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Digital twin platform for integrated design of tokamak divertor components: a VOLTA-based workflow for multi-physics integration

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Agenda

Context

- Nuclear fusion as energy source
- EUROfusion roadmap

The project: Development of a Digital Twin Environment for Fusion Reactor Modelling

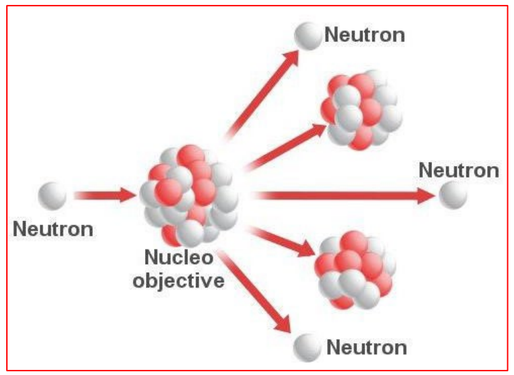
- Design framework for concept design of next-gen machines
- Digital twin of ITER divertor

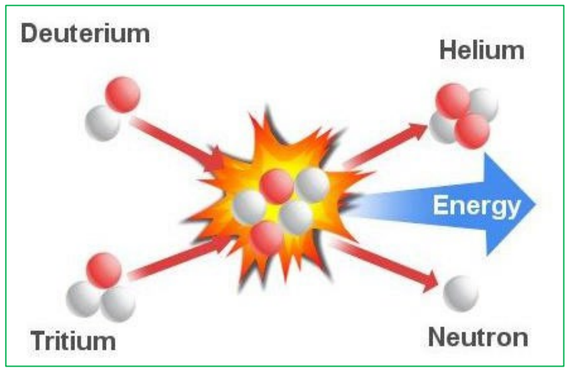
Conclusions and outlook

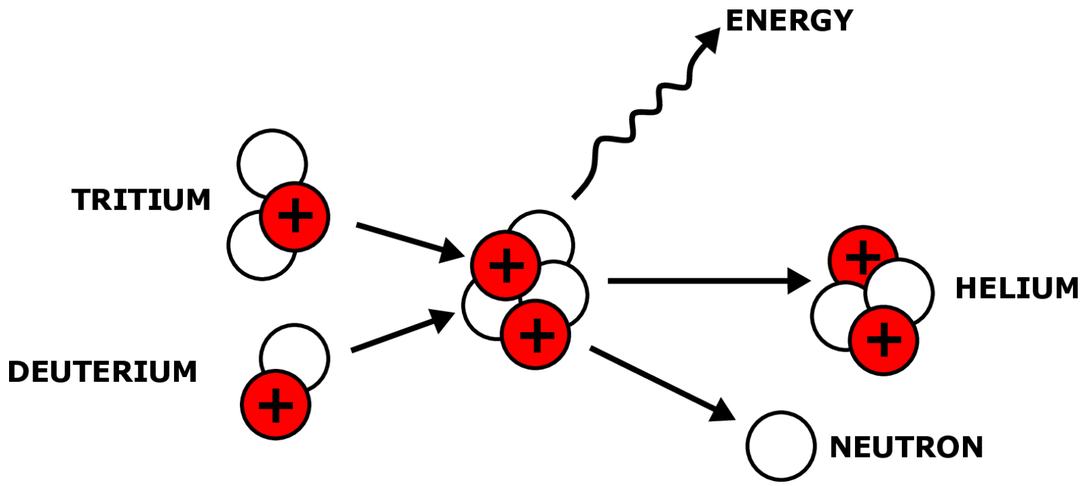
Context

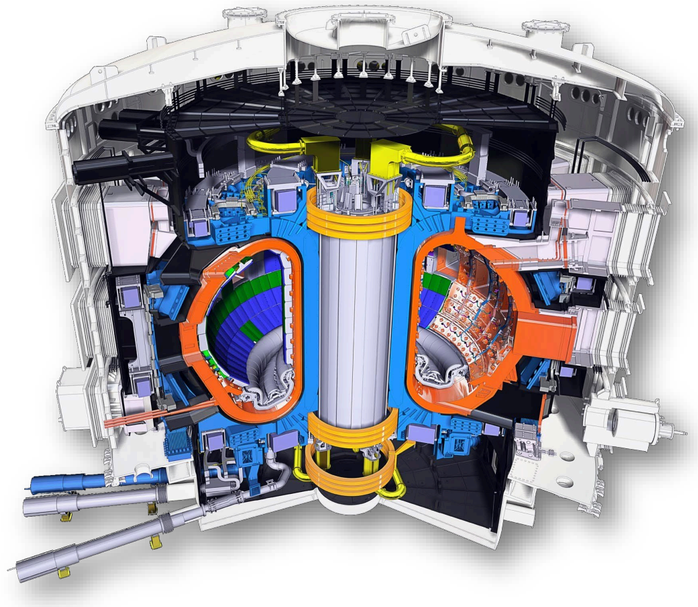
Nuclear Fusion

Fission vs Fusion





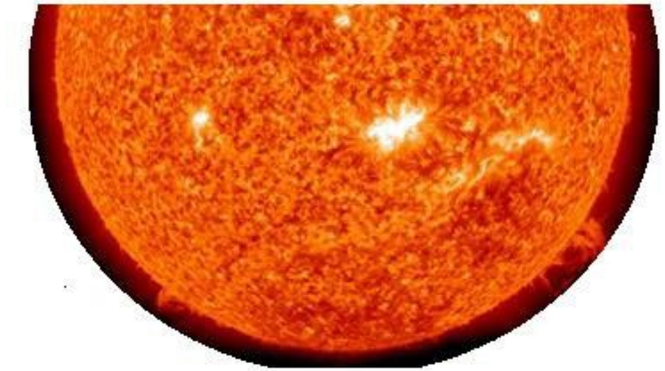




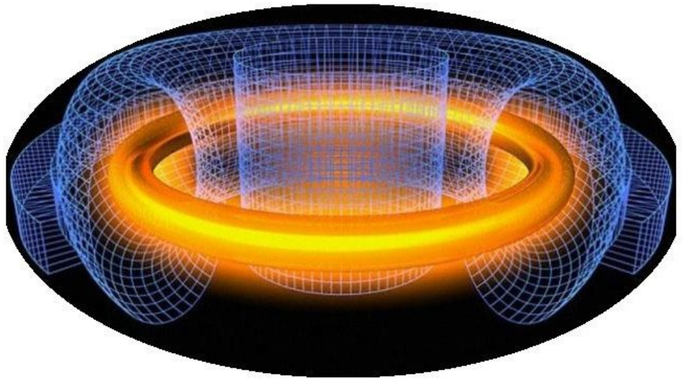
$$^{2}_{1}H + {}^{3}_{1}H \rightarrow {}^{4}_{2}He + {}^{1}_{0}n + energy$$

Nuclear Fusion

CORE OF THE SUN

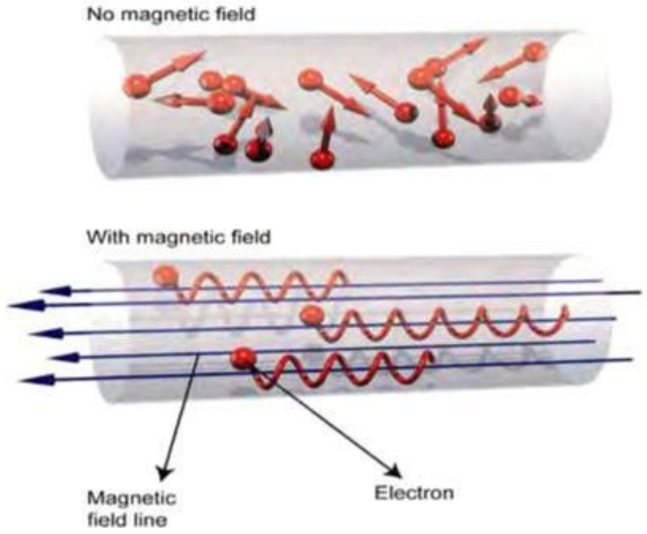


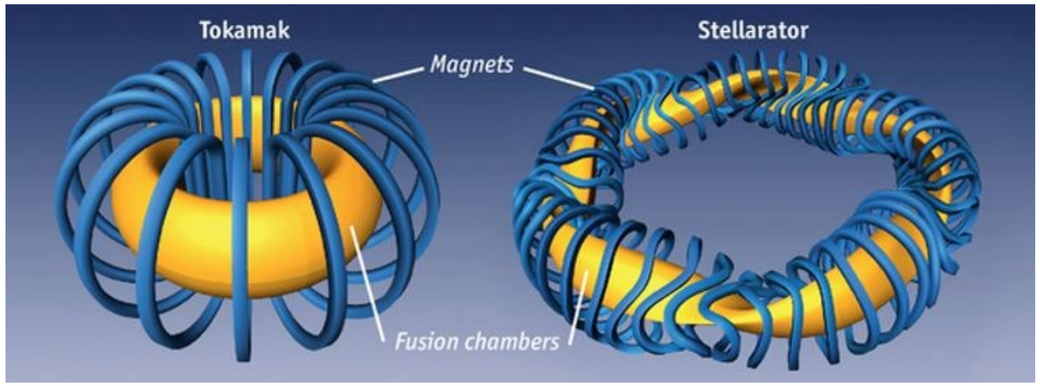
PLASMA IN REACTOR

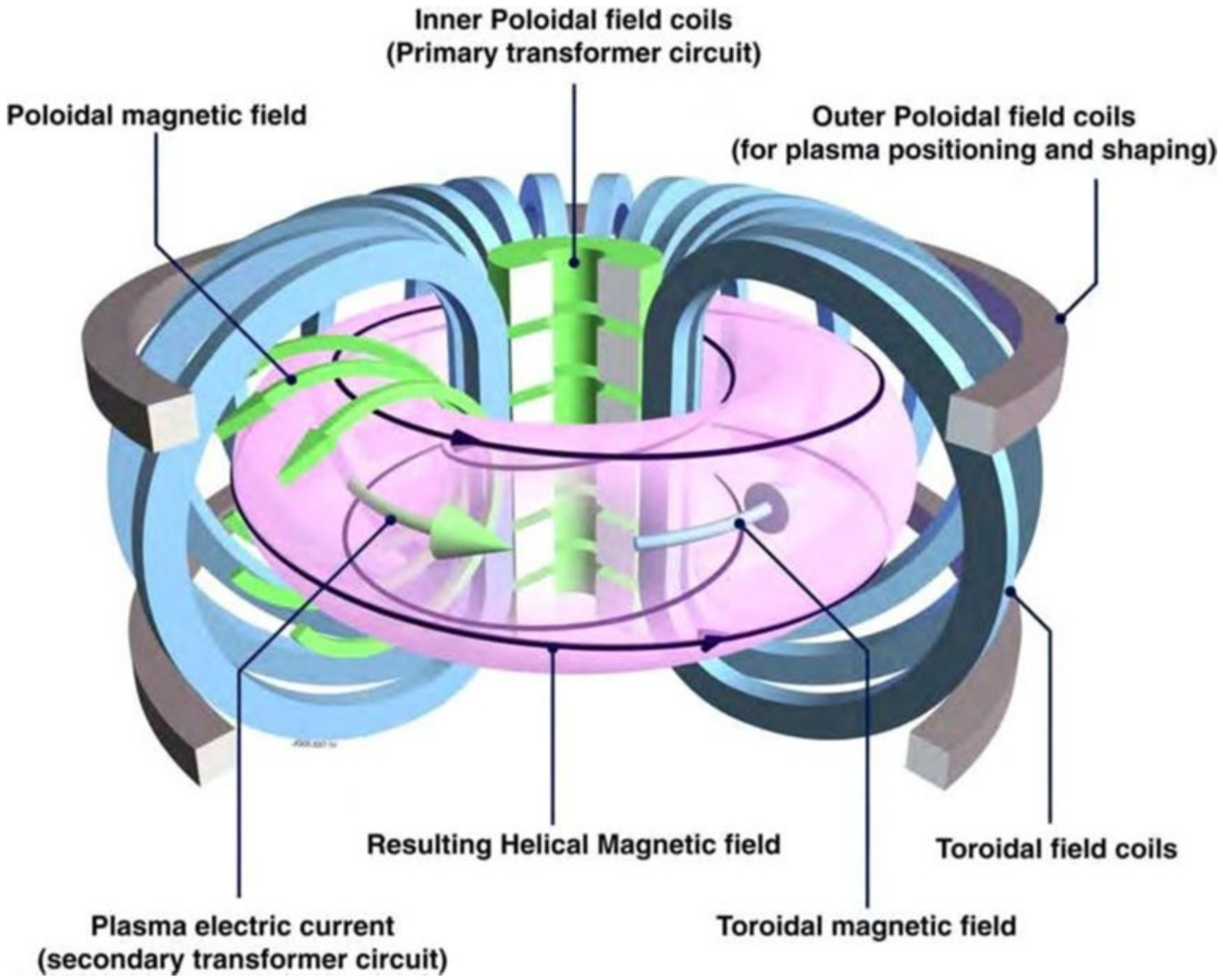


$d + t \rightarrow n + \alpha + 17.6$ MeV.

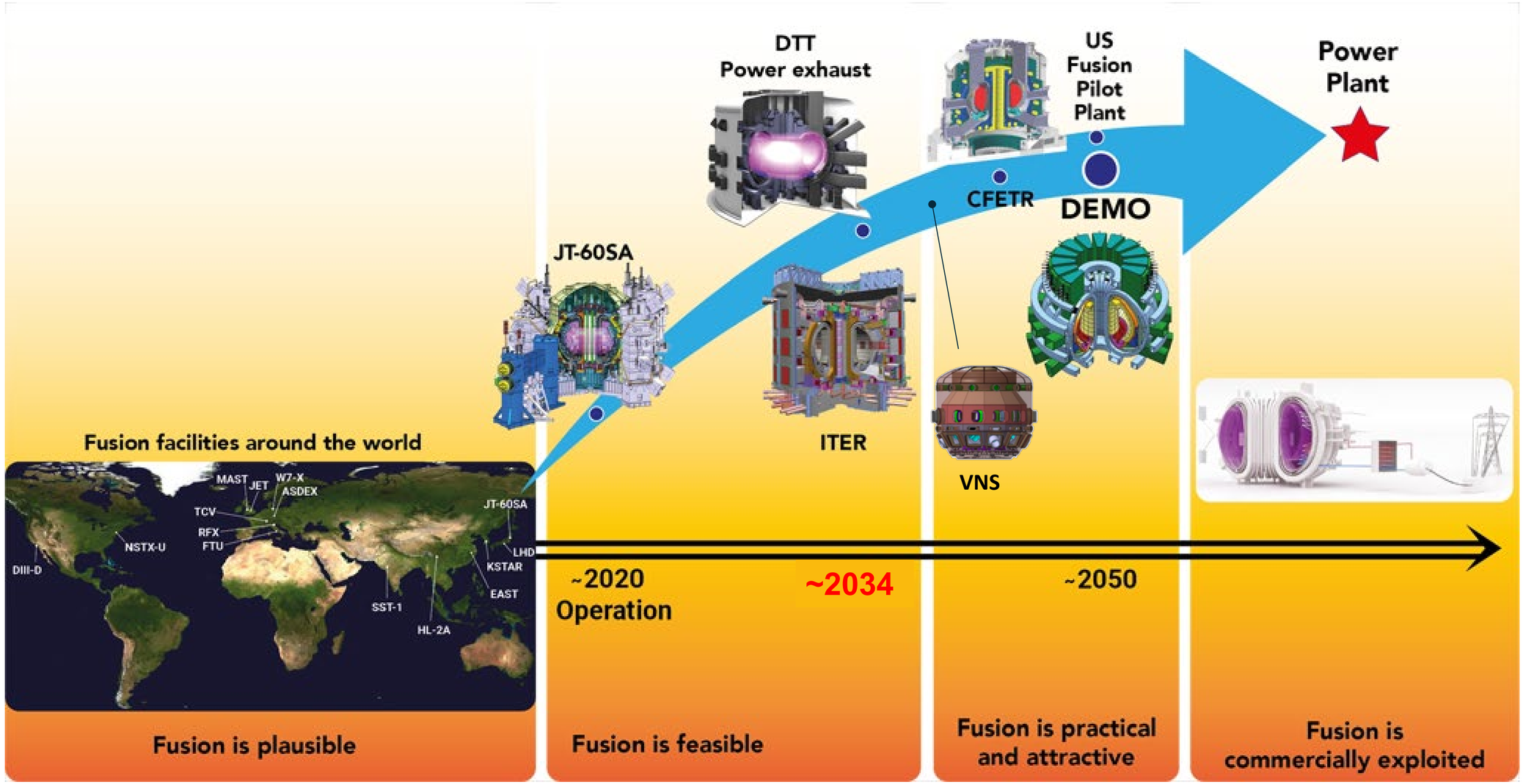
Nuclear Fusion Technologies







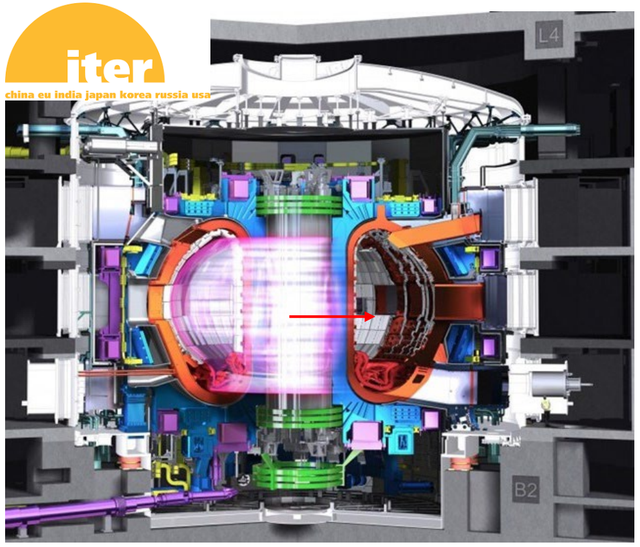
Fusion Roadmap



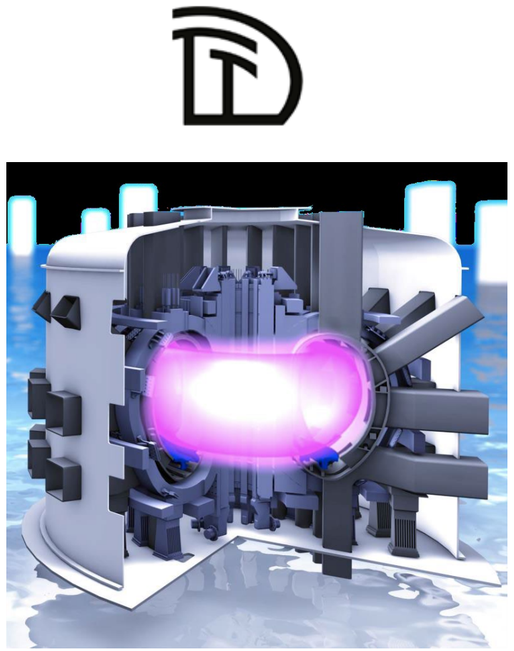
Fusion Roadmap

The strategy of the fusion roadmap is built on three main pillars:

- ITER tokamak that will demonstrate the scientific and technological feasibility of fusion as an energy source,
- a fusion neutron source facility for materials development and qualification and other MSTs
- a demonstration power plant DEMO, which will deliver hundreds of megawatts of electricity to the grid and operate with a closed fuel-cycle



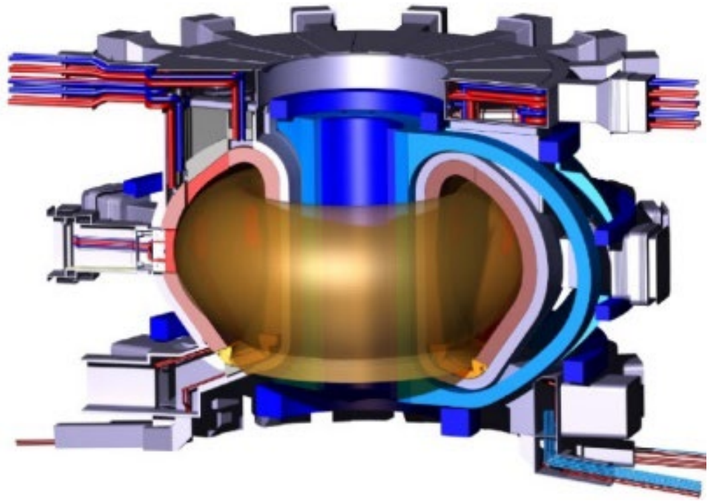
$$Q = \frac{P_{fus}}{P_{ext}} \geq 10$$



MSTs

VNS

EU - DEMO



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EUROfusion

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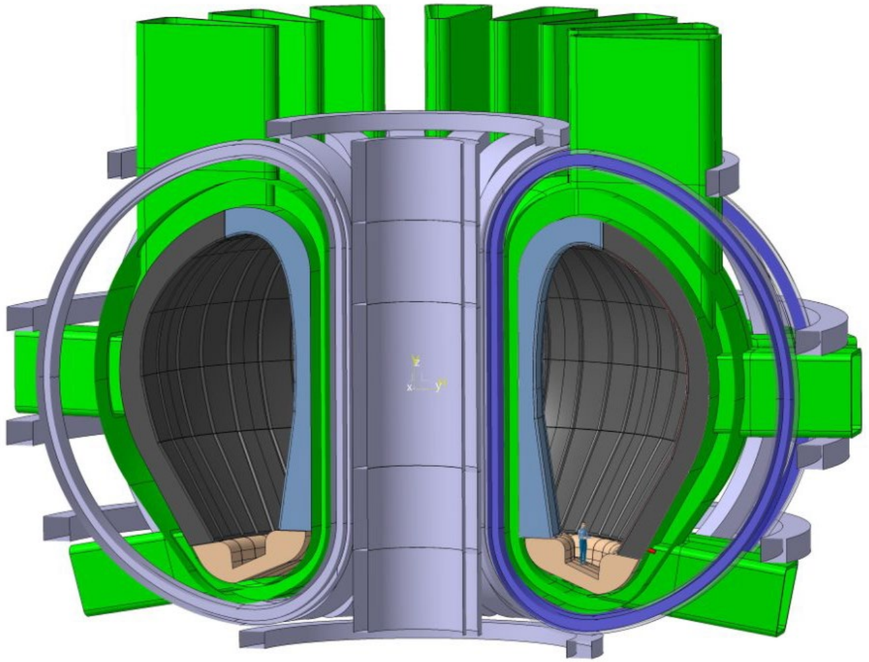
The project: Development of a Digital Twin Environment for Fusion Reactor Modelling

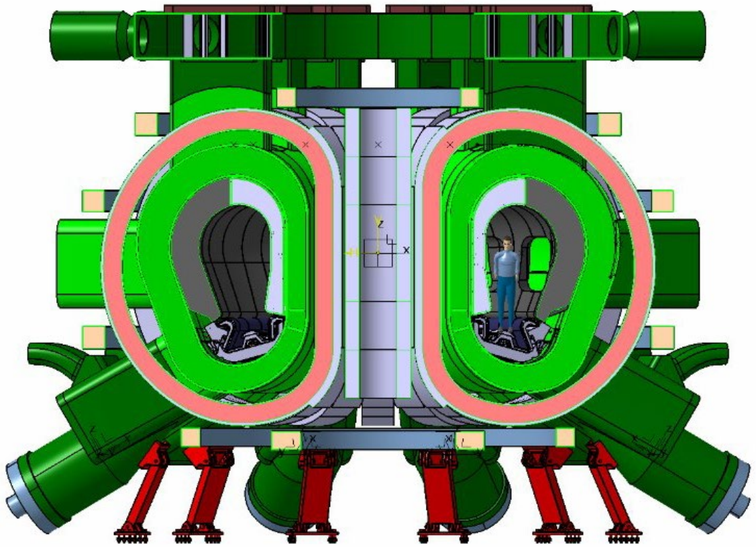
Design framework for concept design of next-gen machines

EUROfusion Tokamak Designs Overview

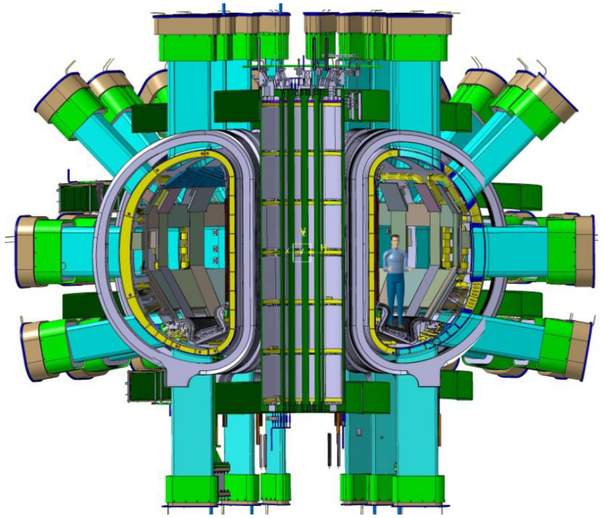
DEMO LAR



VNS



DTT



Parameter	EU DEMO LAR	VNS	DTT
Major radius (R)	**8.6 m**	**2.67 m**	**2.19 m**
Minor radius (a)	3.1 m	0.64 m	0.70 m
Aspect ratio (A = R/a)	2.8	4.25	3.13
V_p	2805.2 m^3	31 m^3	28 m^3
Toroidal magnetic field (B_t)	4.39 T	5.6 T	5.85 T
Plasma current (I_p)	**~18.8 MA**	**2.55 MA**	**5.5 MA**
P_{sep}	**108 MW**	**55 MW**	**33 MW**
P_{sep}/R	~13	~20	~15

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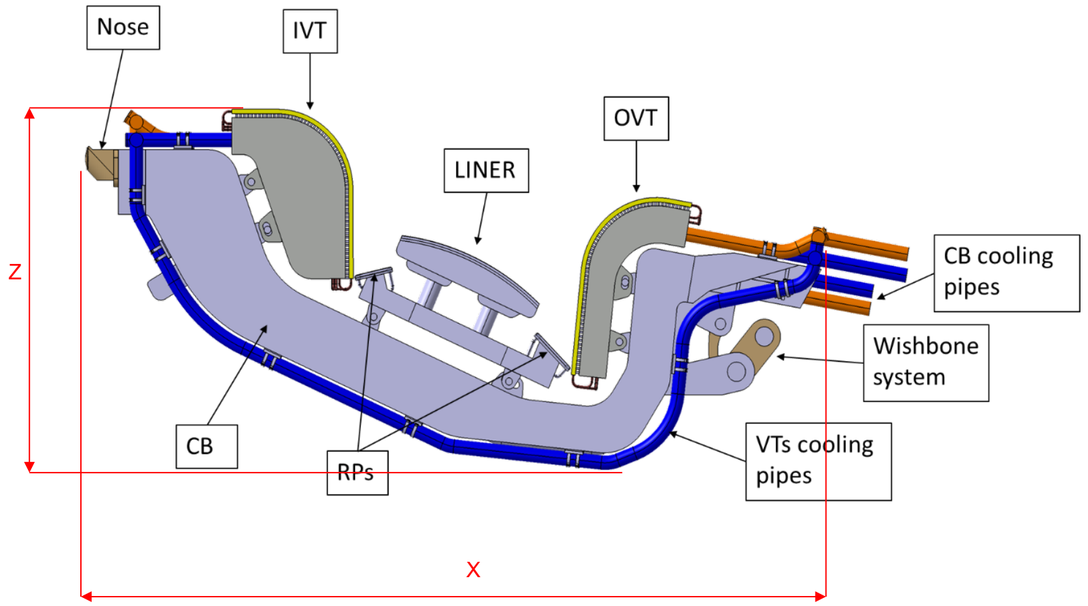
Divertor system



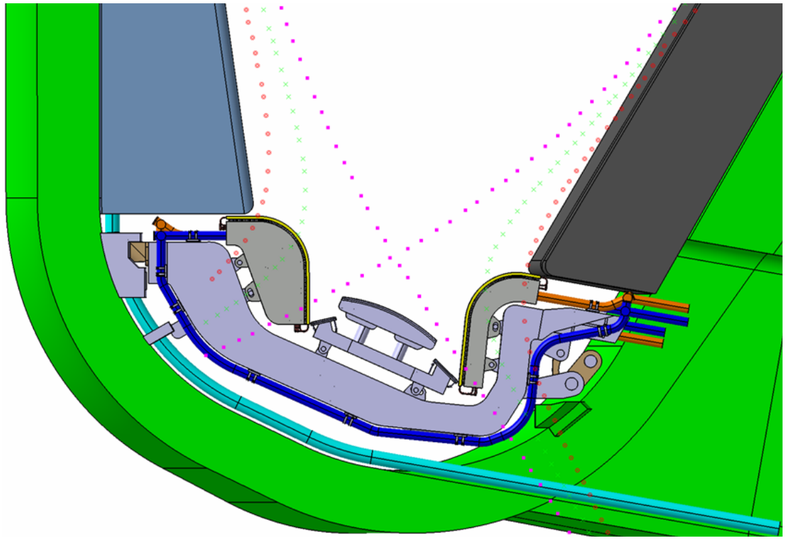
Functions:

- Heat Exhaust: manages and removes excess heat.
- Particle Exhaust: including unburnt fusion fuel and fusion products.
- Reduce plasma impurities.
- Allow efficient pumping of the exhausted particles.
- Provide plasma boundary control
- Protect surrounding walls from thermal and neutronic loads.

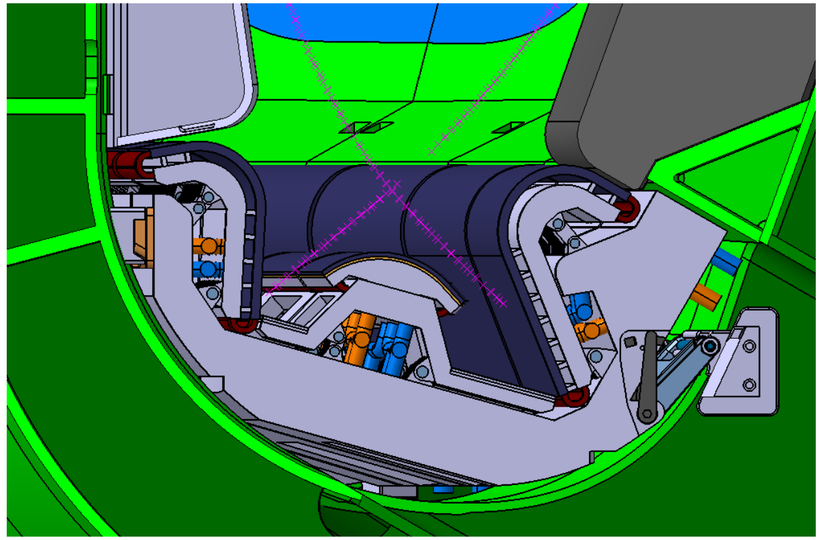
	EU DEMO LAR	VNS	DTT
DIV design status	Conceptual Design	Feasibility Assessment	Manufacturing
Peak heat flux density (NOC)	10 MW/m^2	10 MW/m^2	10 MW/m^2
X [mm]	4985	1538	1211
Z [mm]	2245	890	793

Divertors’ design drivers

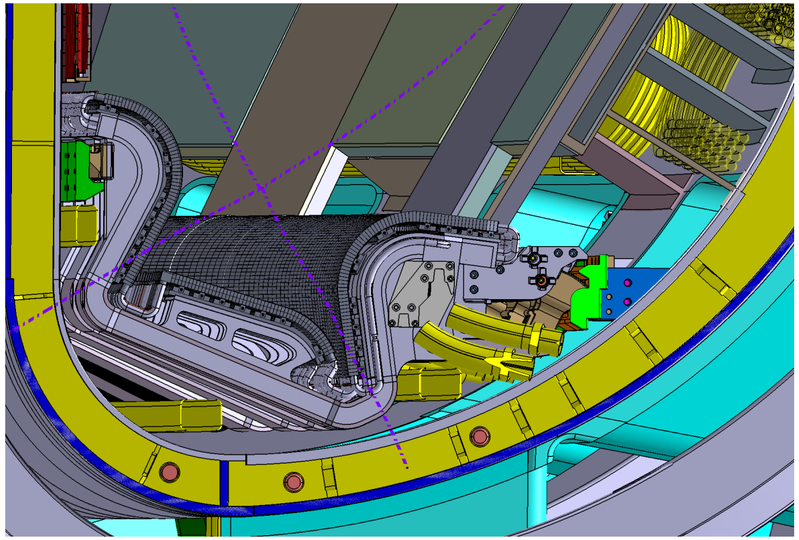
DEMO LAR



VNS



DTT



Design Drivers	DEMO	VNS	DTT
Heat fluxes (detachment/reattachment)	🔴	🔴	🔴
Shielding of VV and TFC	🔴	🔴	🟢
Neutron irradiation and He production	🔴	🔴	🟢
Pumping efficiency	🔴	🔴	🔴
Loads (TH, CP, EM, …)	🔴	🟡	🟡
Plant Availability	🔴	🟡	🟢
Remote Handling compatibility	🔴	🔴	🔴
Radwaste	🔴	🔴	🟢
Flexibility for different magnetic configurations	N.A.	N.A.	🔴

🔴 Absolutely relevant
🟡 Relevant
🟢 Slightly Relevant

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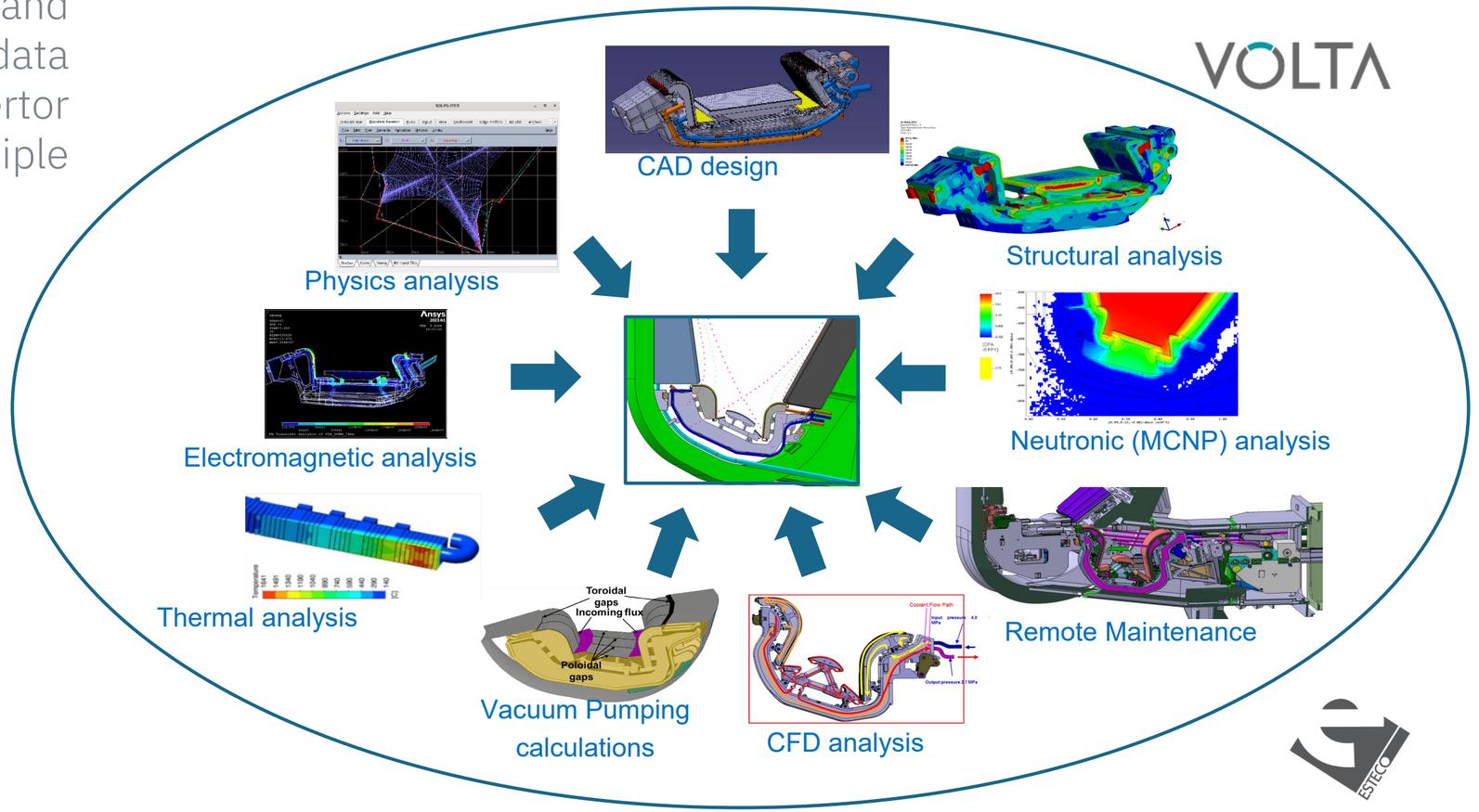
Multi-Physics Challenge: VOLTA SPDM platform

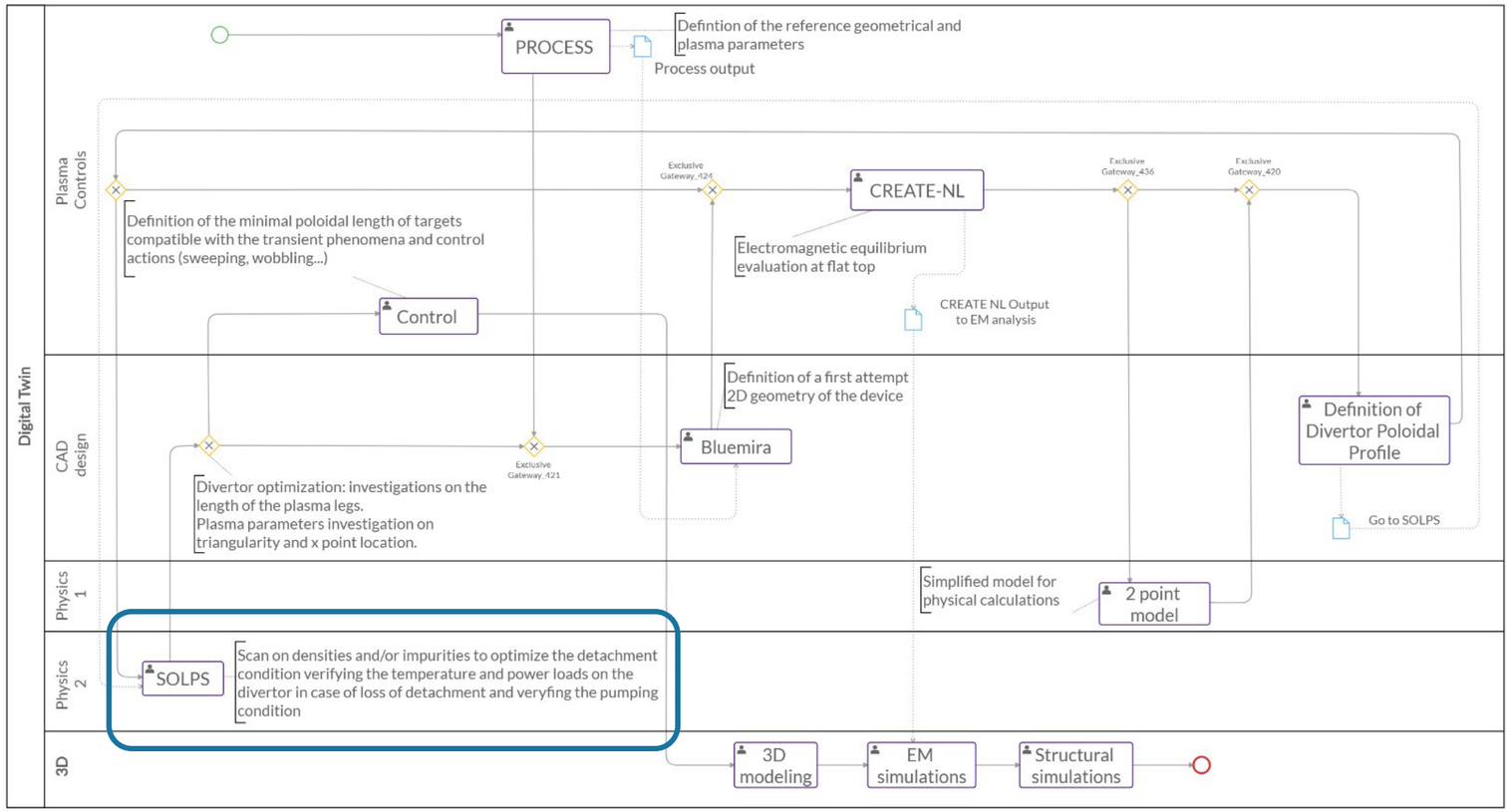
The **divertor** is a complex component subjected to **multiple loads**, requiring an **integrated multi-physics simulation approach** to study its complete behavior.

The VOLTA platform has been adopted to enhance collaboration, facilitate data and information sharing, and ensure full data traceability throughout the divertor development process across multiple development teams, including:

- CAD
- Structural Analysis
- Physics Analysis
- Electromagnetic Analysis
- Vacuum Pumping
- ...

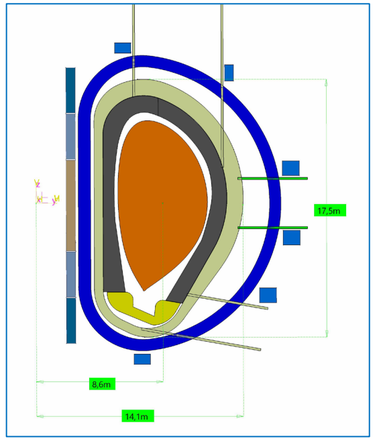


BPMN Workflow for Divertor Design

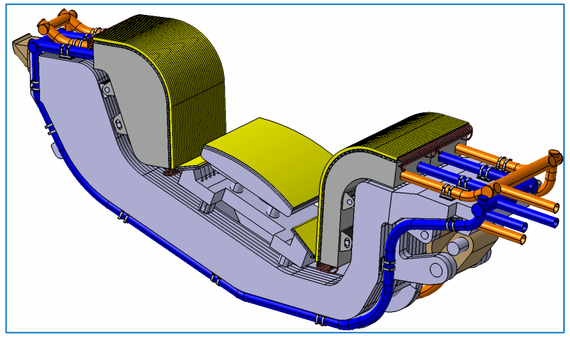


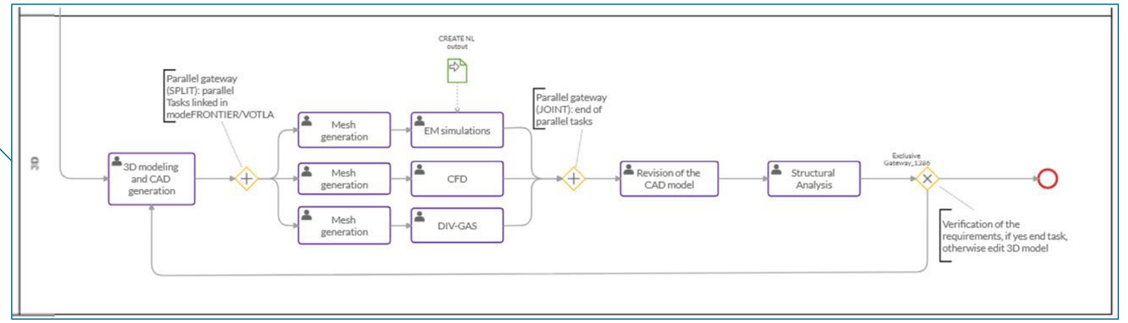
The BPMN workflow has been developed to ensure process traceability, coordination between multidisciplinary teams, and structured management of divertor development activities, from conceptual design to structural assessment.

First conceptual design



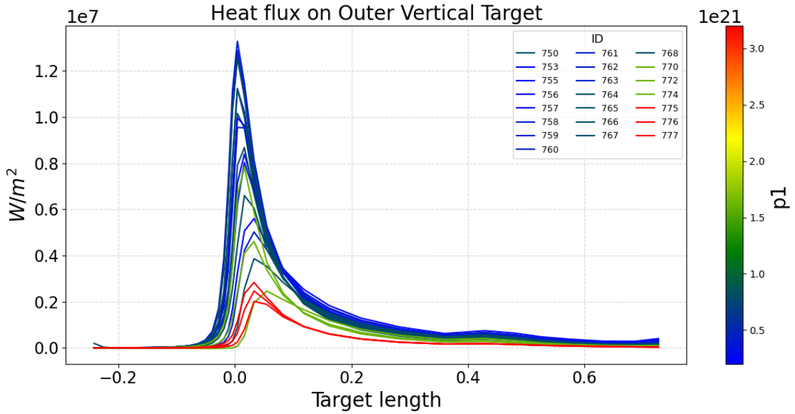
Detailed design of the divertor

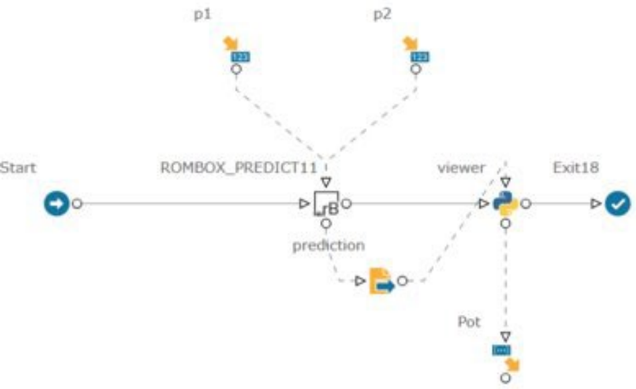


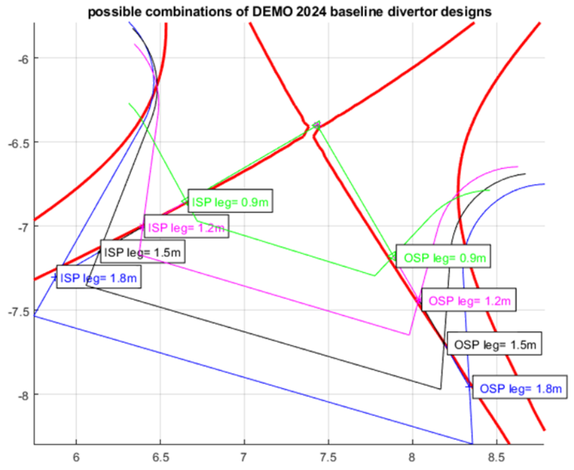


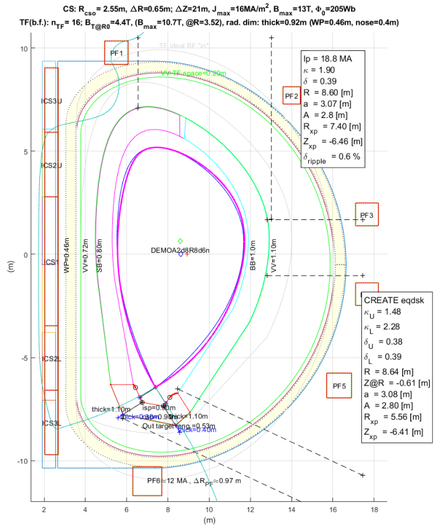
Fast Prediction of Heat Flux Using ROMs

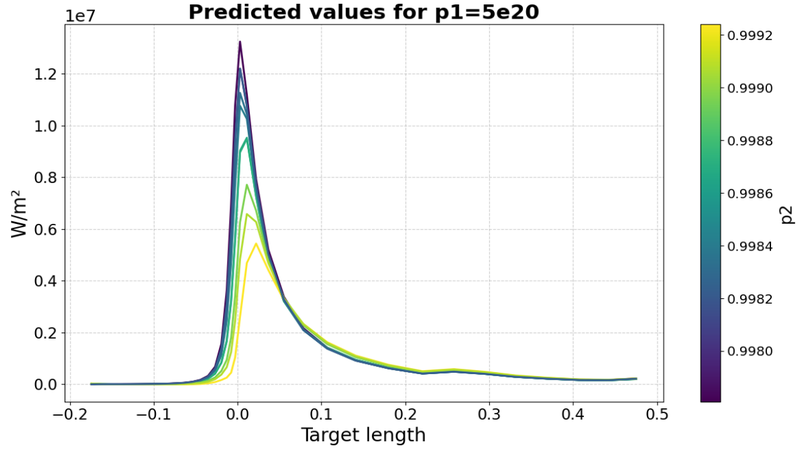
- Divertor heat flux is one of the most demanding loads, strongly dependent on plasma physics
- **High-fidelity simulations** require **several days** to compute results
- modeFRONTIER has been used to train **Reduced Order Models** (ROMs) for fast prediction of heat flux across different plasma configurations
- This approach significantly reduces the computational time required for scenario evaluation





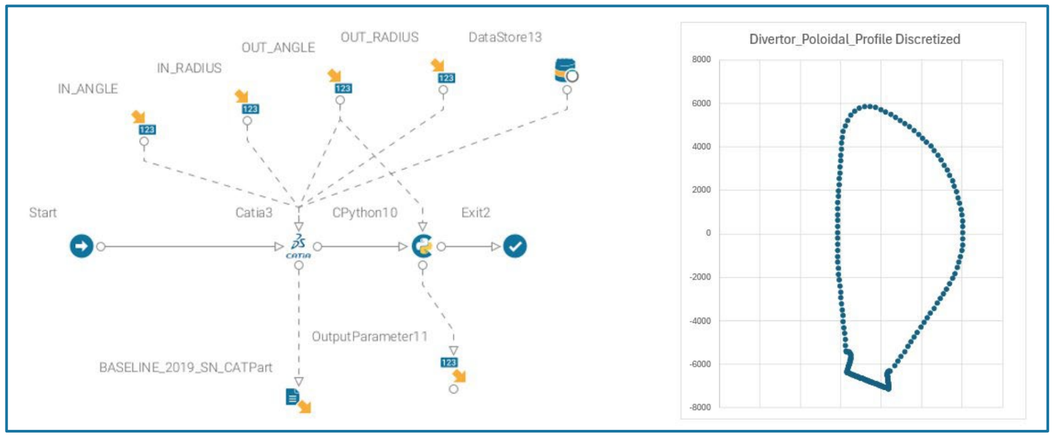


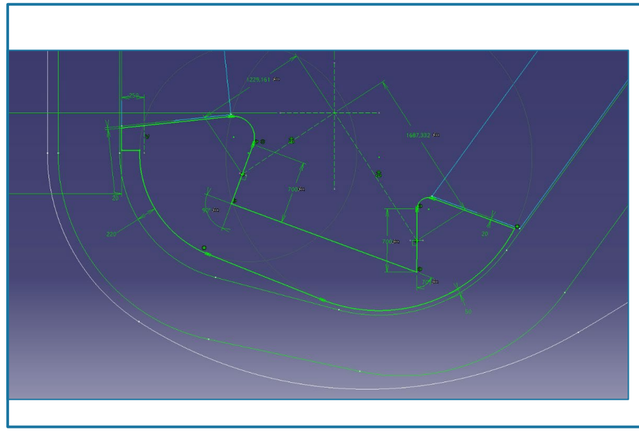


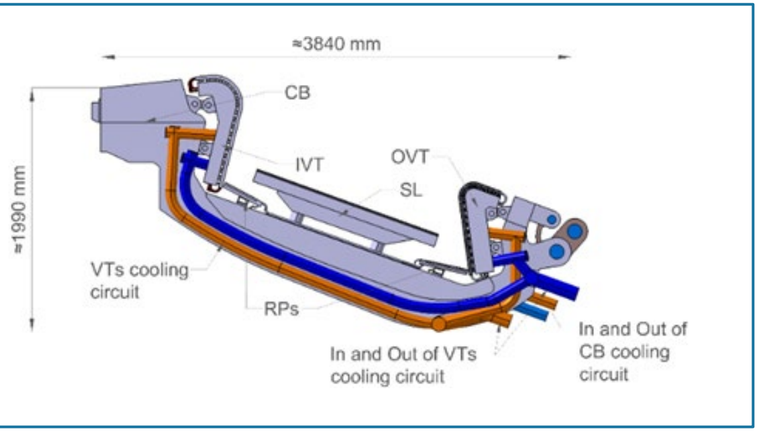


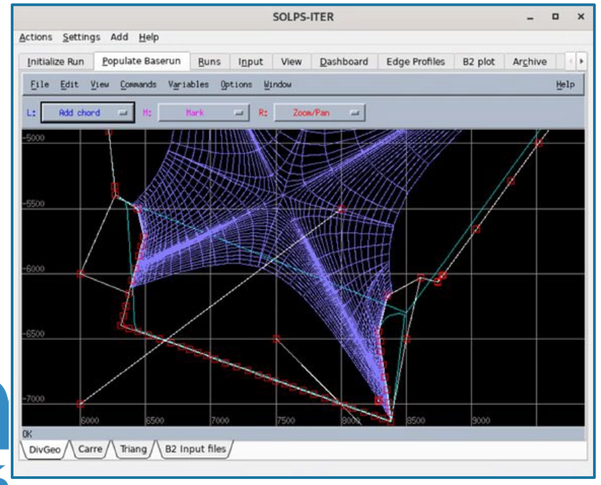
Geometries evaluation

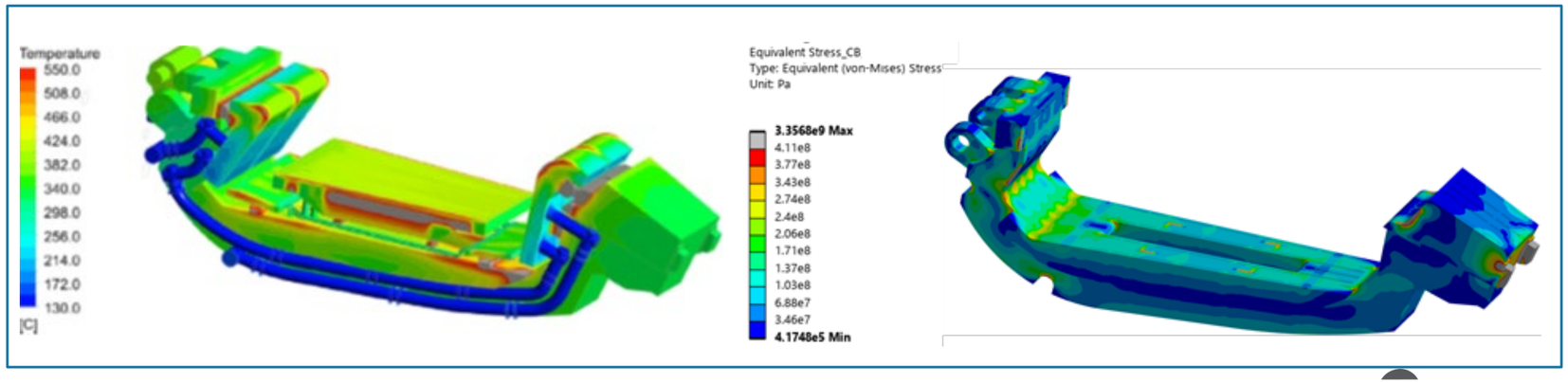
Generation and Discretization of 2D Geometries for divertor and FW through modeFRONTIER







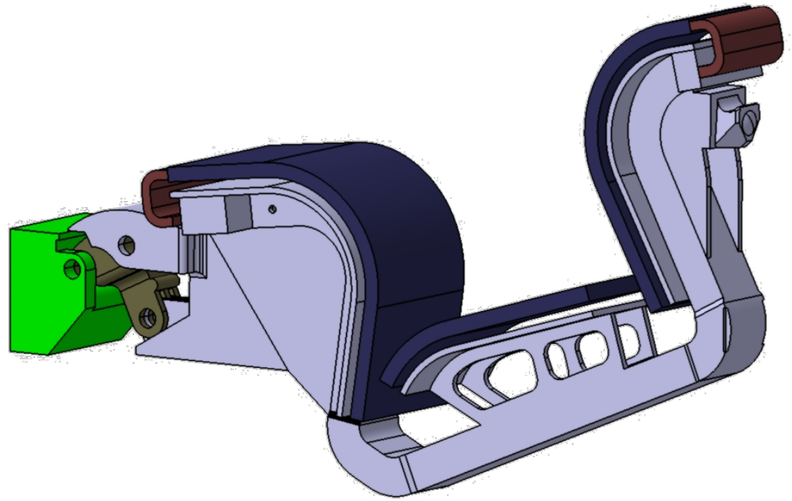




DTT DIV parametric design optimization in VOLTA

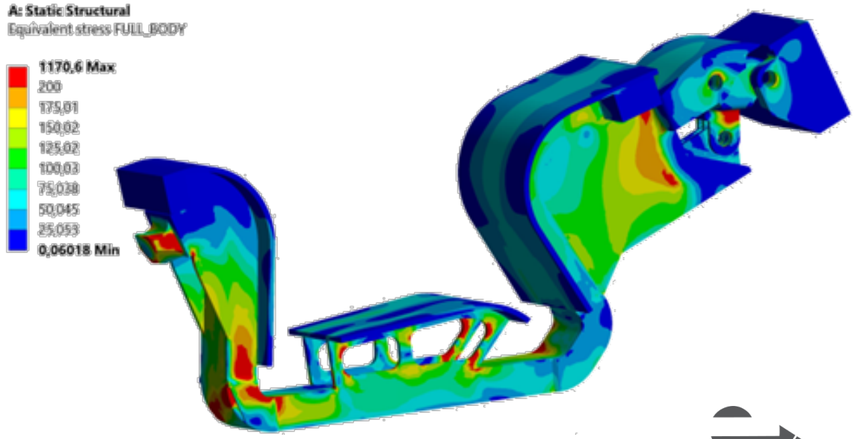
One of the most critical scenarios for the divertor is the Vertical Disruption Event (VDE):

- Occurs when the plasma loses stability and rapidly moves toward the vessel structures
- Causes severe transient thermal and mechanical loads
- One of the most demanding scenarios in divertor design

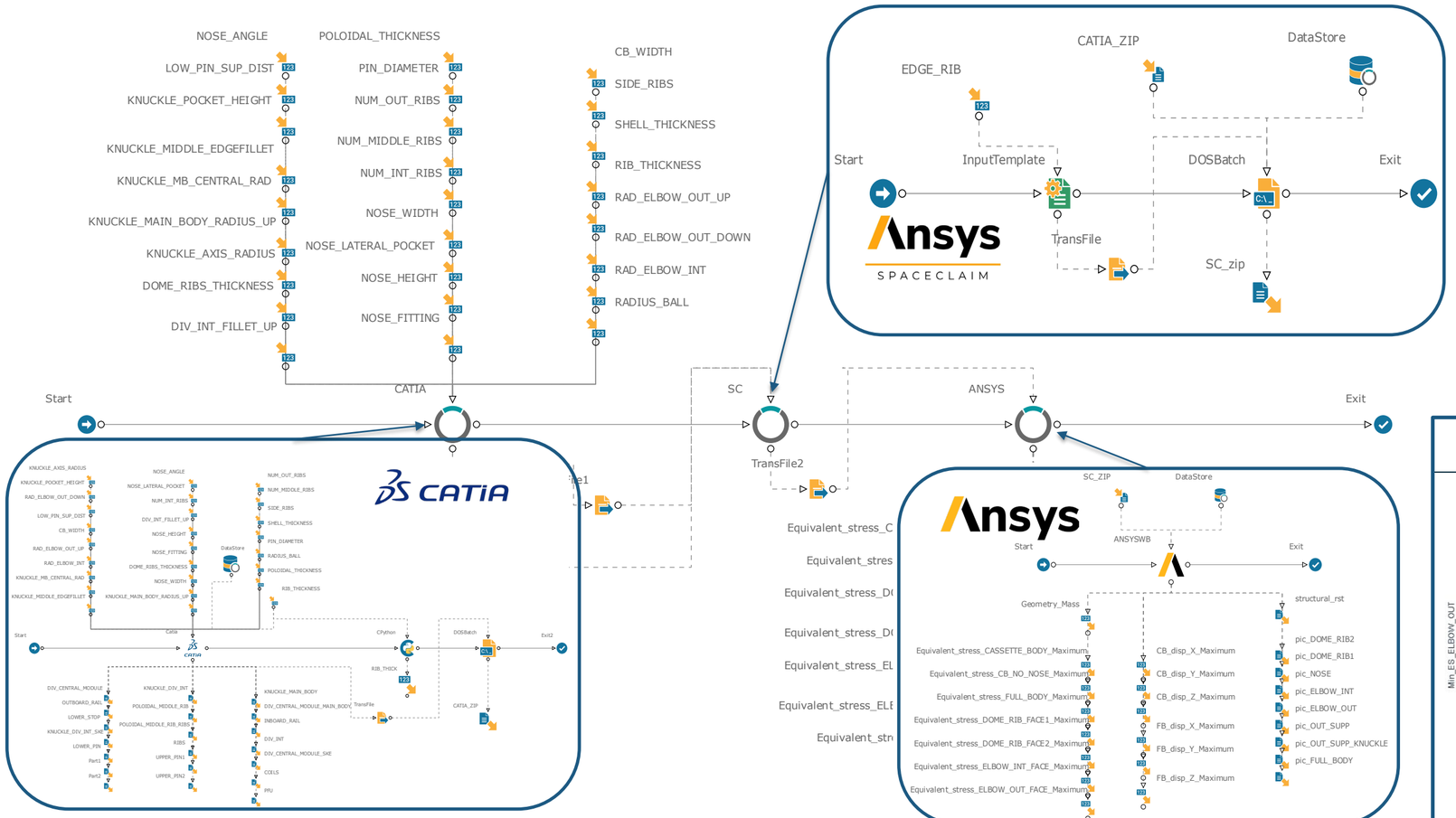


In this context, modeFRONTIER enables the development of an autonomous workflow for design exploration and automated structural analyses of the divertor system:

- The objective is to optimize the geometry of the divertor cassette through systematic evaluation of different design configurations
- This automated approach allows the assessment of many cases while significantly reducing engineering time and manual effort



DTT DIV parametric design optimization in VOLTA



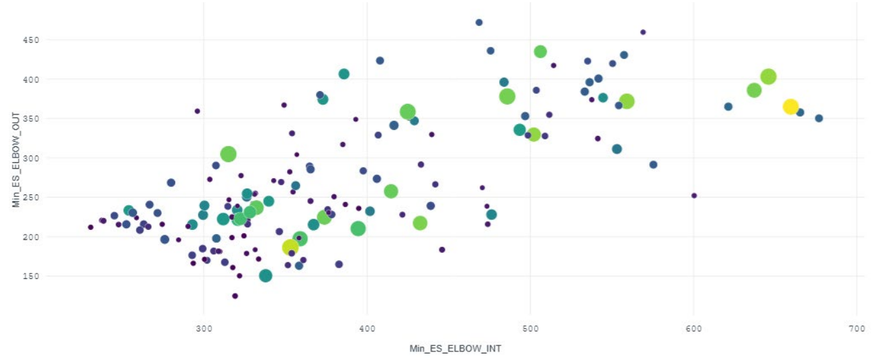
Optimization process:

- Definition of different geometrical parameters
- Identification of more stressed areas where reduce the stresses
- DOE of 160 designs were evaluated

Objectives of the optimization:

- Reduction of the stresses in the specified areas
- Minimize the weight of the divertor

DOE distribution for two critical area in relation of the stresses



DTT DIV parametric design optimization in VOLTA

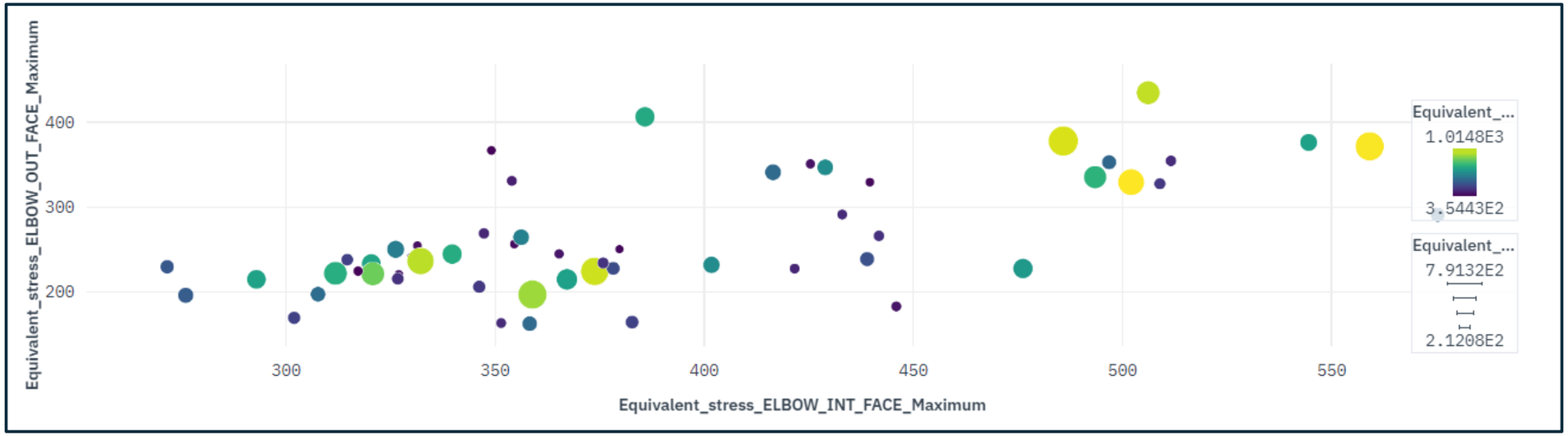
25 Variables

DOE:
ULH

60 design

Sensitivity analysis

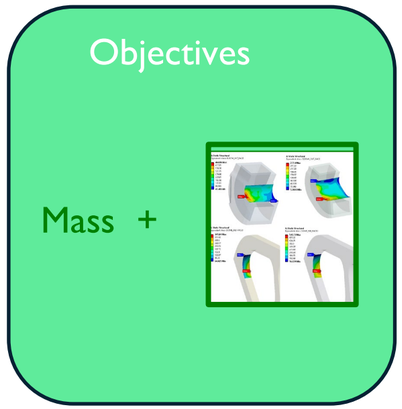
15 Variables



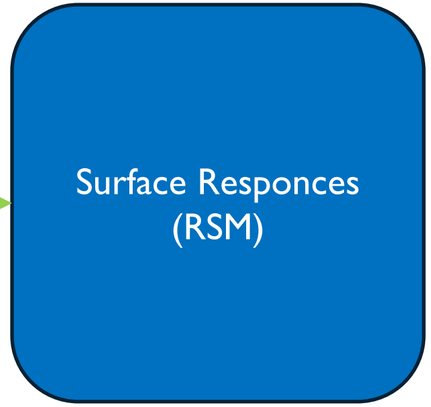
DTT DIV parametric design optimization in VOLTA

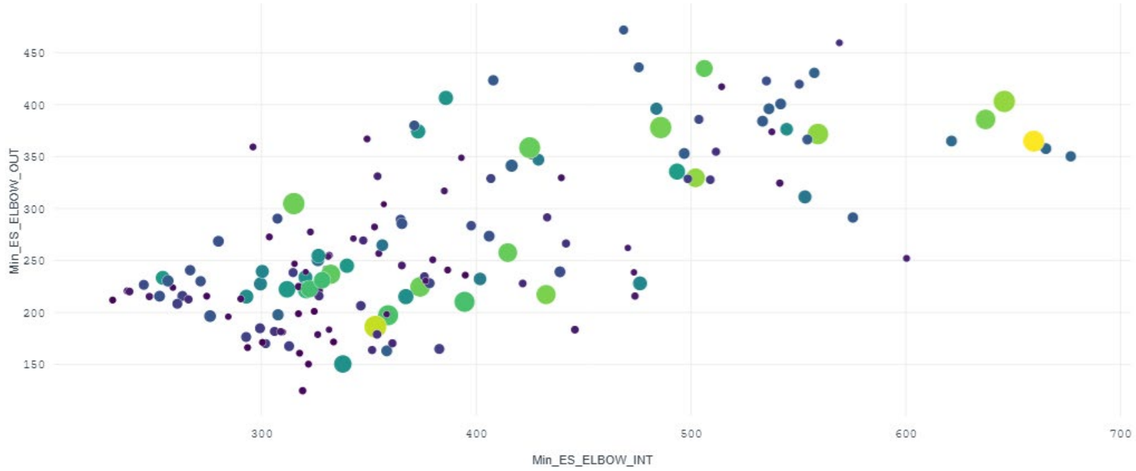
60 design

15 Var.



100+60 design

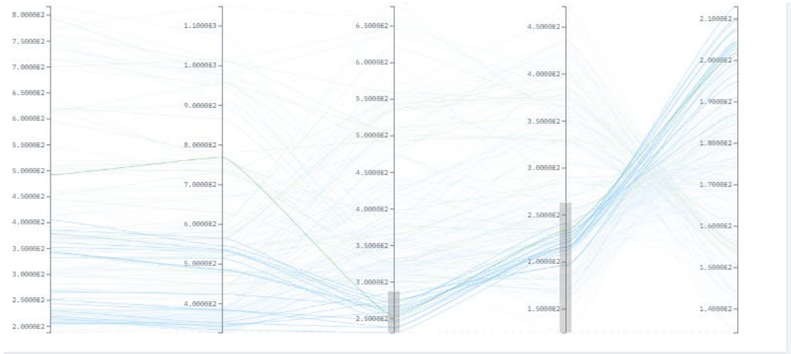


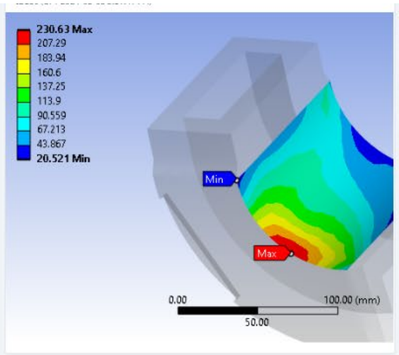


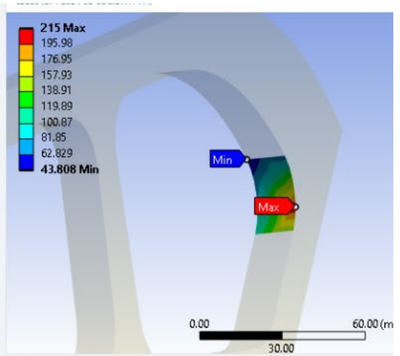
DTT DIV parametric design optimization in VOLTA

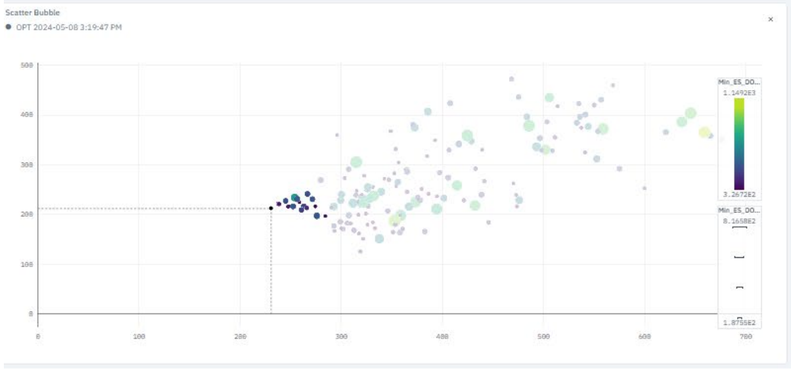
DTT DIV parametric design optimization in VOLTA

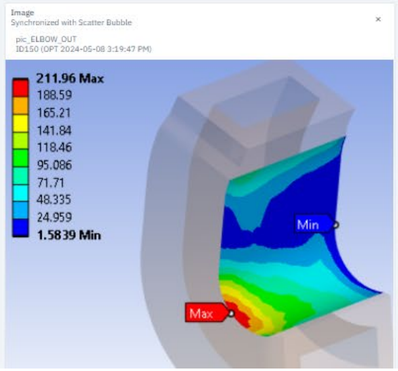
The VOLTA visualization tools enable the analysis of different design configurations and support faster, more informed decision-making by improving the understanding of system behaviour.

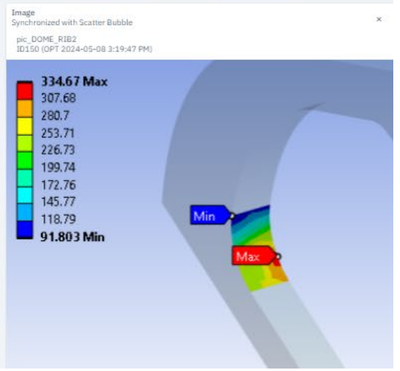




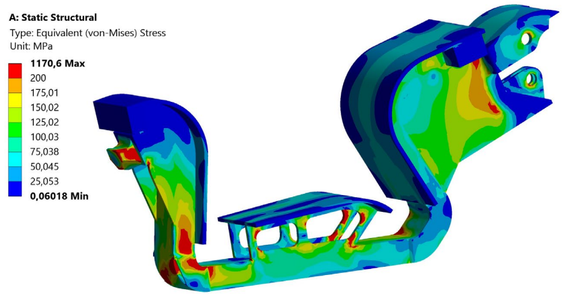




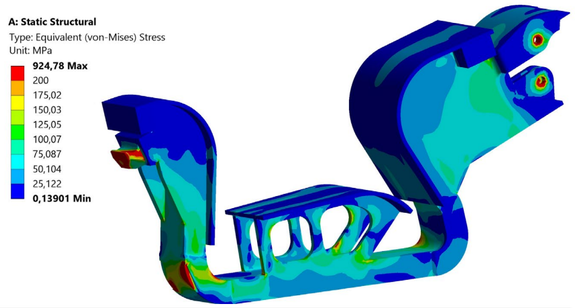




First configuration



Opt. configuration

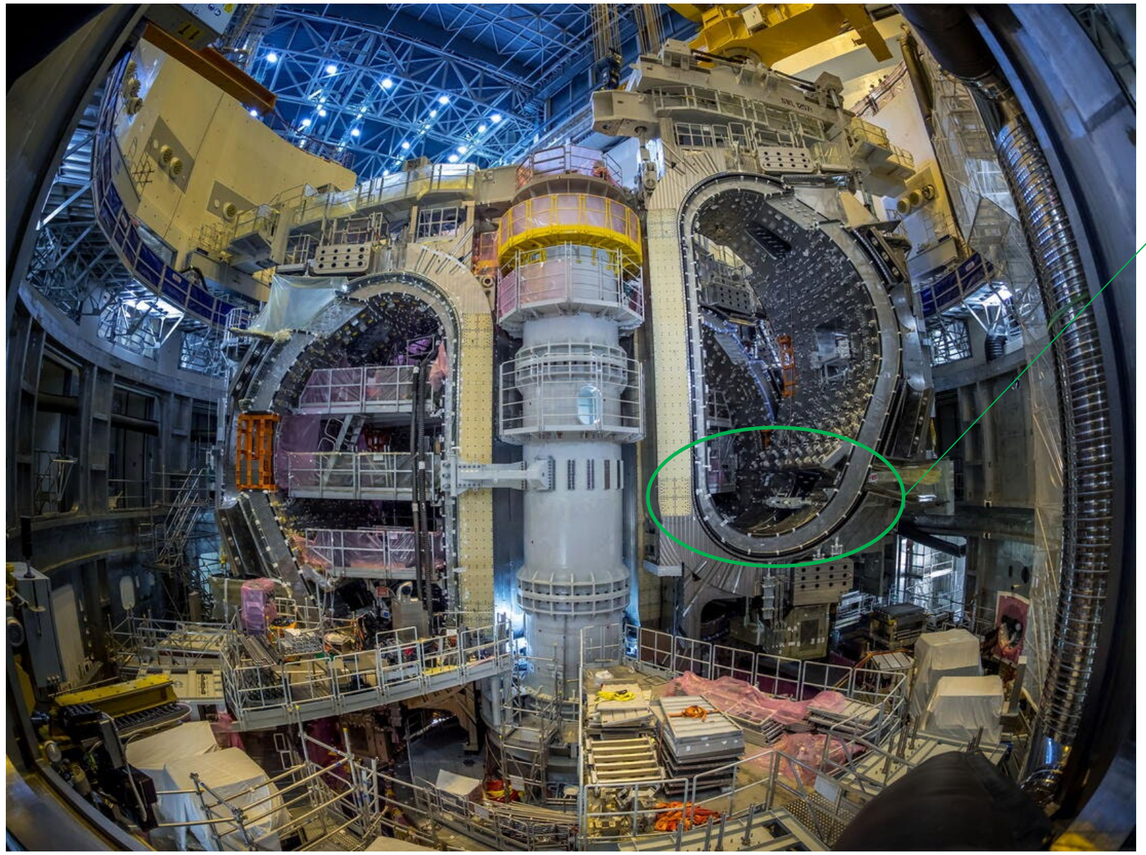


	Eq. Stress			
	First Conf. [MPa]	Opt. Conf. [MPa]	**Difference** [MPa]	% Diff. [%]
DOME_RIB_FACE1	341.8	215.0	**-126.8**	-37.1%
DOME_RIB_FACE2	545.7	334.7	**-210.3**	-38.5%
ELBOW_INT_FACE	464.9	230.6	**-234.3**	-50.4%
ELBOW_OUT_FACE	277.4	212.0	**-65.4**	-23.6%

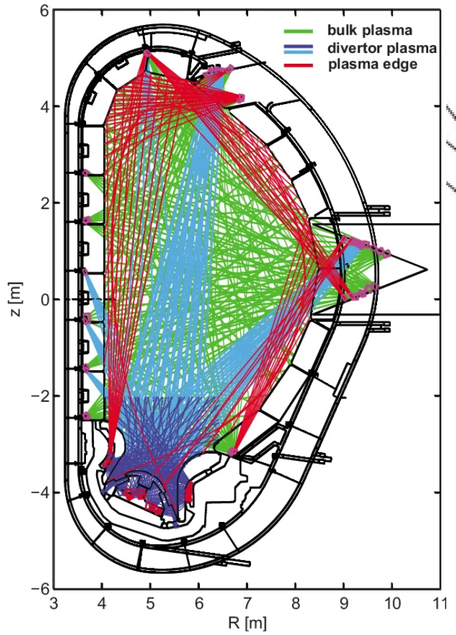
The project: Development of a Digital Twin Environment for Fusion Reactor Modelling

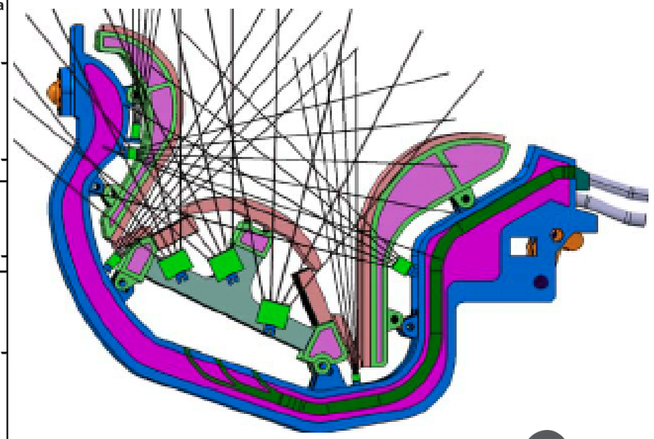
Digital twin of ITER divertor

ITER Divertor Digital Twin



Divertor diagnostics





Main objective of our project: develop a full digital twin of the ITER divertor, including the input data from the synthetic diagnostics to reconstruct the divertor behaviour during operations

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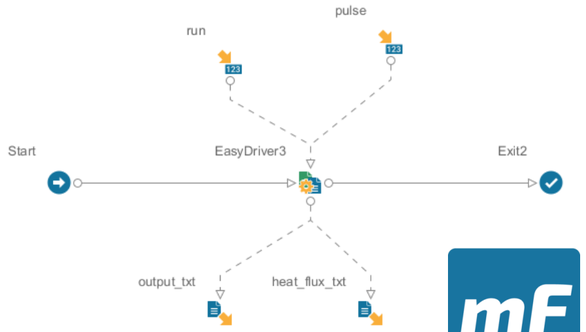
ITER Divertor Digital Twin

VOLTA

CRESCO8

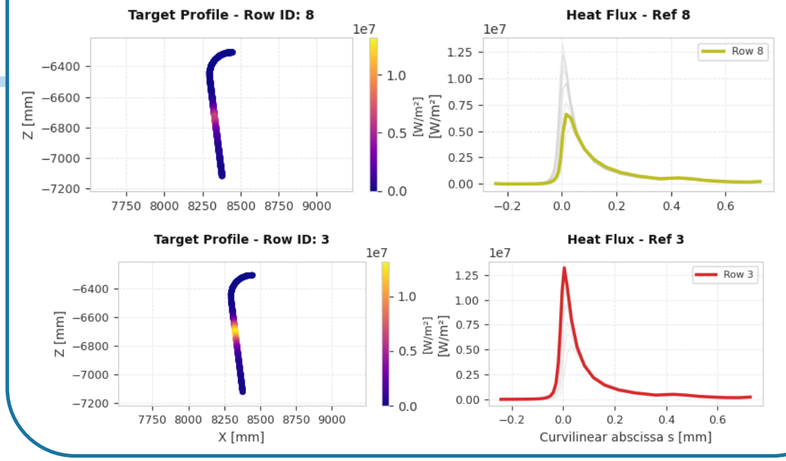
Installed on **CRESCO8 HPC** — accessible via web interface:

- Shares simulation data across multiple workgroups
- Coordinates and manages the project lifecycle
- Full traceability of data and simulation runs
- Integrated data visualisation and analysis tools
- Launch simulations directly from the web UI



mF

- Simplifies access to and enables sharing of high-fidelity simulation data stored in IMAS within VOLTA across different team members.
- These simulations are used to train Reduced-Order Models (ROMs) for fast predictions.



Integrated Modelling and Analysis Suite (IMAS)

IMAS

- Unified software collection for all ITER physics modelling and analysis
- Hosts high-fidelity plasma simulators (e.g. ITER-SOLPS)
- Experimental and simulation data are stored as standardized, device-independent IDS (Interface Data Structures)

```
There are 1333 entries, getting them all...
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10:34:07 INFO     Parsing data dictionary version 3.38.1 @dd_zip.py:89
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```

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Conclusions and outlook

Conclusions and outlook

- Using VOLTA, we are enhancing the design activities execution and the collaboration of the research units involved in the EUROfusion activities

- Divertor conceptual design benefits from the ROMs related to the “time-consuming” simulations like SOLPS for calculation of PLASMA loads

- DTT divertor structures have been optimized using modeFRONTIER, solving specific issues related to the EM loads

- VOLTA on CRESCO8 is directly communicating with IMAS database to get input data for ITER divertor digital twin

Outlook

- Integration in the design workflow of Vacuum pumping performances and CFD to be further developed
- Specific section for Requirements management and traceability and V&V loop to be included in the design workflow
- ITER divertor digital twin to be fully developed basing on the CRESCO8-IMAS communication infrastructure

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Thank you

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