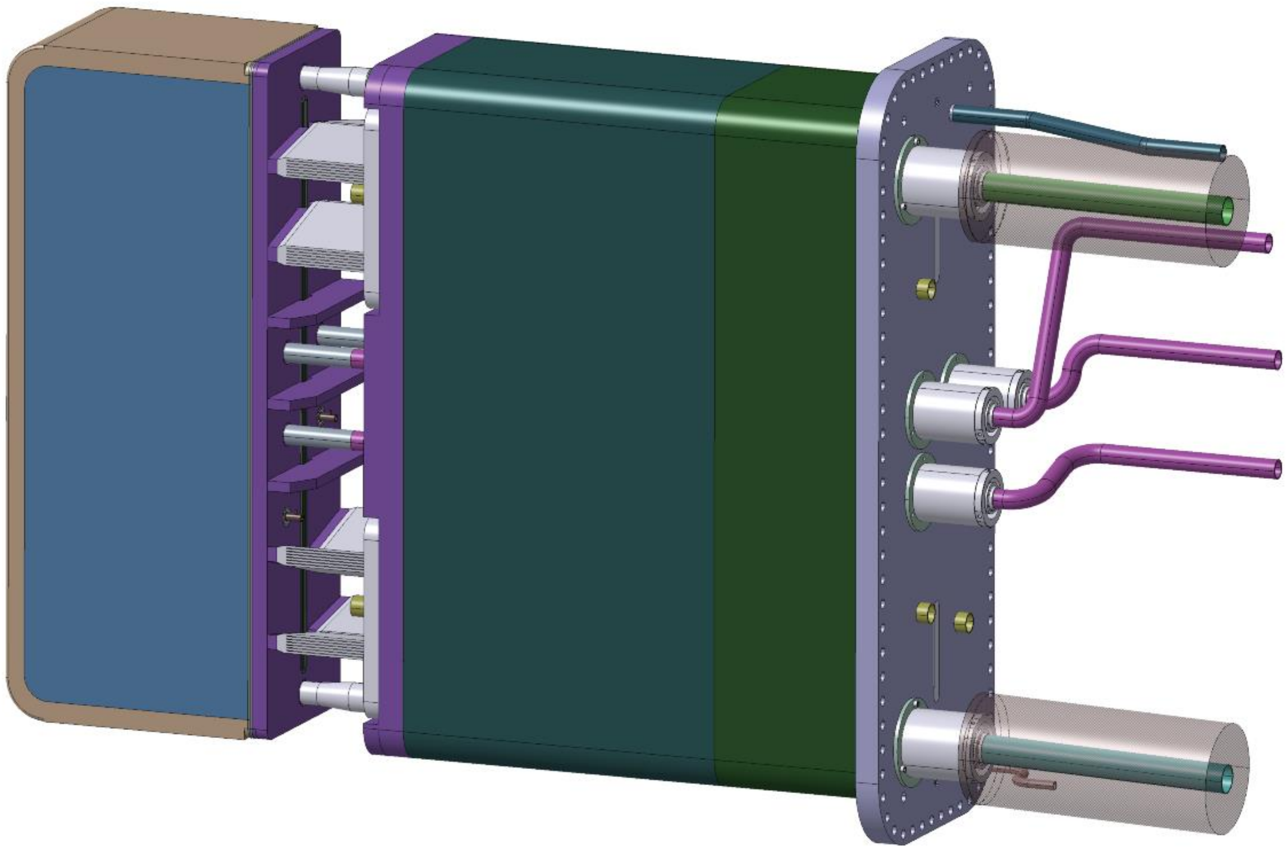


01

PREAMBLE

Preamble

- The European **TBM (Test Blanket Module)** program under development will test two alternative concepts for tritium generation and extraction in ITER:
  - **Helium cooled /ceramic pebble breeder** concept (HCCP), in collaboration with KOREA DA.
  - **Water cooled / lithium lead breeder** concept (WCLL)
- The design and manufacturing of these first-of-a-kind components if led by **F4E**, who coordinates and supervises the European efforts to this aim.
- For both concepts, the **ESTEYCO** Mechanics team is involved in the design and analysis of the TBM-box, which is the actual plasma-facing module for tritium breeding, as well as the TBM shield in the WCLL concept.



WCLL TBM-Set

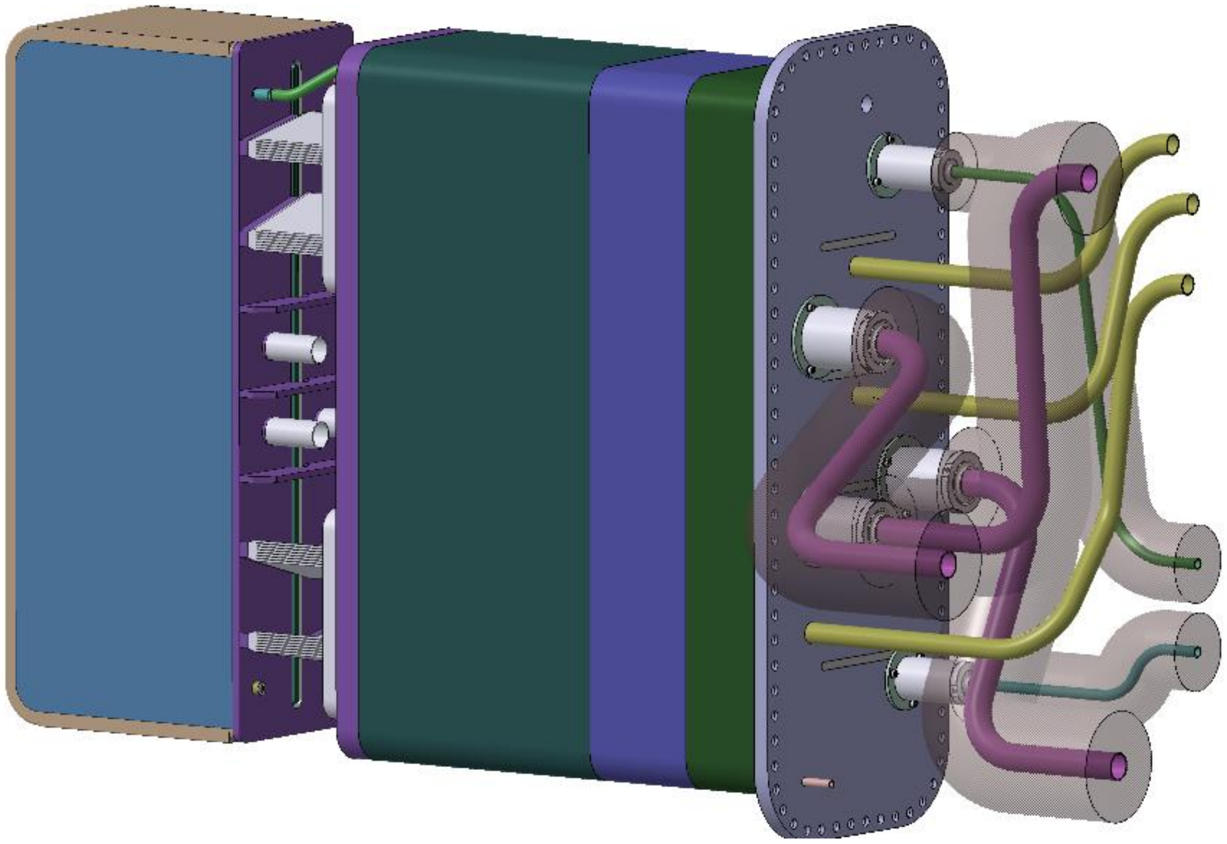
Preamble

- The design-by analysis activities are performed in a very challenging context due to:

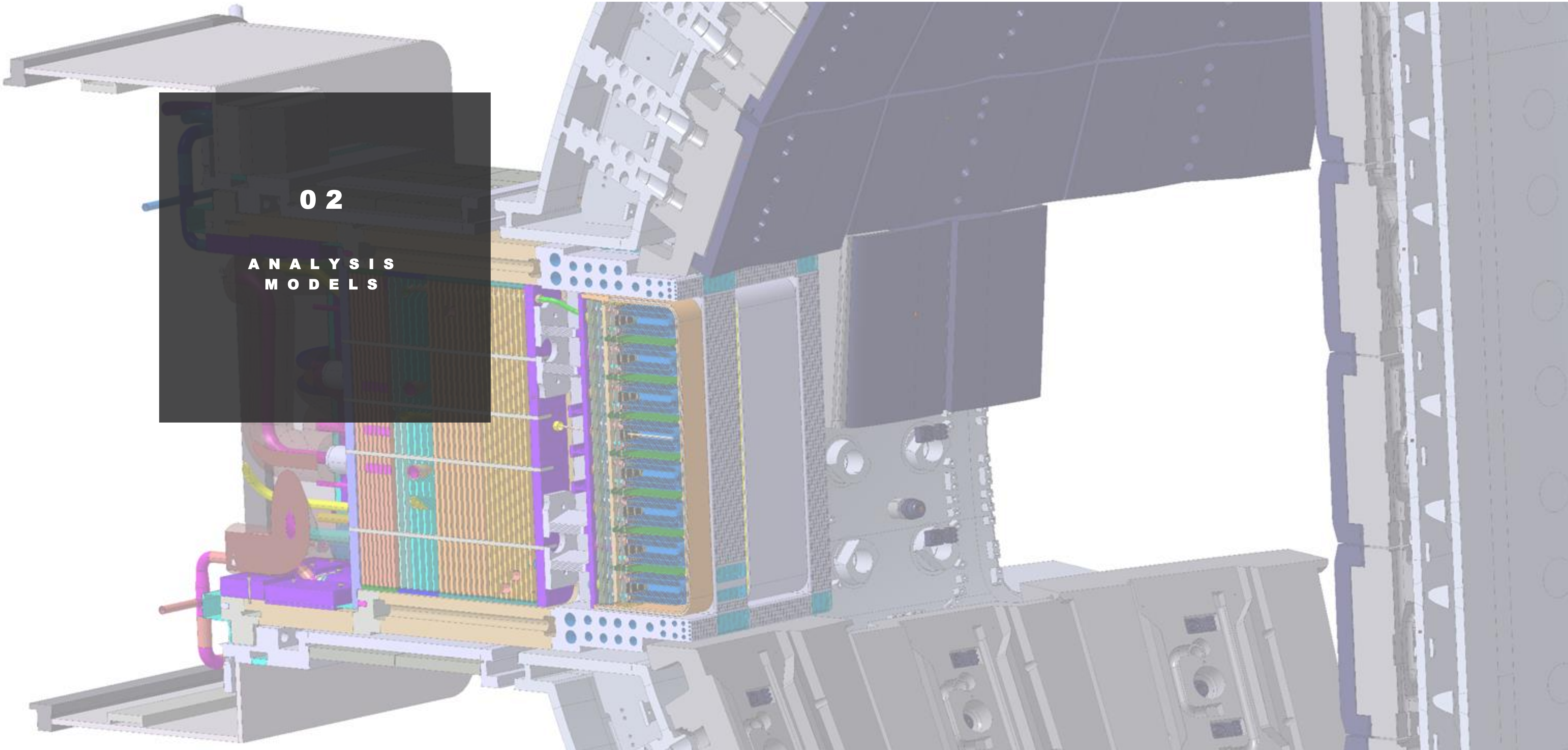
  1. The **variety and characteristics** of the **loads**
  2. Amount and complexity of the **failure modes**
  3. The use of a **new structural material** under development
  4. The **magnitude of the loads** in a restricted design space.

- In the past years, Esteyco has developed **advanced methodologies and proprietary tools** to virtually test alternative design solutions in a consistent, integral and agile manner and linked to the applicable nuclear design code (RCC-MRx).

- This presentation will try to give an overview of the most relevant developments for the simulation of the TBM-Set under the complete set of loads and the subsequent structural integrity assessment with an unprecedented level of comprehensiveness and detail.



HCCP TBM-Set

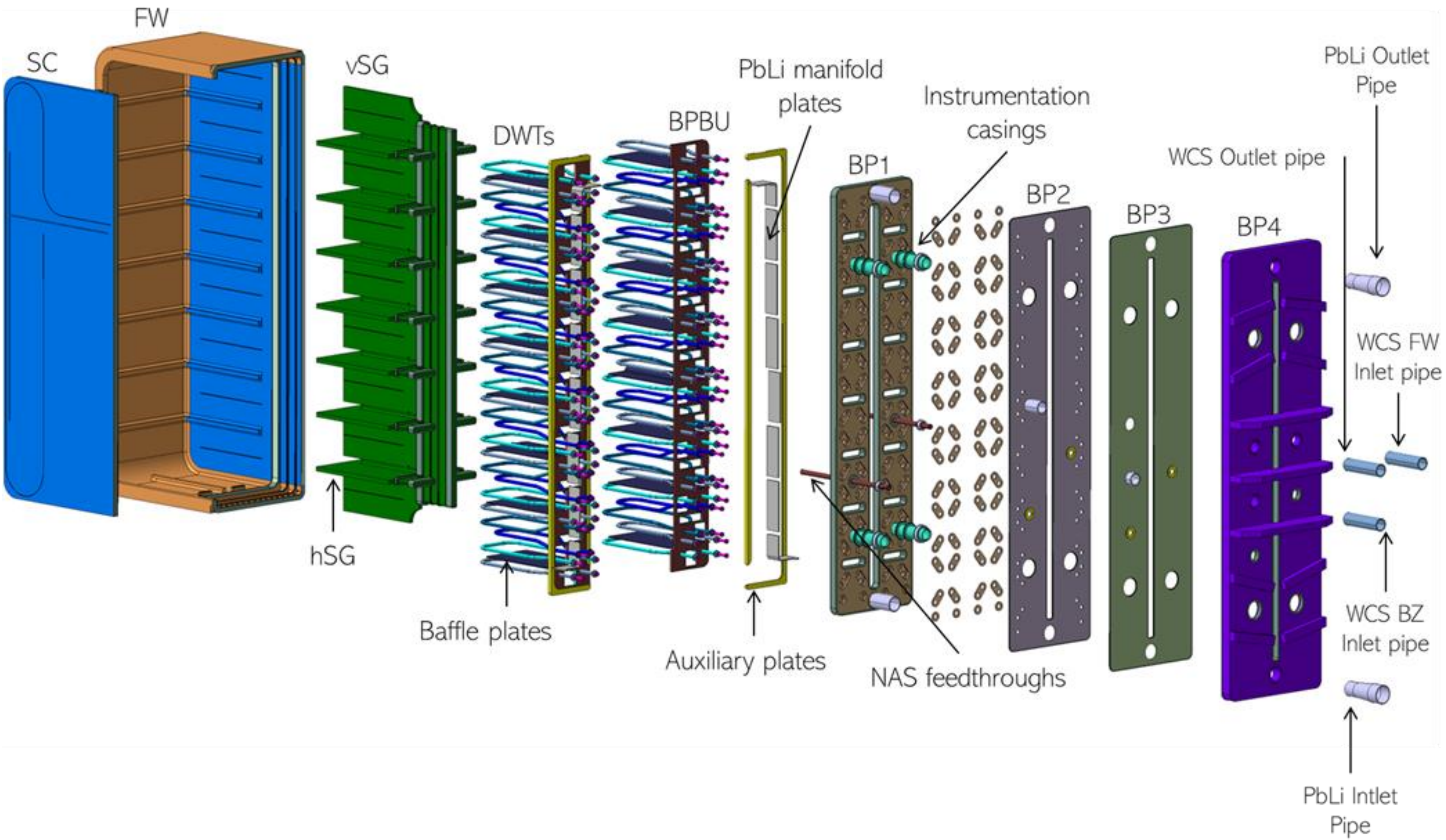


02

ANALYSIS MODELS

Analysis models

WCLL TBM Geometry



Analysis models

Rationale

The development of analysis models is driven by:

- High complexity. Intrincate geometry of the TBM.

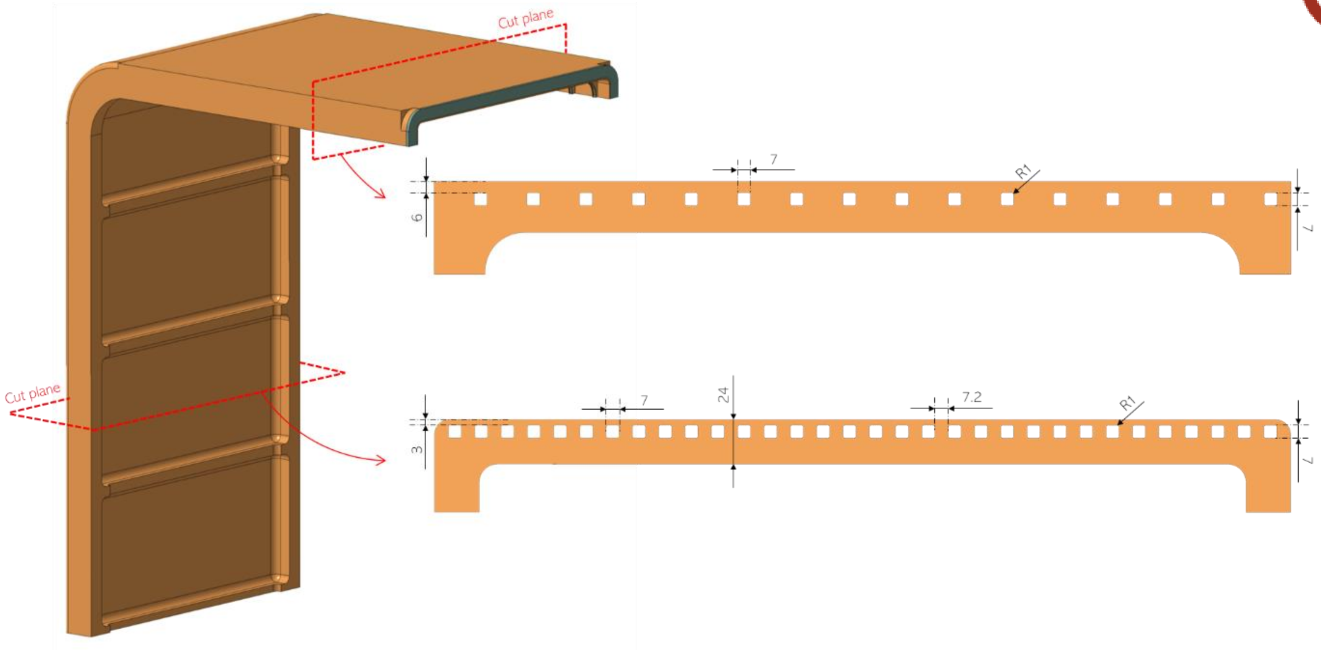
  Importance of details at a **local scale**. A detailed model is needed for the cooling circuit channels, Double Wall Tubes, Cooling Plates, connections, roundings, fillets, etc

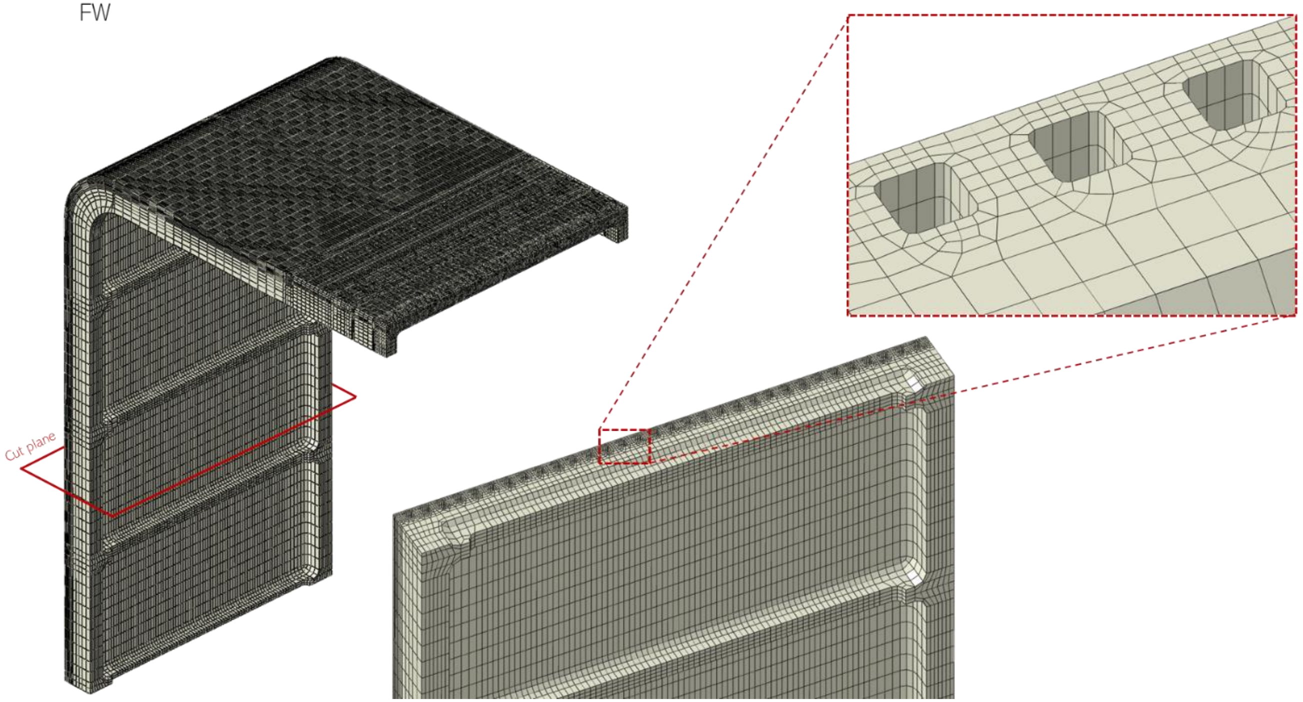
- Global effects and structural concept

  At a **TBM scale**, the FE models must correctly represent the structural system and the load paths.

- Structural integrity assessment

  Models must be developed considering the needs of the subsequent structural integrity evaluation at different locations and components.

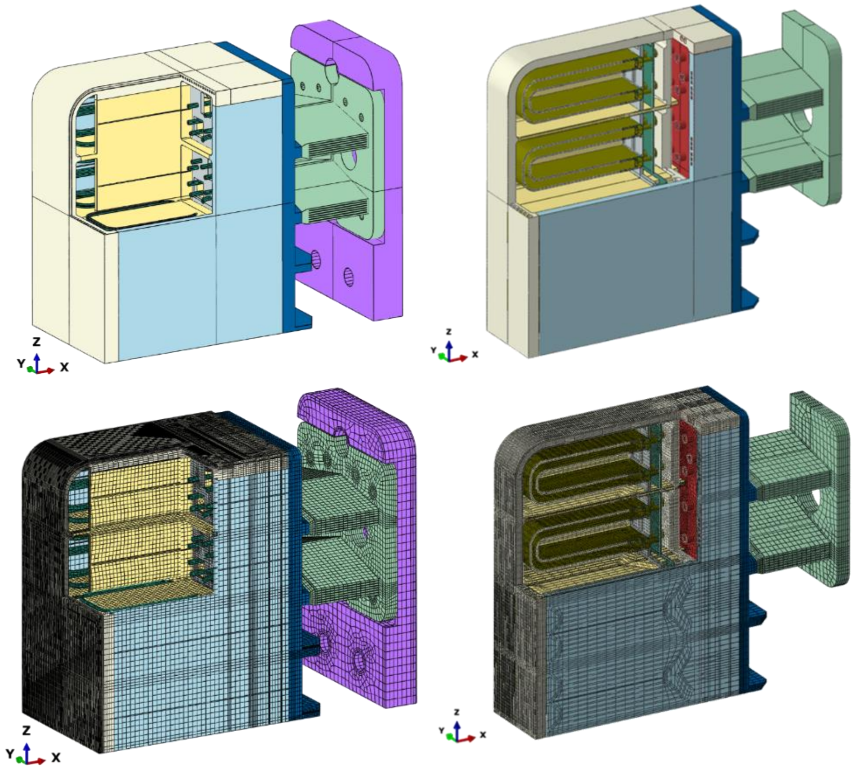




Analysis models

Different levels of detail

Symmetric models

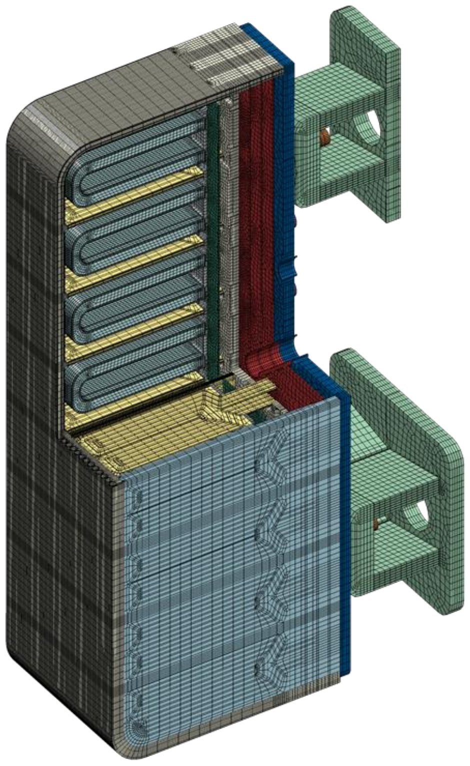


Quarter or Half TBM

Symmetric loads:

- Thermo-mechanical loads
- Pressure loads

Full-scale TBM models

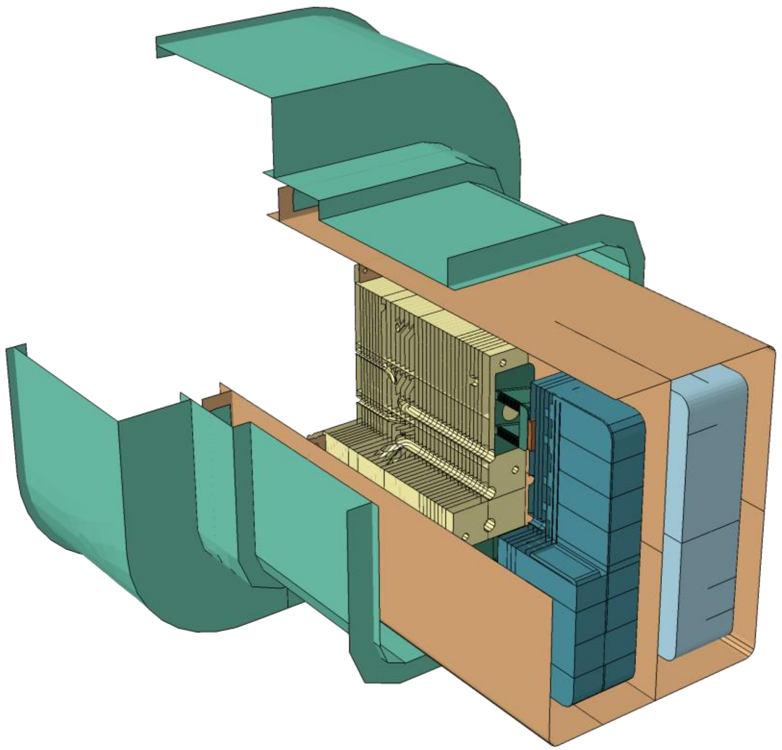


Full-scale TBM

Asymmetric loads:

- Inertial loads (Gravity, seismic)
- EM loads

Global models



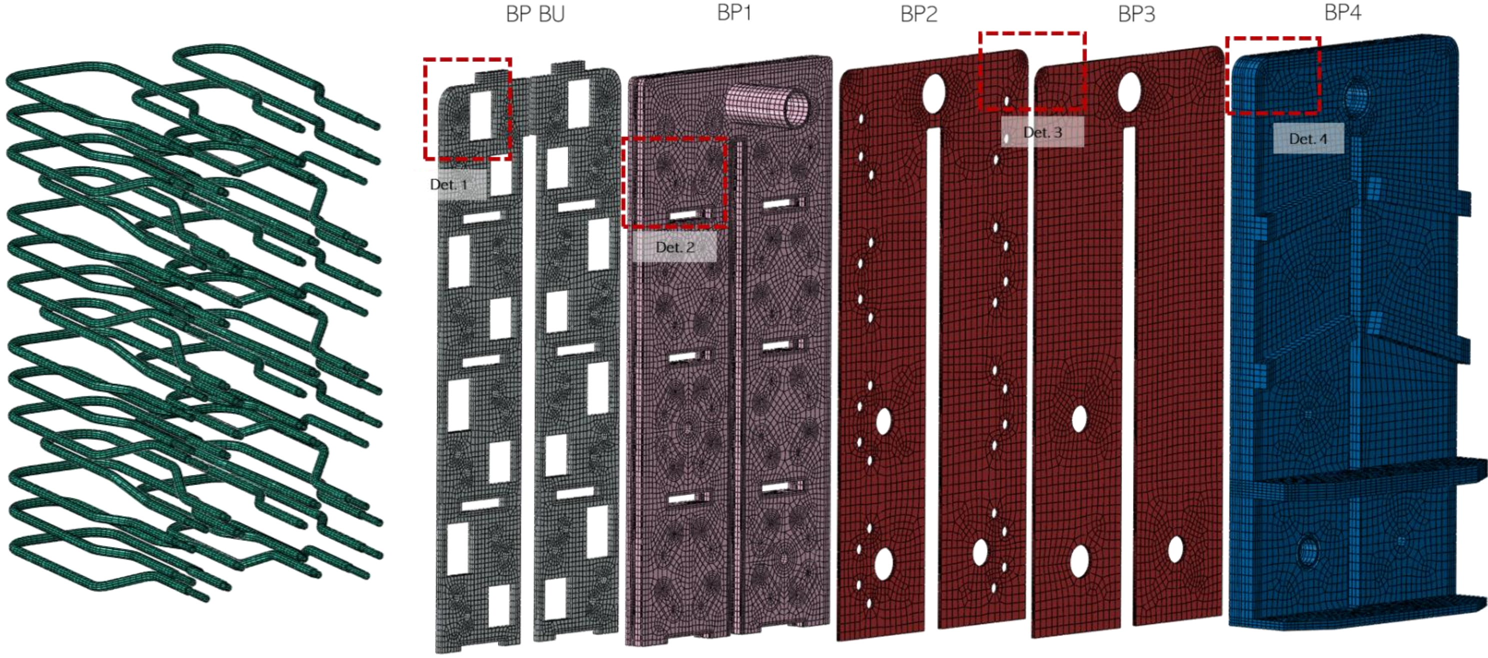
Full port or TBM-Set models

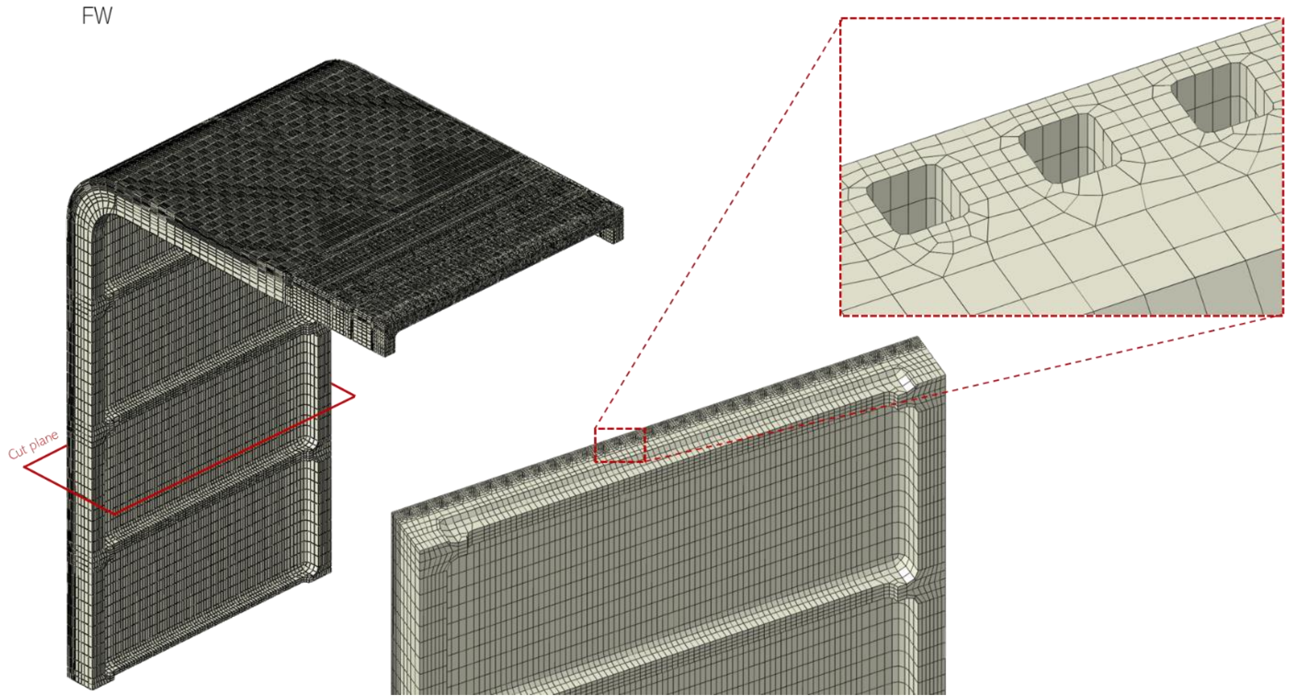
- System characterization
- Global or coupled phenomena
- Auxiliar analyses

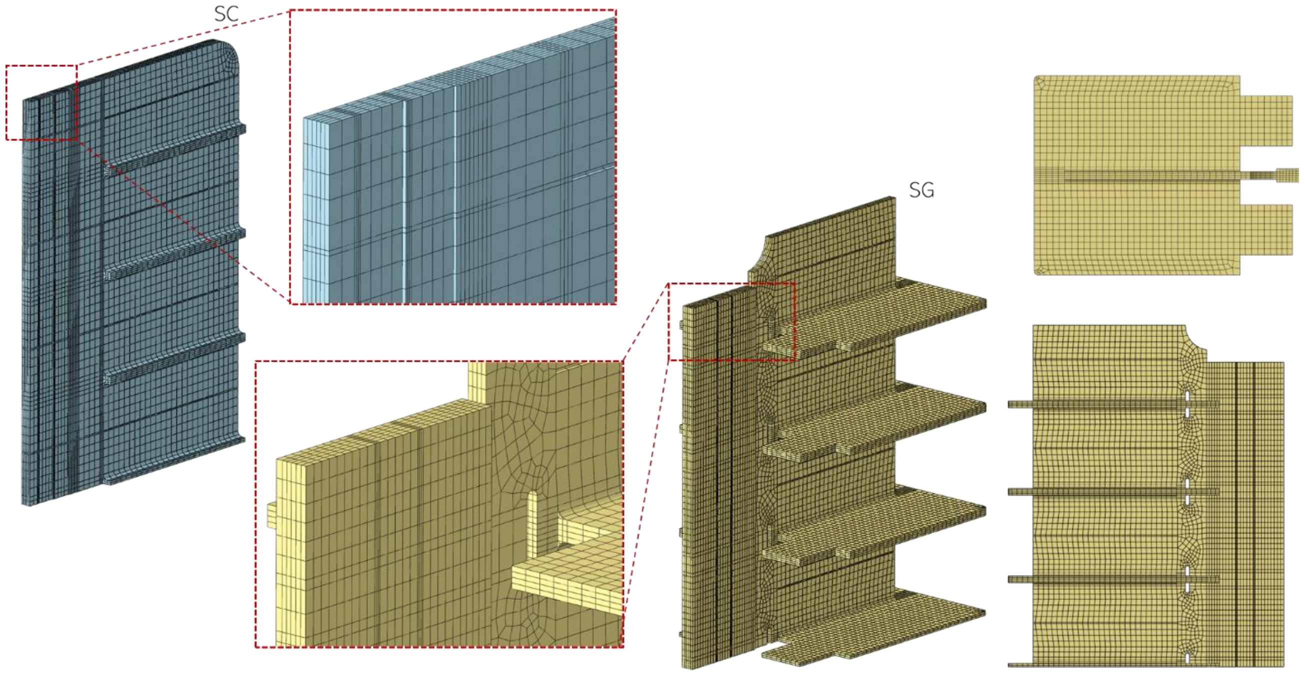
Analysis models

Geometrical discretization

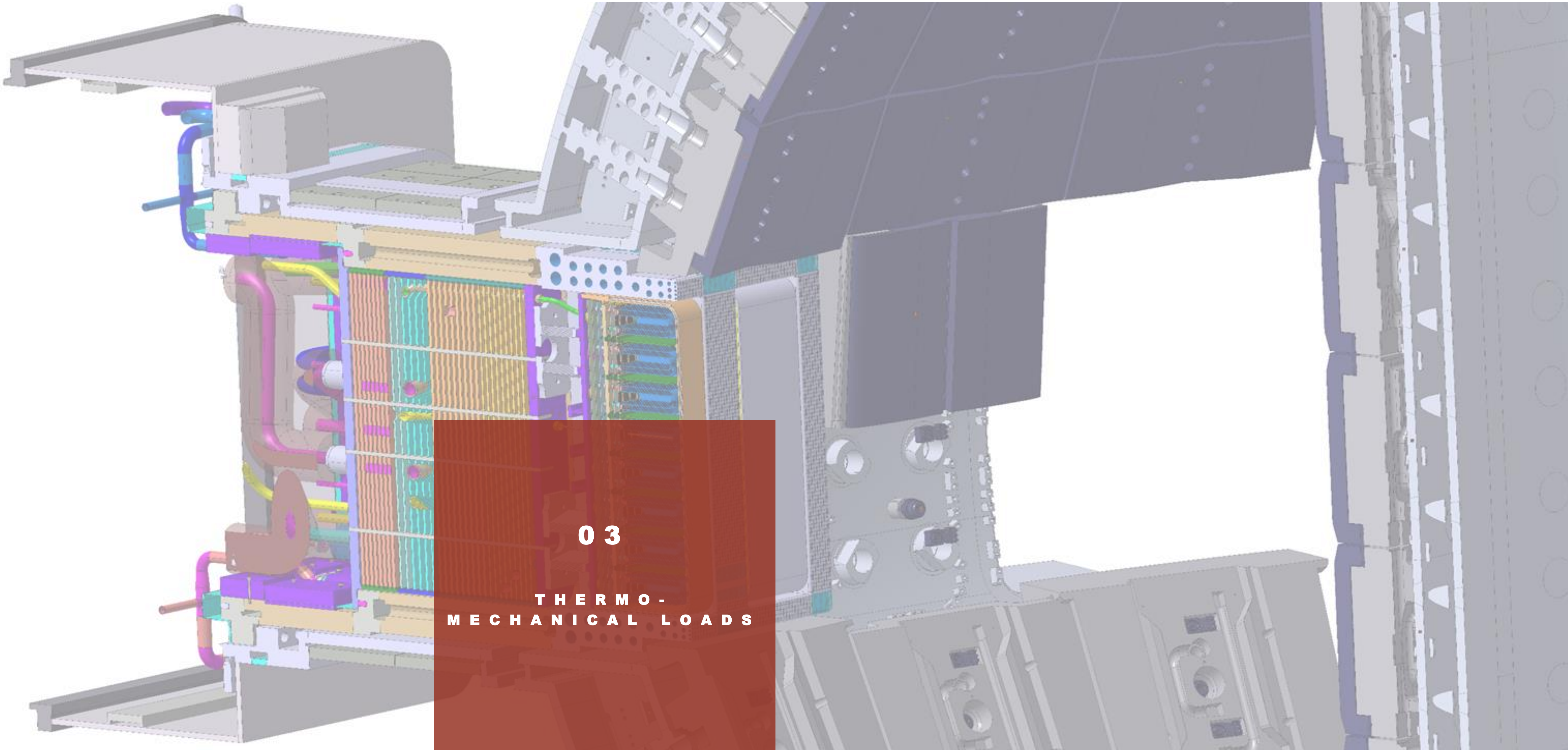
- **Mechanical representations** of the system (FE models) have been generated with **unprecedented spatial resolution** including 2nd order elements **for stress analysis** (thermal and pressure).
- This allows obtaining **representative results** for **almost any local TBM component**, which can be reliably included in the structural integrity assessment.







ESTEYCO



03

THERMO-MECHANICAL LOADS

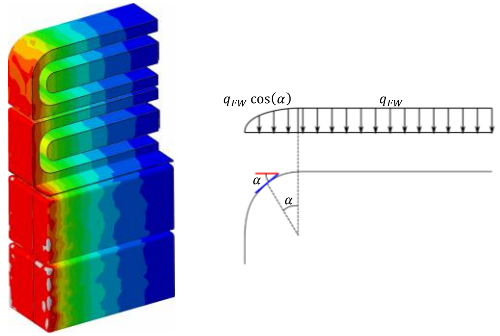
Thermo-mechanical loads

Thermo-mechanical analysis strategy

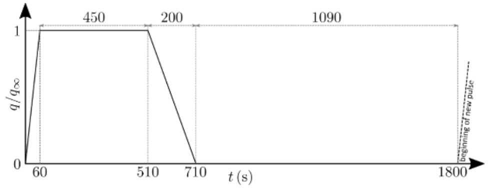
1D-HEAT

Modeling tool for cooling channels

ESTEYCO Mechanics proprietary tool

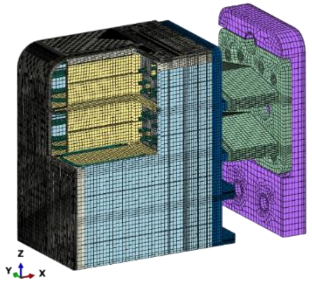


Different thermal loads

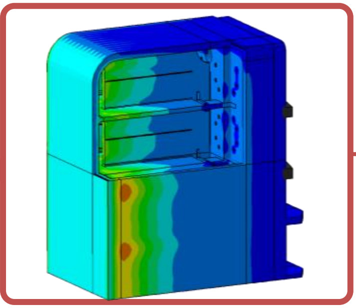


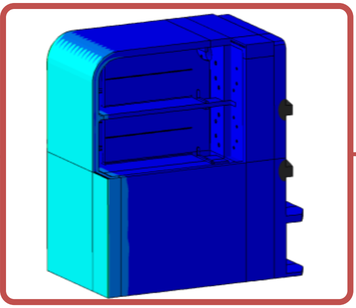
Thermal load time evolution

Transient thermal model



Temperature fields at different times





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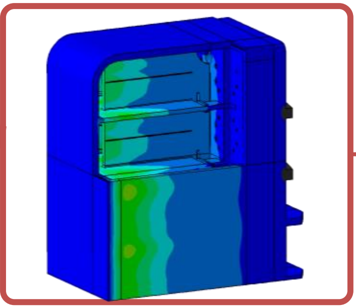
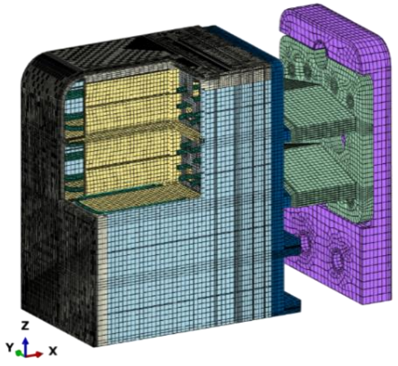
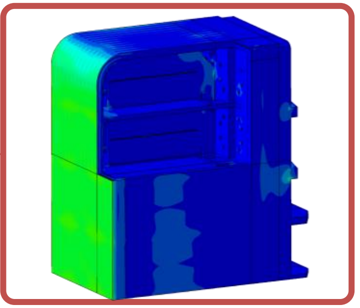
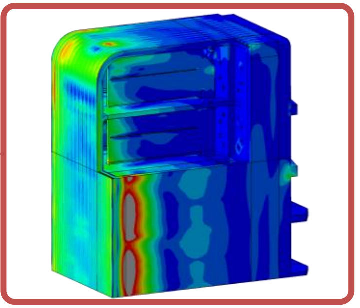


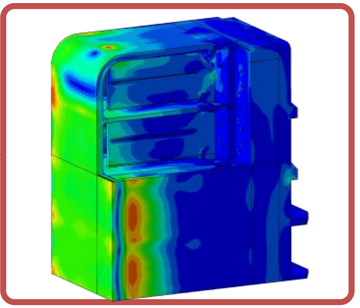
Static thermo - mechanical model



Stress fields at different times



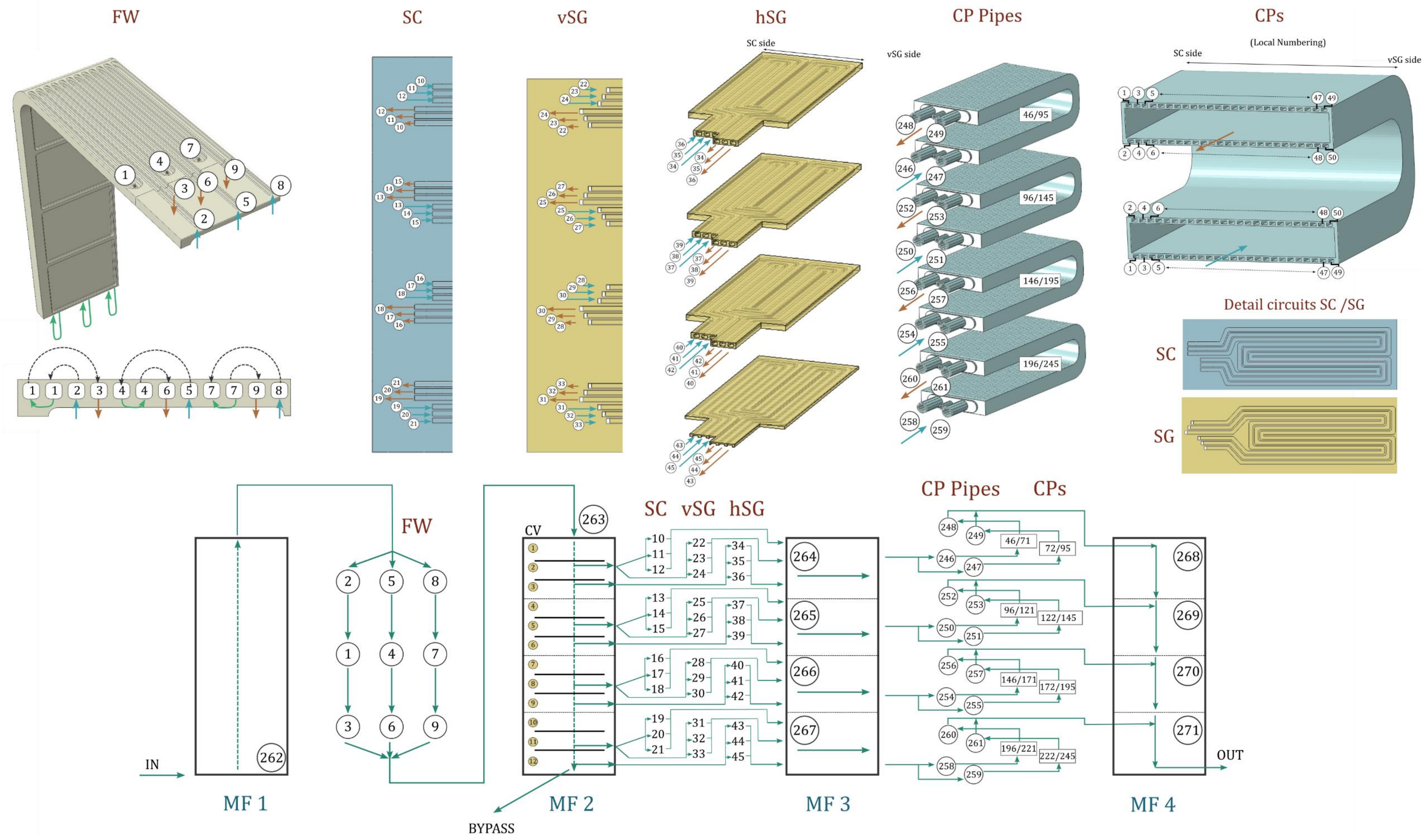




Thermo-mechanical loads

Cooling circuit complexity

1D-HEAT



1D-HEAT

- Solves for the **fluid temperature evolution along the channels**
  - Semi-implicit solver with different discretization alternatives
  - Both transient and steady-state solution
  - Allows inclusion of direct heat over the fluid
  - May include longitudinal convection over the fluid (although typically not required due to high *Pe* in cooling channels)
- **Estimates heat transfer coefficient** based on 1D correlations
  - Dittus-Boelter, Gnielinsky, Natural convection correlations, rough/smooth wall, etc.
  - Corrections for near-wall temperature and nucleate boiling heat transfer enhancement

Solid temperature

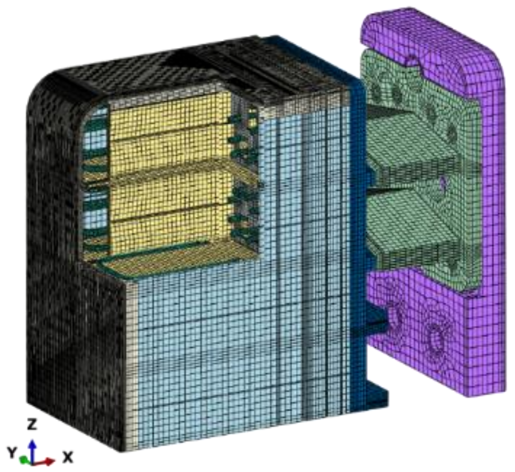
At each time step (weak coupling strategy)

Fluid temperature
Heat transfer coefficient

Energy conservation is ensured between fluid and solid phases

ABAQUS

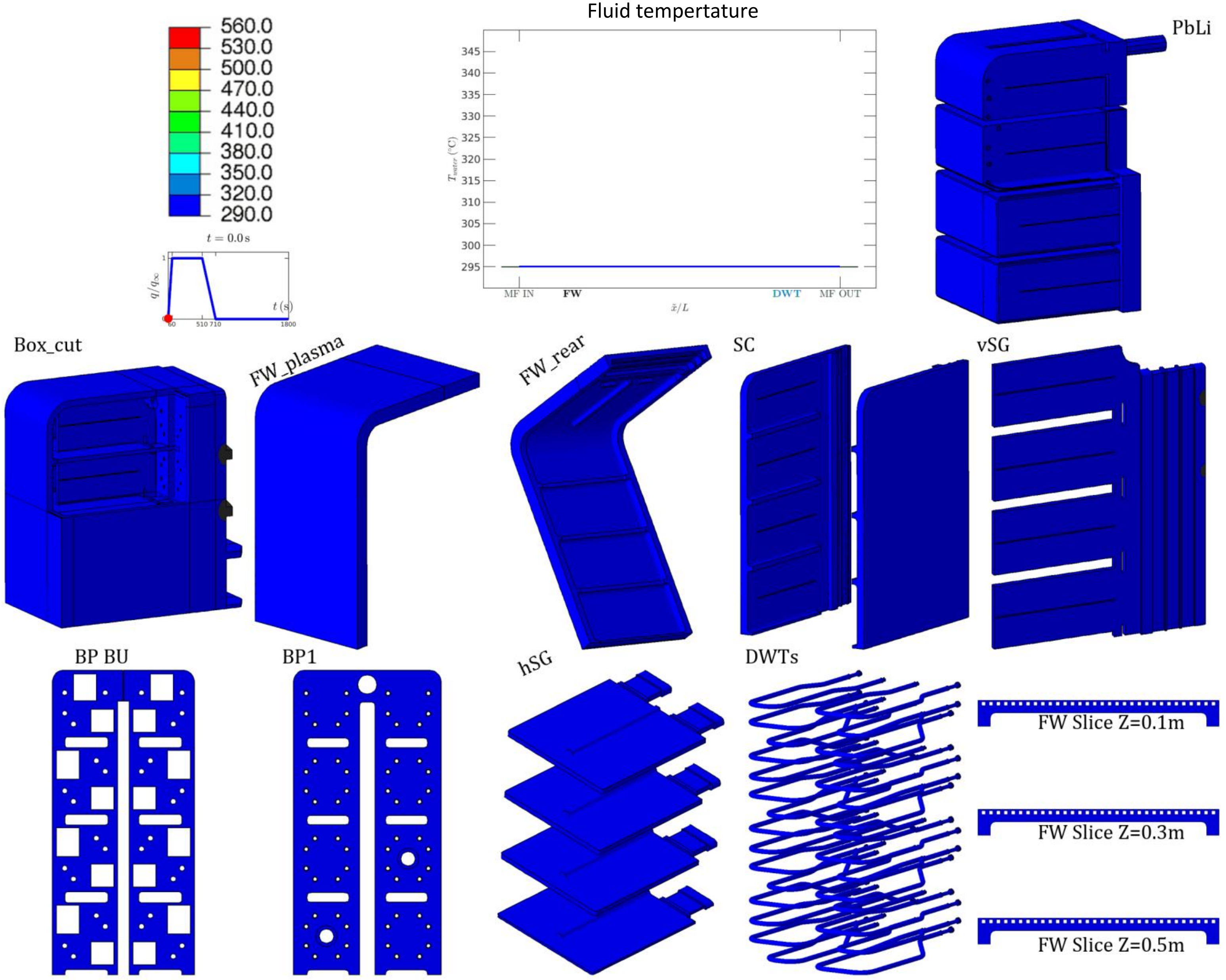
- Solves for the solid temperature
- All FE discretization supported (solid, shell & beam elements)



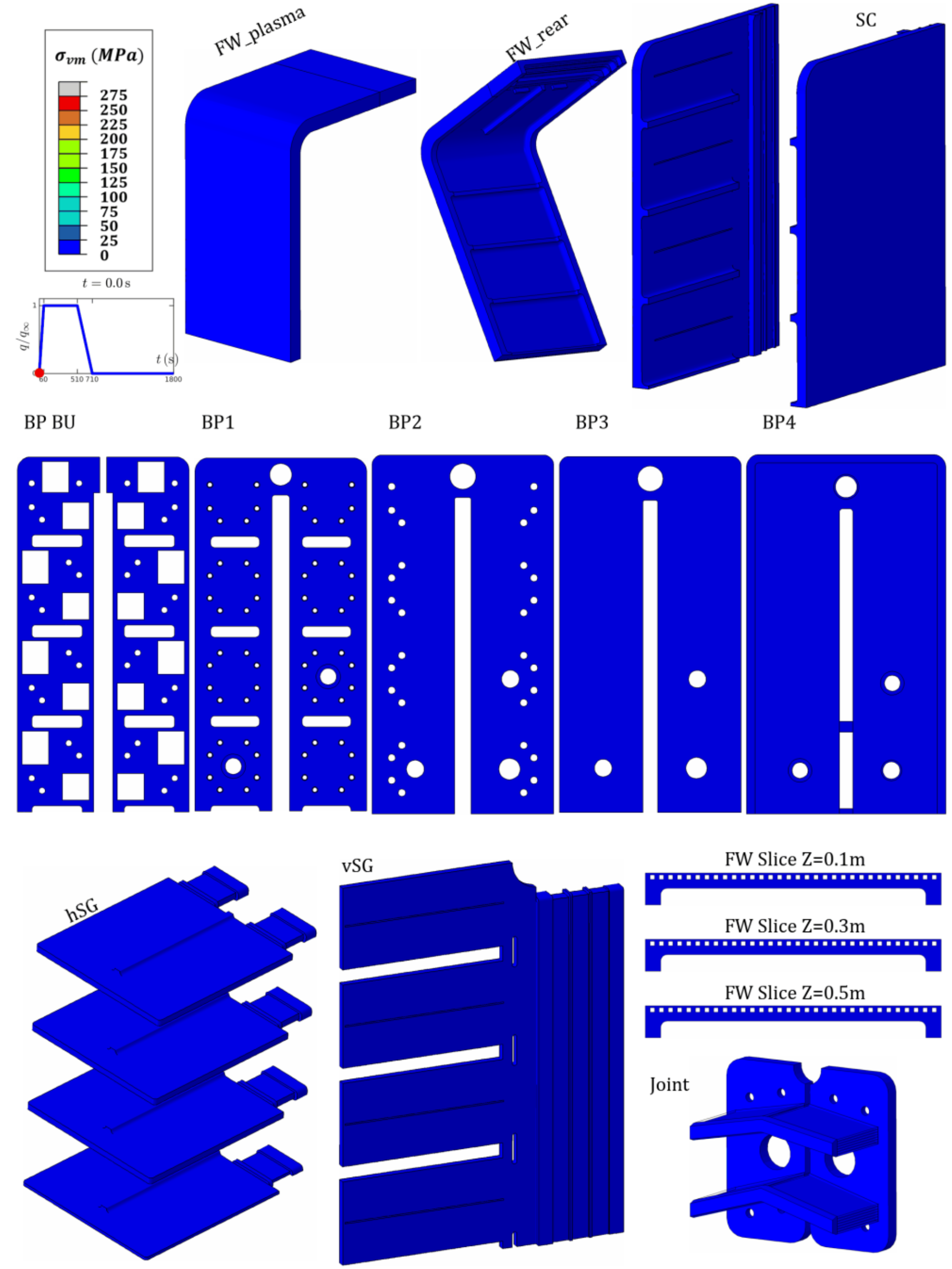
Thermo-mechanical loads

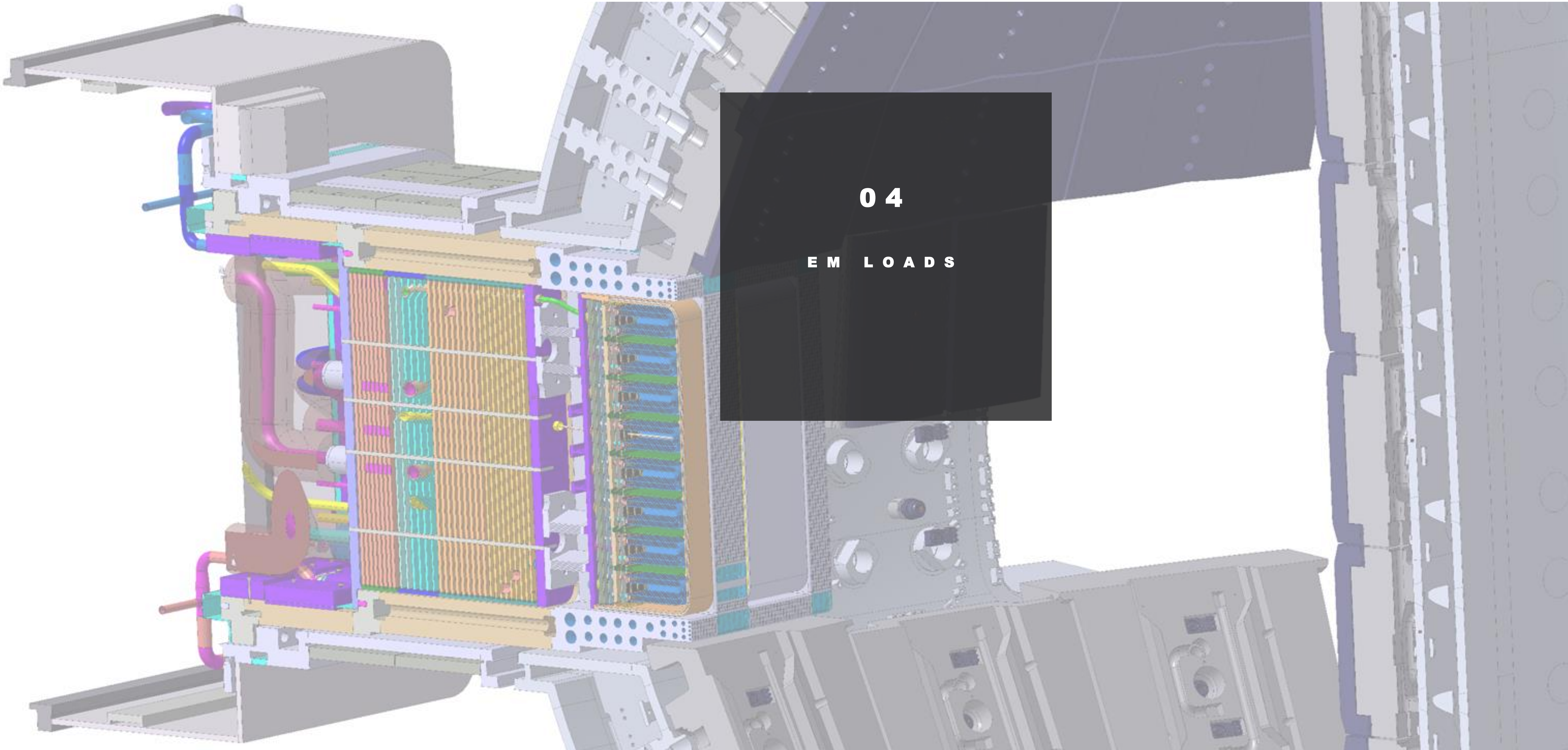
Temperature / stress results

Temperature evolution



Stress evolution





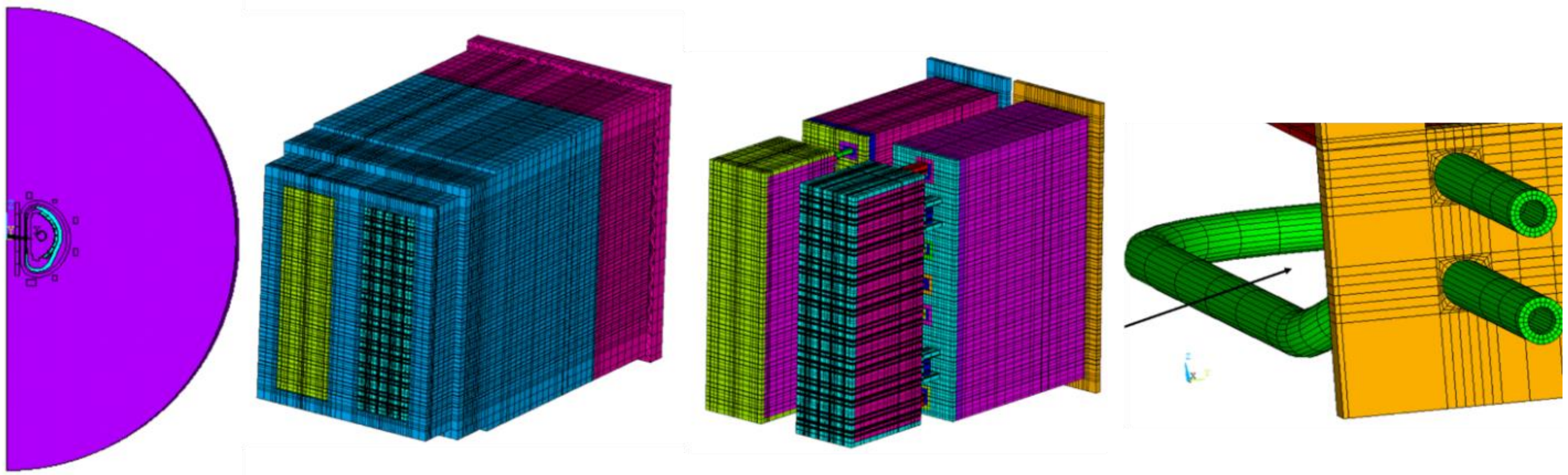
04

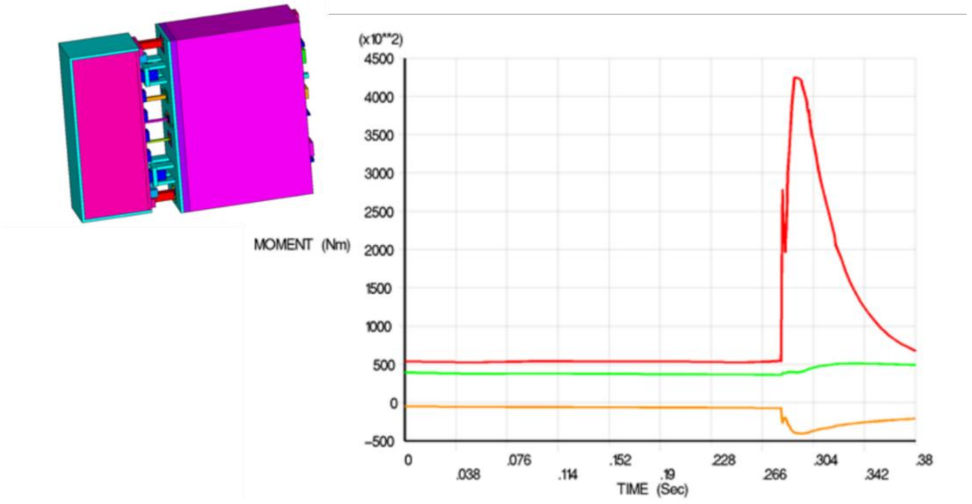
EM LOADS

EM loads

Input data

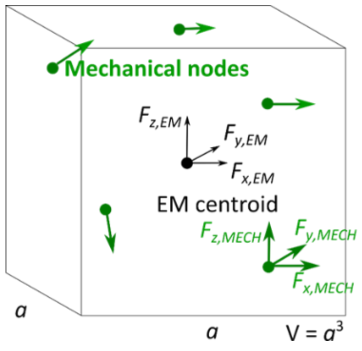
EM Input loads

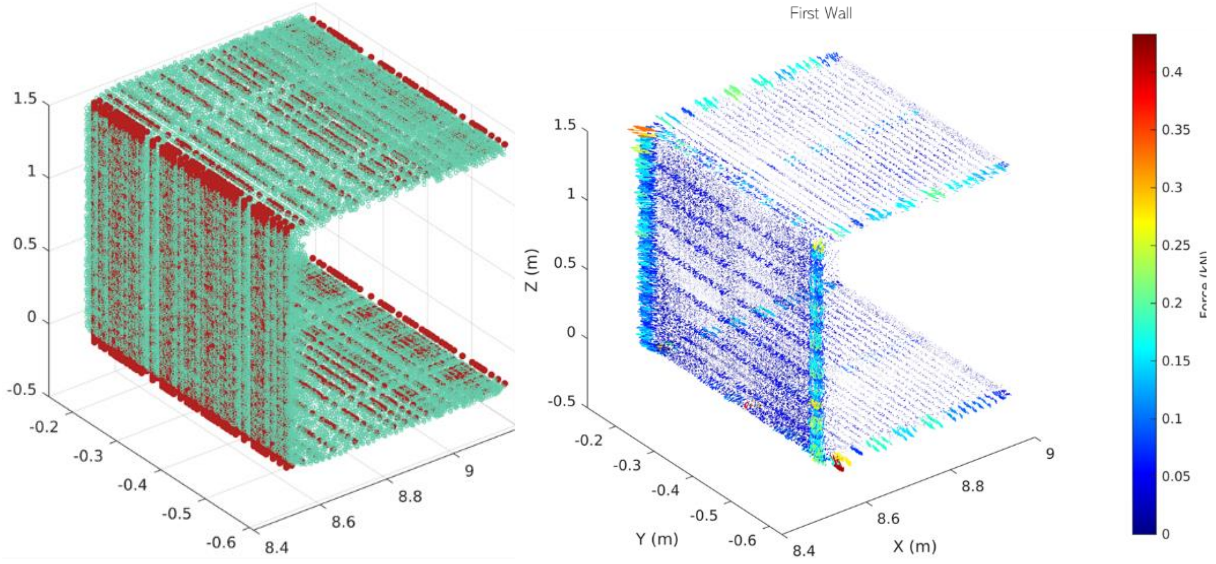




[1] NATEC - F4E_D_2MTTPY v1.0, "Engineering Analysis Report - WCLL-TBS Electro-Magnetic Analysis," 2020.

- At a TBM level, EM loads are **transient events** with a **very complex** distribution.
- **Input EM loads** are given in the form of time-history records of point loads at the EM mesh
- A **distribution algorithm** is implemented in Matlab to distribute these loads in mechanical FE models (ANSYS or Abaqus)





Distribution of EM loads

Detailed model	Global model	Detailed model
Dynamic characterization	Transient dynamic analysis	Equivalent static analysis

Dynamic characterization (Detailed model)

- Dynamic characterization
- Validation of coarser models
- Preliminary study of the effect of EM loads

Transient dynamic analysis (Global model)

- Global transient response
- Interface loads (TBM – SHIELD)
- Dynamic amplification factor (DAF)

Equivalent static analysis (Detailed model)

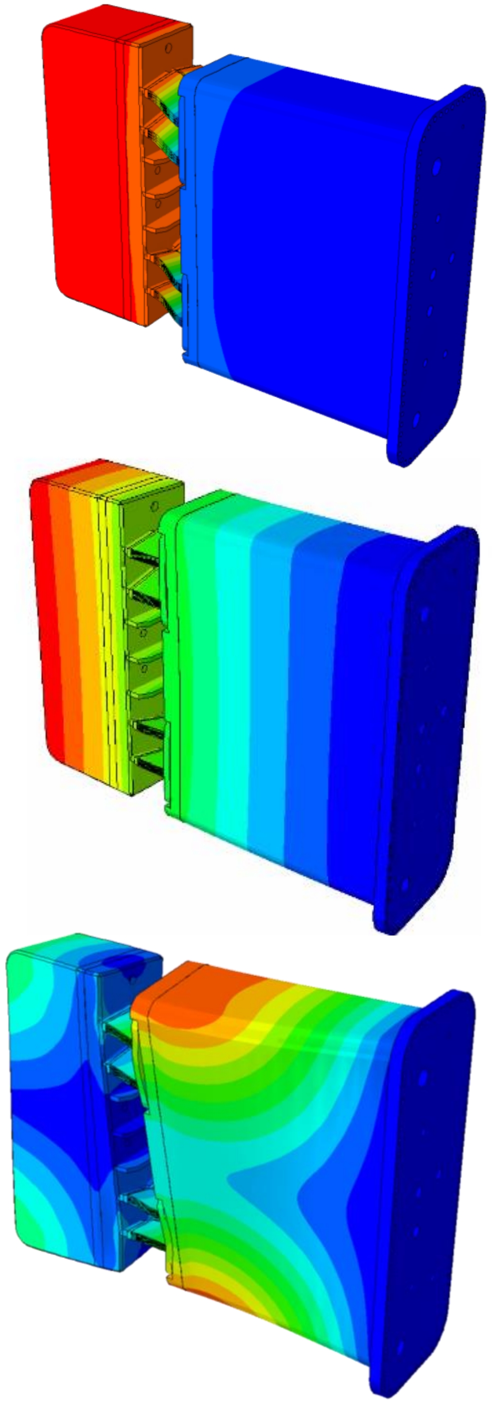
- Mechanical analysis of TBM
- Combination with other loads
- Structural integrity assessment

Detailed model

Dynamic characterization

- **Analysis of the input load signals** and primary quantification of their importance.
- **Modal analyses:** Study of main modal shapes and natural frequencies
- Validation of simplified models
- First estimation of dynamic effects based on simple SDOF models

Mode shapes



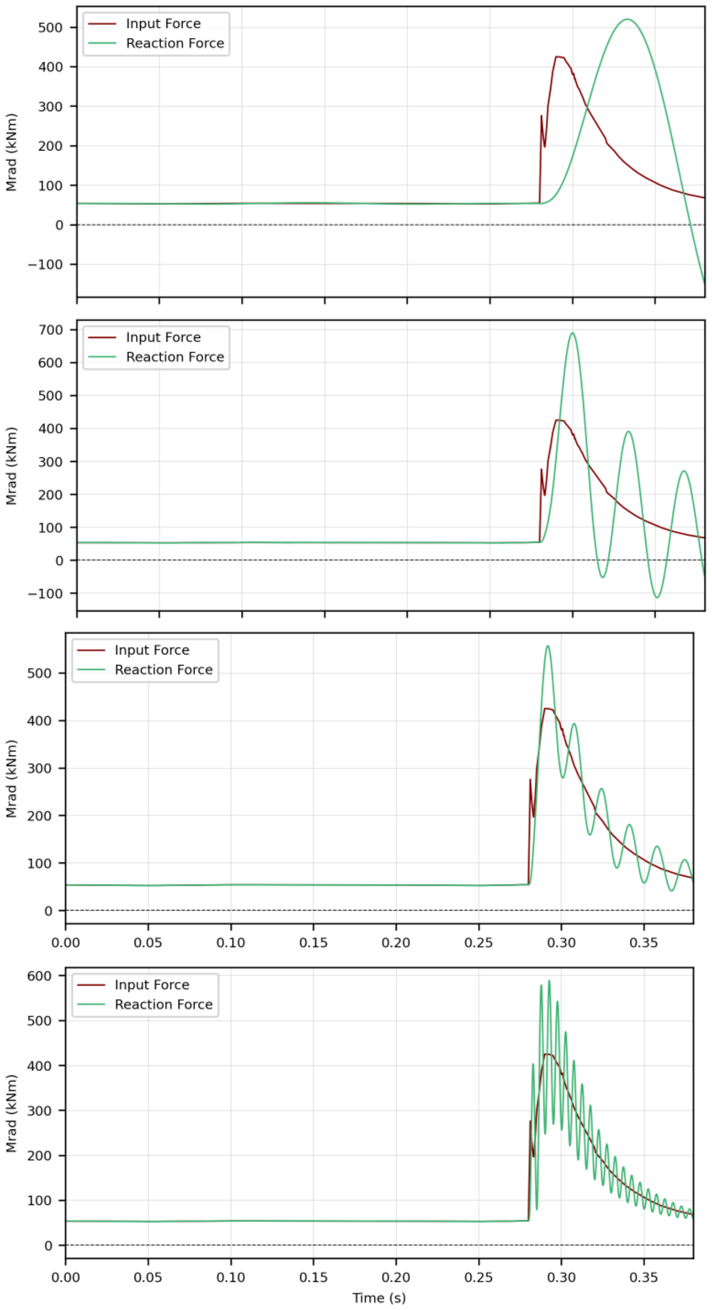
8 Hz

30 Hz

60 Hz

200 Hz

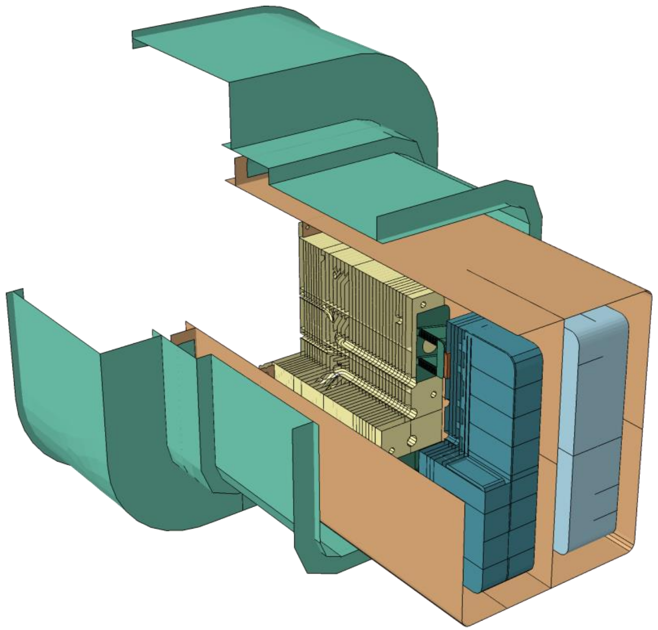
SDOF analyses

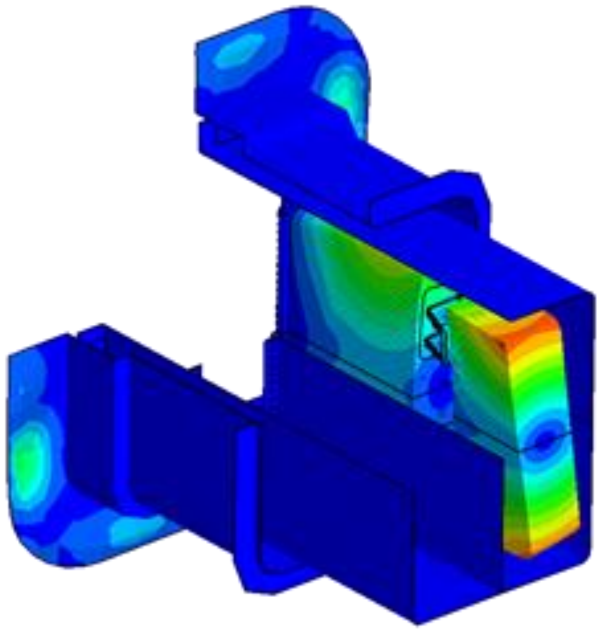


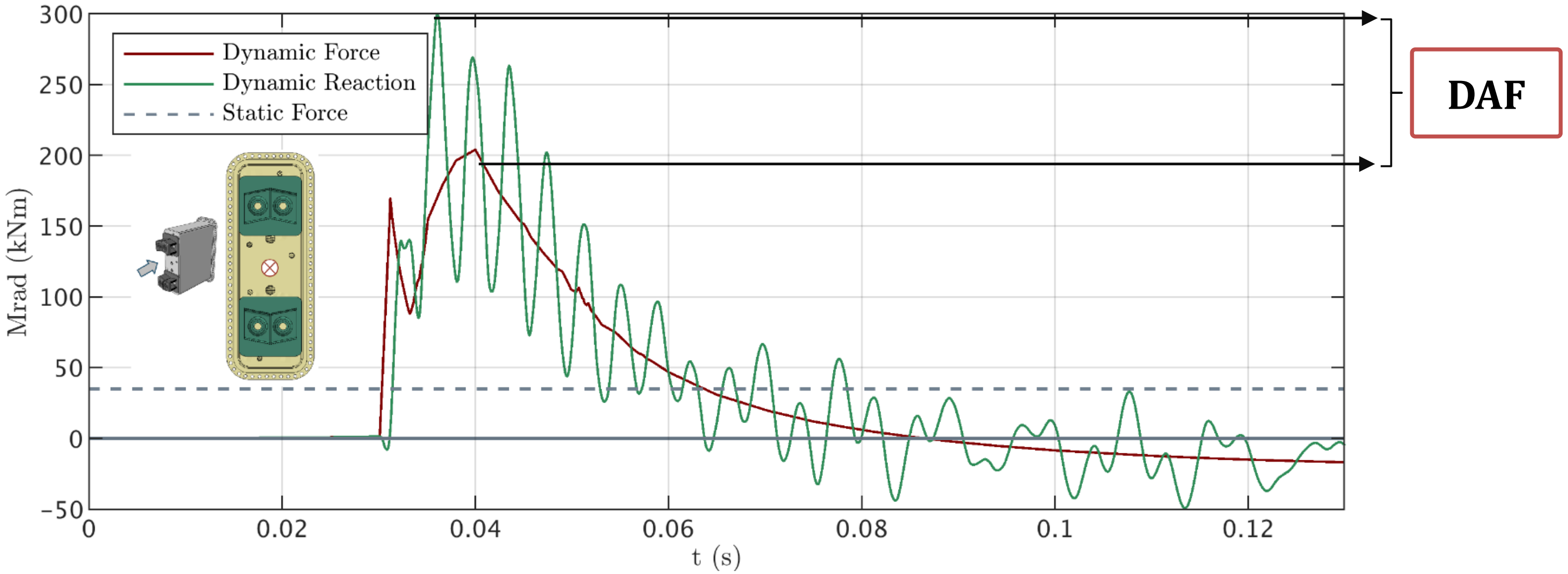
Global model

Transient dynamic analysis

- **Simplified global FE model:** complete port
- Input transient **EM loads are distributed**
- **Time-history transient dynamic analyses**
- Magnitudes of interest are monitored, specially the moment of radial axis
- A **Dynamic Amplification Factor (DAF)** is derived







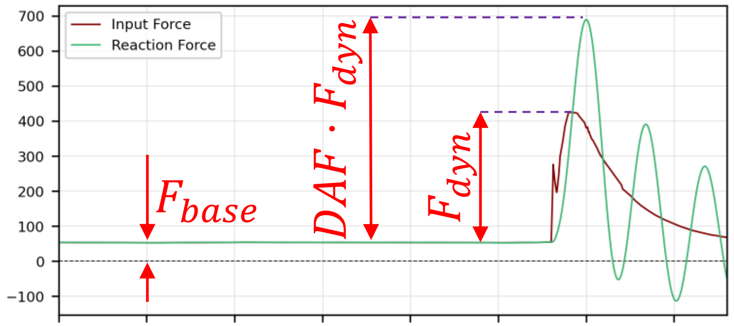
Derivation of DAF

EM loads

Equivalent static analysis

Detailed model

Equivalent static analysis

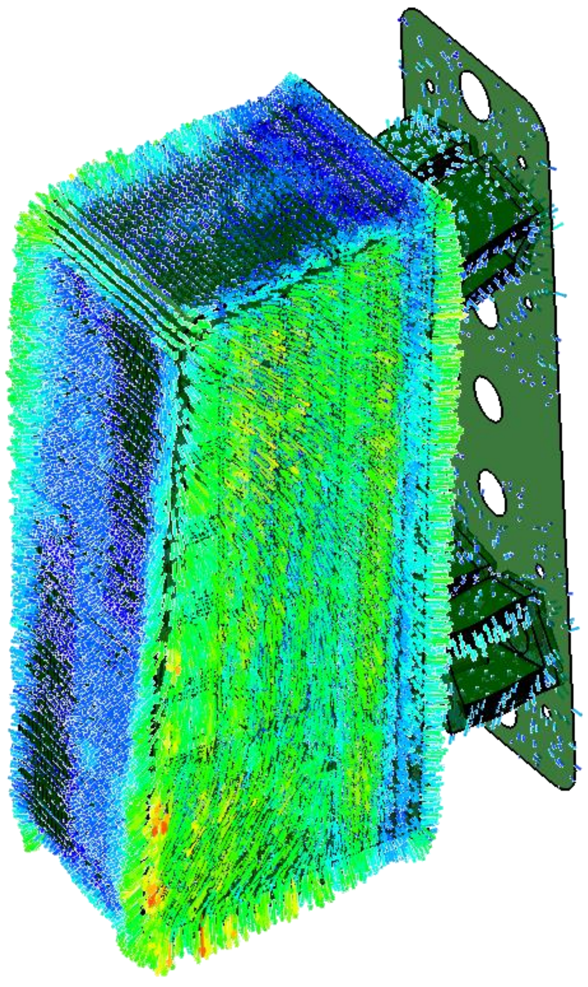


- **Equivalent static loads** are derived from:

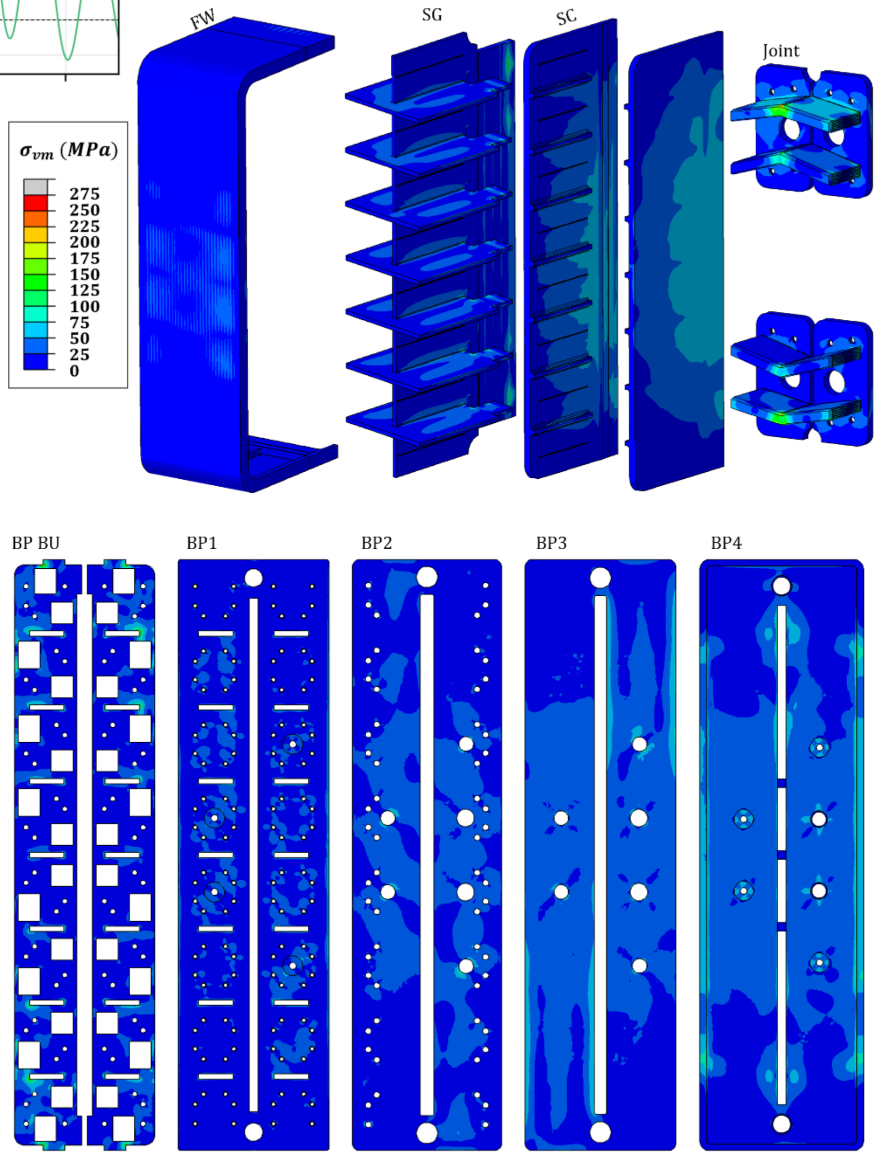
$$F_{eq} = F_{base} + DAF \cdot F_{dyn}$$

F_{base}	Static part of EM forces – Normal operation
DAF	Dynamic Amplification Factor
F_{dyn}	Dynamic part of EM forces : Peak value

- Input **EM loads are distributed** locally
- The resulting static case is combined with other loads

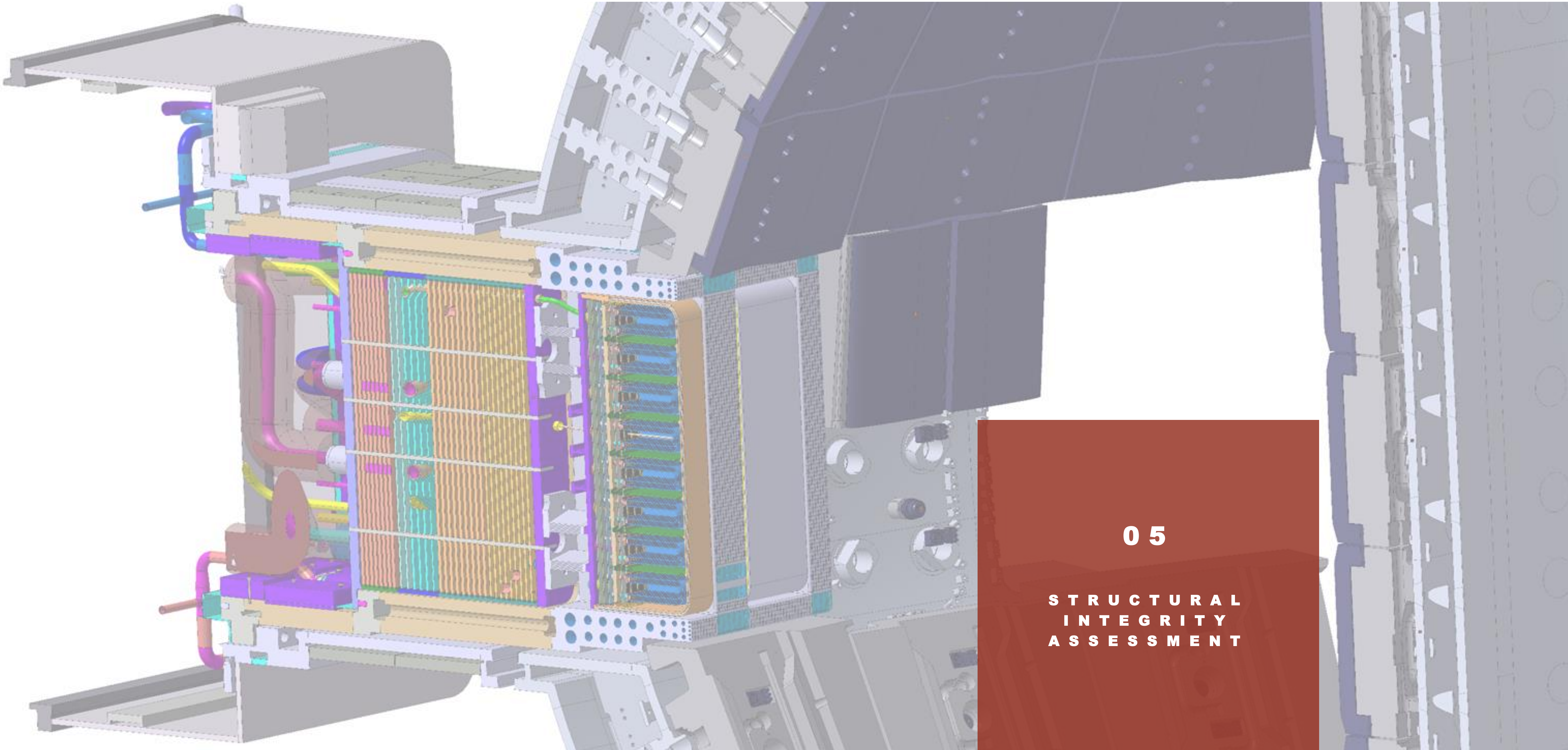


Distributed EM loads



Evaluation of stress levels

ESTEYCO

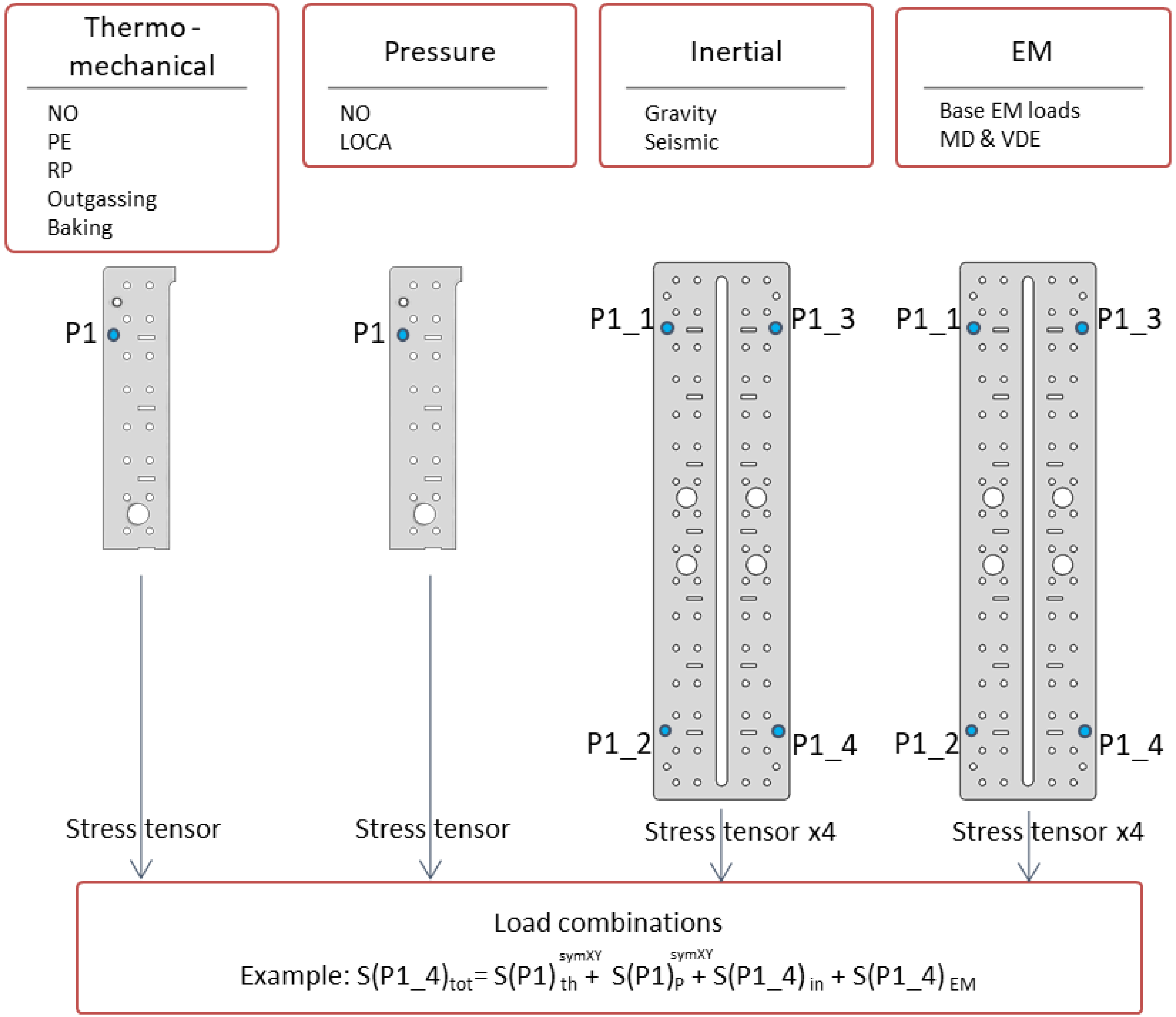


05

STRUCTURAL INTEGRITY ASSESSMENT

Combination of different loading scenarios

- Due to the variety and nature of load cases involved, different mechanical representations are needed for **static, transient thermal and dynamic analyses**.
- A **consistent superposition of stress tensors** from all load cases (thermal, pressure, EM and inertial) and different FE models has been achieved in order to undertake detailed structural integrity assessments for all load combinations.



Structural integrity assessment

RCC MRx design-by-analsis rules

Elastic Analysis

Temperature and stress fields as a function of time

(Negligible thermal ageing curve not available; only partial data in RCC-MRx 2015 -> not for now)

Negligible Ageing Test
RB 3216.5

$$\sum_{i=1}^{N}\left(\frac{t_i}{T_i}\right) \le 1$$

Ageing significant?

NO / YES

Reduction of allowable limits

Immediate excessive deformation and immediate plastic instability (LT)
RB 3251.112 (A), 3251.12 (C), 3251.13 (D)

$$\overline{P_m} \le S_m(\theta_m) \qquad \overline{P_l} \le 1.5 \cdot S_m(\theta_m)$$
$$\overline{P_l + P_b} \le 1.5 \cdot S_m(\theta_m)$$

(Rule applicable to Eurofer but currently partial concern regarding the S_m value due to cyclic softening)

OK √

Progressive deformation (LT) / 3Sm rule
RB 3261.1118

$$\max(\overline{P_l + P_b}) + \overline{\Delta Q} \le 3 \cdot S_m(\theta_m)$$

(If irradiation significant, use irradiated properties when available)

Progressive deformation (LT) / Efficiency diagram
RB 3261.1117

$$\overline{P_1} < K_{dp1} S_m(\theta_m); \overline{P_2} < Kdp_2 \cdot 1.5 S_m(\theta_m)$$

(Properties of efficiency diagram for 9%Cr steel is used instead of Eurofer – not yet available-)

OK √

Fatigue in non-singular zones (LT)
RB 3261.1123

$$V(\Delta\varepsilon_j) = \sum_j \left(\frac{n_j}{N_j}\right) \le 1$$

(For zone of geometric singularity and when "distance d" available, use RB3261.113. Until then, use the existing rule also for singular zones)
(If irradiation significant, use irradiated properties when available)

OK √

(Irradiation especially significant for Eurofer due to loss of uniform elongation. Negligible irradiation curve is available. Maximum allowable irradiation –limit of validity of elastic analyses- partially available in RCC-MRx 2018)

Negligible Irradiation Test
RB 3216.2

$$\sum_{i=1}^{N}\left(\frac{t_i \cdot \varphi_i}{\phi_{\text{allowable}_i}}\right) \le 1$$

Irradiation significant?

NO / YES

Immediate plastic flow localization (LT)
RB 3251.2121 (A), 3251.22 (C), 3251.23 (D)

$$\overline{P_m + Q_m} \le S_{em}(\theta_m, G_{tm})$$

(Related to loss of uniform elongation. Particularly relevant for Eurofer –even in non-irradiated state-. S_{em} values included in RCC-MRx 2018)

OK √

Immediate fracture due to exhaustion of ductility (LT)
RB 3251.2122 (A), 3251.22 (C), 3251.23 (D)

$$\overline{P_l + P_b + Q + F} \le S_{et}(\theta_m, G_t)$$

(Not expected to be an issue for Eurofer)

OK √

Negligible Creep Test
RB 3216.1

$$\sum_{i=1}^{N}\left(\frac{t_i}{T_i}\right) \le 1$$

Creep significant?

(Currently only Tentative Negligible Thermal Creep curve in literature; not in RCC-MRx yet.
HT rules apply for Temperatures above 375ºC)

YES

Creep differed excessive deformation (HT)
RB 3252.111 (A, C)

$$U_{A,C}(\Omega\overline{P_m}) \le 1$$
$$U_{A,C}(\overline{P_l + \phi P_B}) \le 1$$

OK √

Creep differed rupture (HT)
RB 3252.131 (A, C, D)

$$W_{A,C,D}(1.35\Omega\overline{P_m}) \le 1$$
$$W_{A,C,D}(1.5(\overline{P_l + \phi P_B})) \le 1$$

OK √

Progressive deformation (HT)
RB 3262.111
Two effective primary stresses to be calculated in accordance with RB 3262.1111 to RB 3262.1116 (P1 and P3)

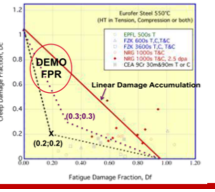
RB 3262.1117

$$\varepsilon_{plastique}(1.25\ P_1) + \sum \varepsilon_{fluage}(t_i, 1.25\ P_1^i) \le D_{max}$$
$$\varepsilon_{plastique}(1.25\ P_3) + \sum \varepsilon_{fluage}(t_i, 1.25\ P_3^i) \le 2D_{max}$$

OK √

Creep-Fatigue in non-singular zones (HT)
RB 3262.1122

(V_A, W_A) ->



(Conservatism depends on creep-fatigue interaction diagram, which currently needs further validation. Creep strain curves necessary for the calculation of W_A available from RCC-MRx 2015)
(If irradiation significant, multiply W by 10)

OK √

Buckling
RB 3270

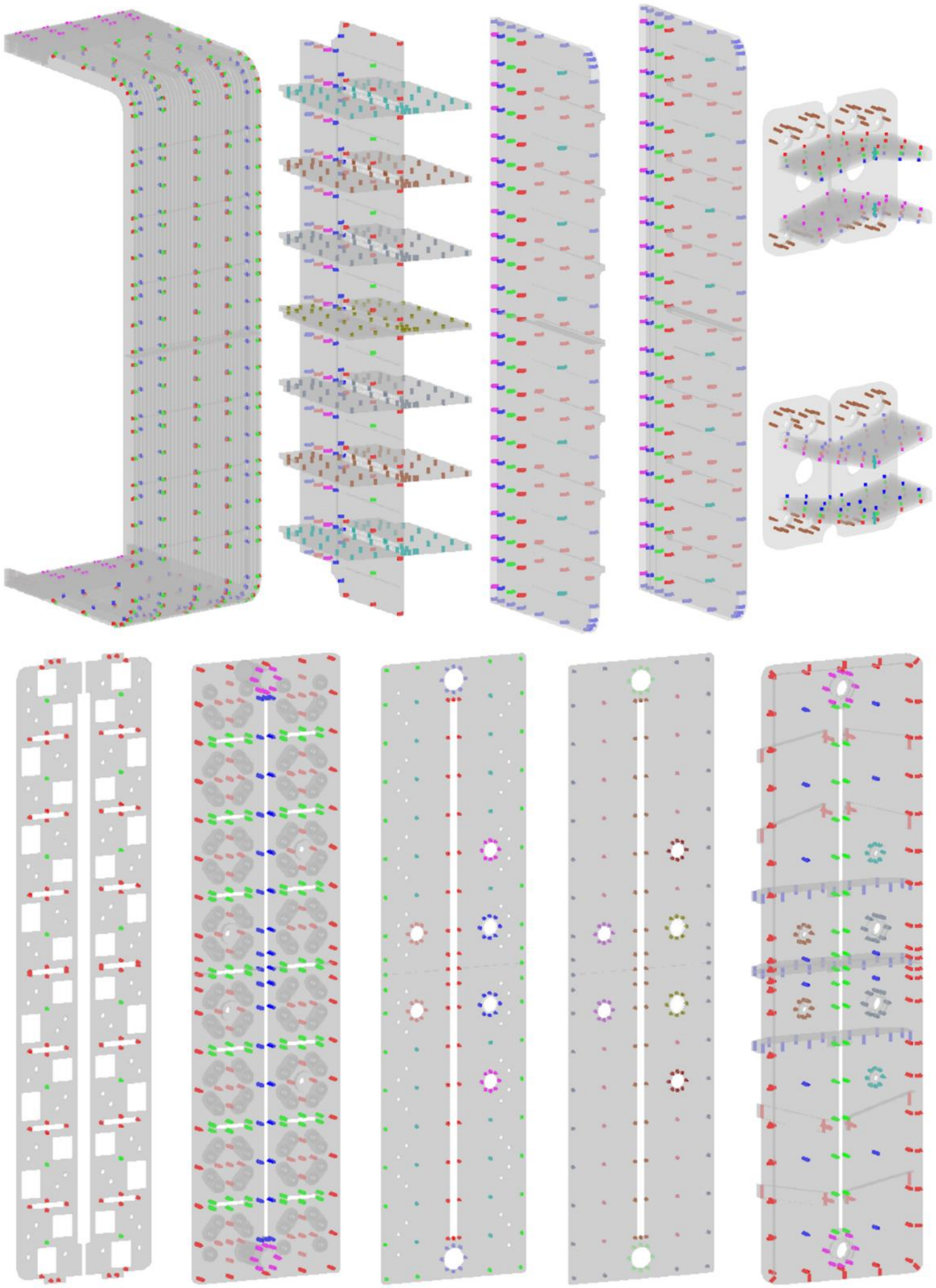
OK √

Fast fracture
Appendix 16

SL-Check

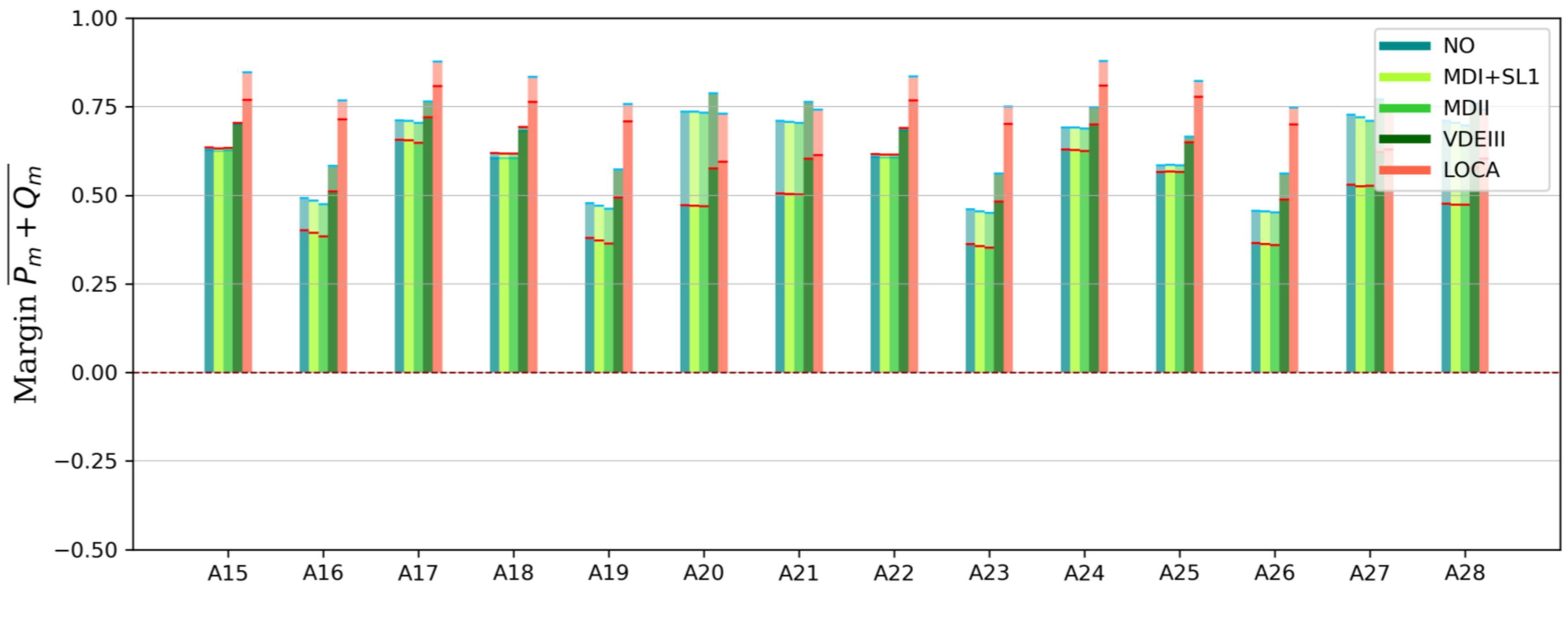
- ESTEYCO Mechanics proprietary tool
- Virtual testing of design solutions under representative scenarios generates a huge amount of relevant information → **Specific tools** to efficiently handle, process and display this information.
- Specifically tailored for code-compliance check of transient phenomena (e.g., TBM Sets under pulsated operation)
- This includes an **extensive coverage of TBM box locations** for the SIA: ≈5,000 supporting lines for detailed check of applicable RCC-MRx design rules.
- A specific package of scripts (**SL-Check**) has been developed in Python. It is an automatic tool **linked to Abaqus** that:
  - **Extracts results** from the complex FE models (Solid & Shell discretization are allowed)
  - Performs the structural integrity assessment **according to RCC-MRx**
  - Provides an **advanced set of visualization tools** to understand the results and assess the structural performance.

Supporting line location

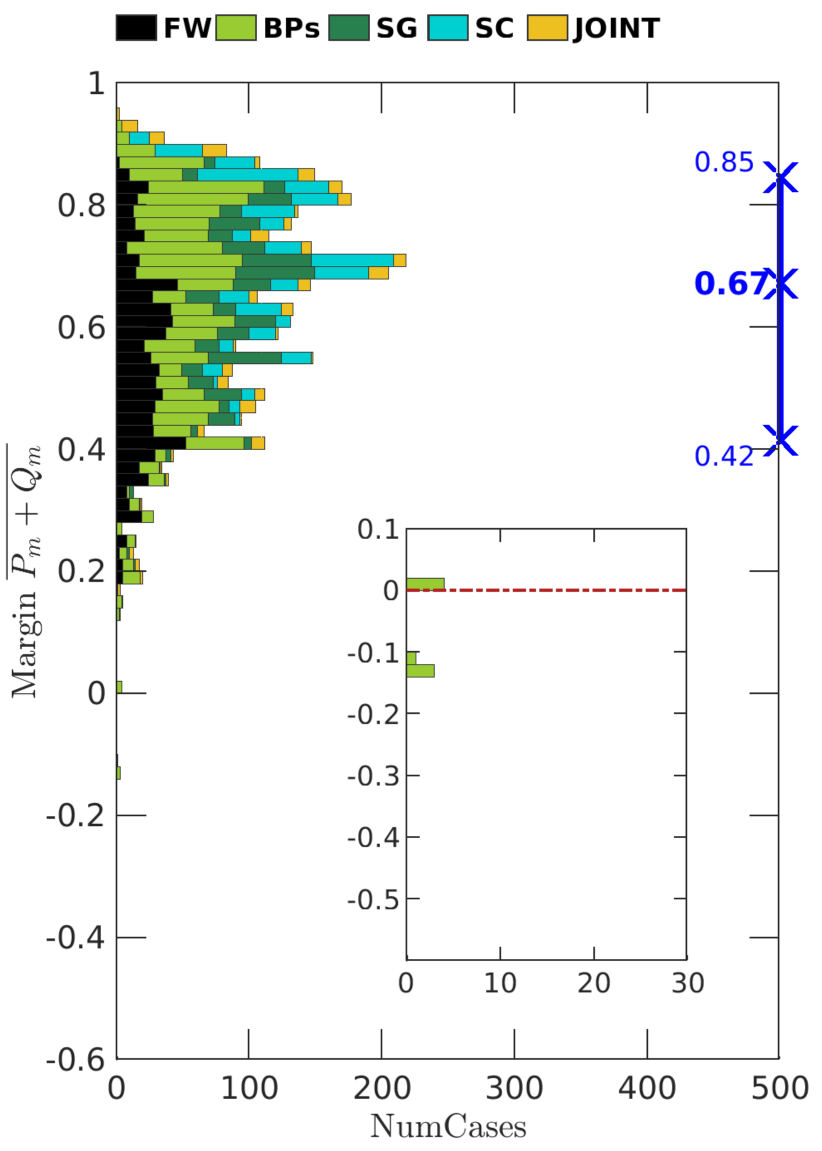


SL-Check

Bar Graphs

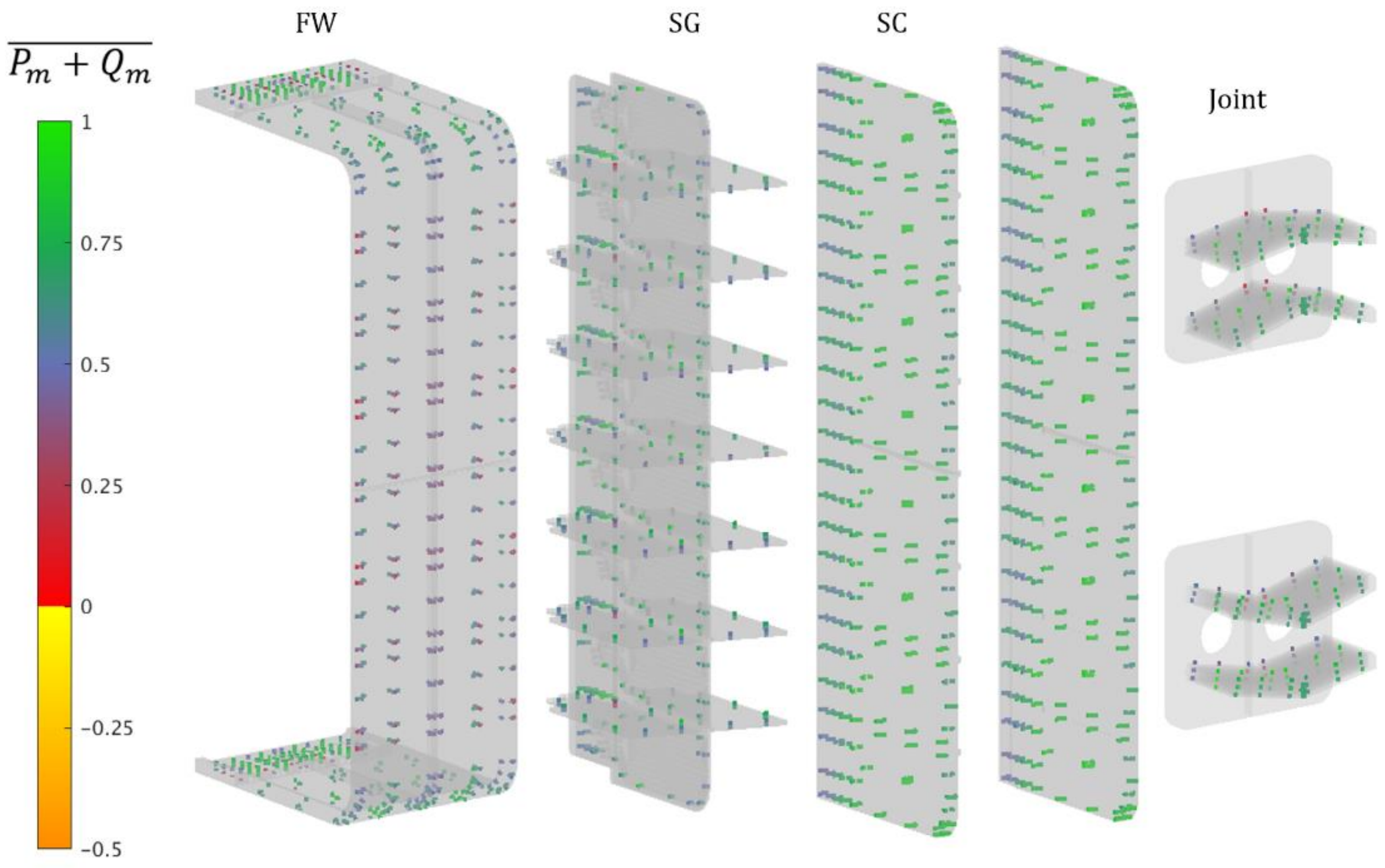


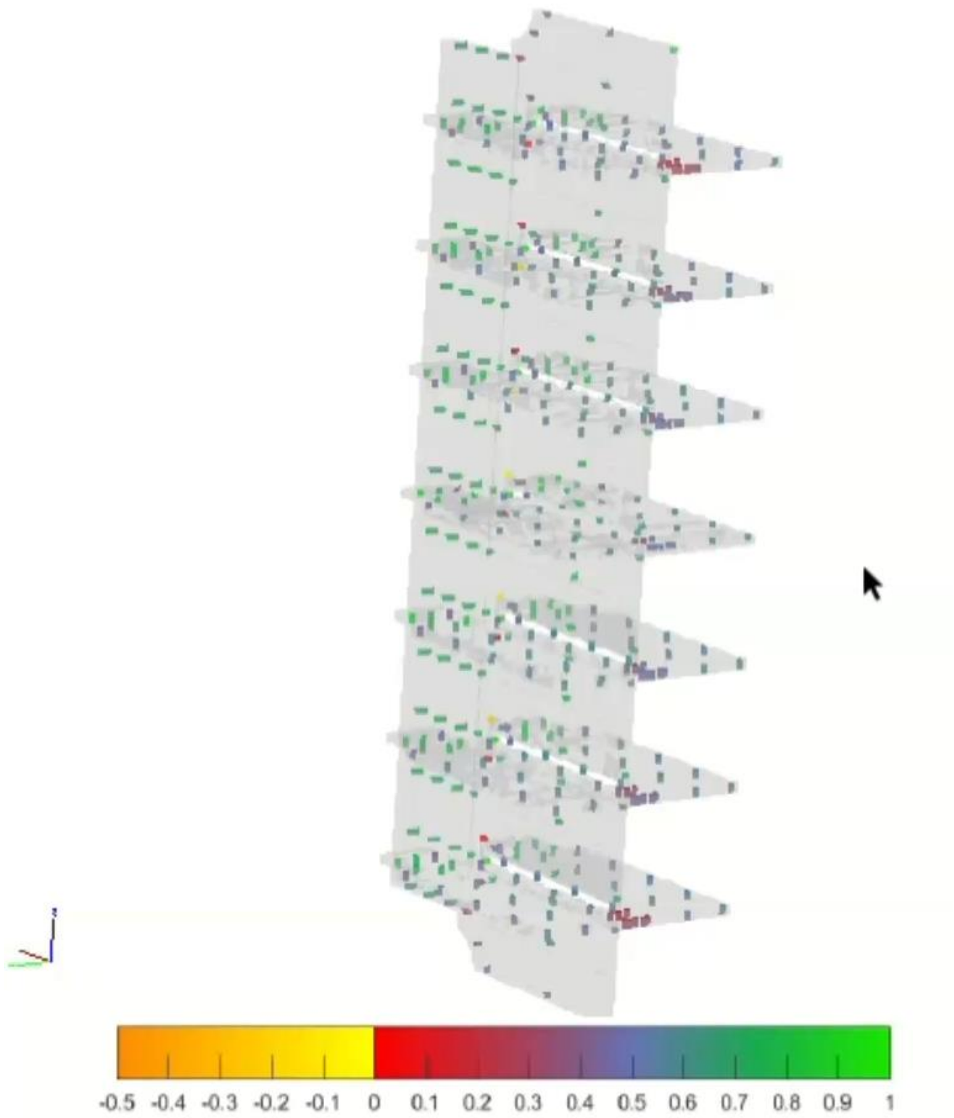
Histograms

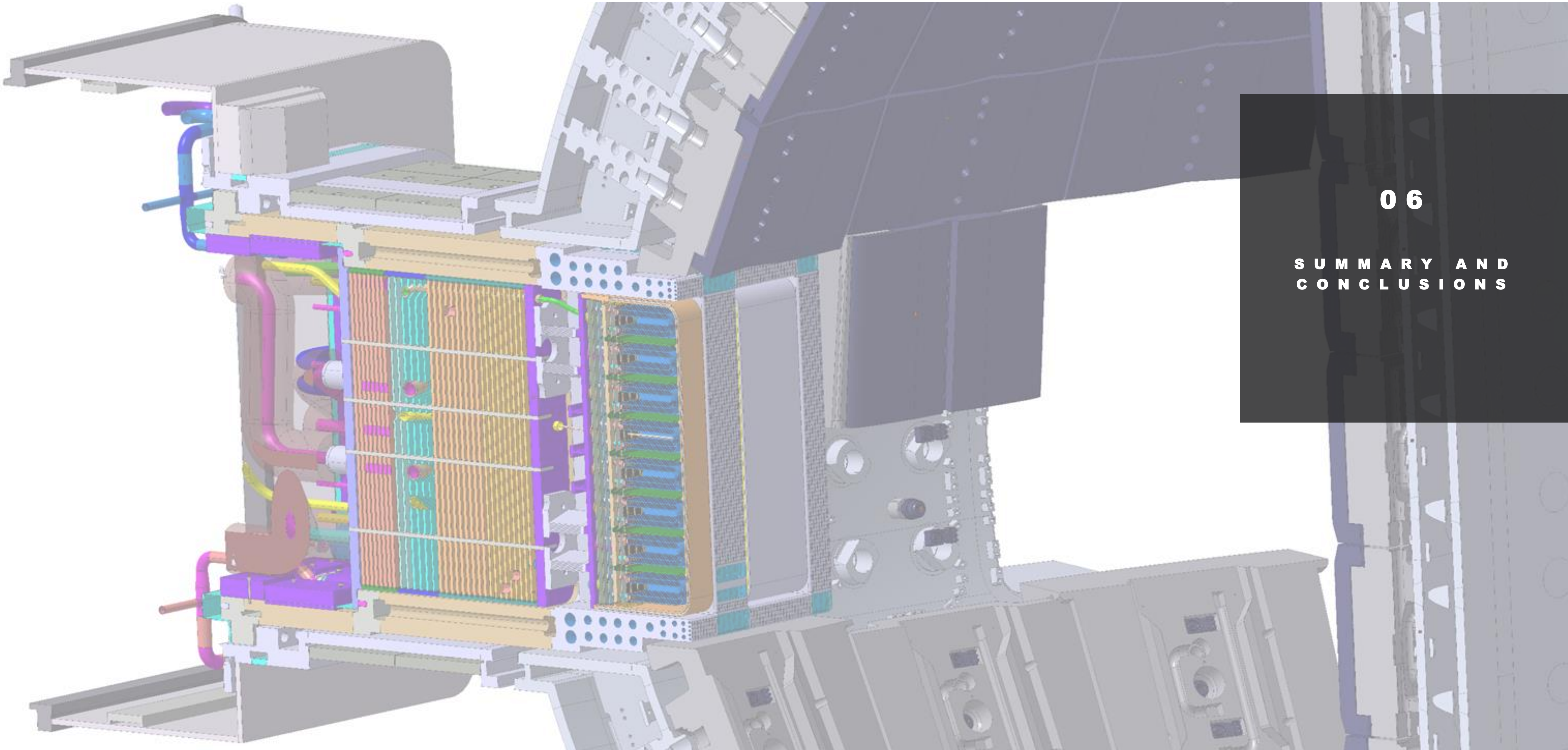


SL-Check

3D Maps







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SUMMARY AND CONCLUSIONS

Summary and conclusions

- **Highly challenging design and analysis context due to**
  - The variety and characteristics of the loads
  - Amount and complexity of the failure modes
  - The use of a new structural material under development
  - The magnitude of the loads in a restricted design space.
- Over the last years ESTEYCO Mechanics team has develop a series of tools and methodologies that enable conducting the **design-by-analysis tasks in a streamlined, automatic and consistently repeatable manner** to reduce time required for analysis loop and provide a more **agile assessment** on the impact of **design modifications**
  - **1D-HEAT** to couple the temperature evolution along cooling channels with the solid temperature
  - A consistent procedure to tackle highly dynamic loads such as EM disruptions
  - **SL-Check** to consistently perform structural integrity assessment according to RCC-MRx and to visualize the results to provide feedback on the design modifications

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THANKS for your attention

Questions ??

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