A multi-physics integrated approach to breeding blanket modelling and design

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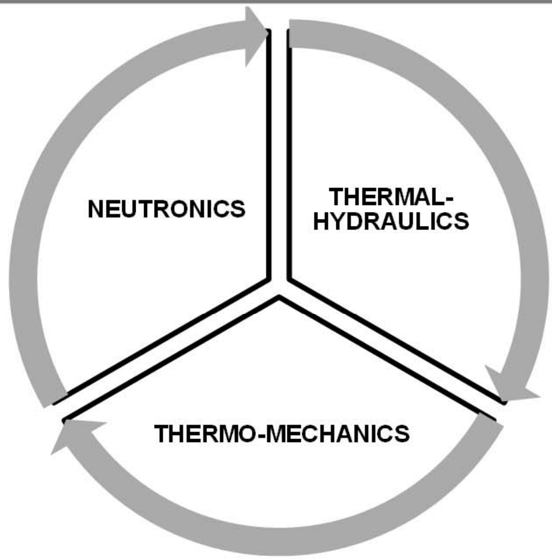
INVITED TALK - MS-052/MS-100 Computational Models for Multiscale/Multiphysics of Extreme Heat Flux Materials
9th International Conference on Computational Methods (ICCM2018)
6th – 10th August 2018, Rome

INSTITUTE FOR NEUTRON PHYSICS AND REACTOR TECHNOLOGY (INR)
KARLSRUHE INSTITUTE OF TECHNOLOGY (KIT)



Background

- Breeding blanket (BB) is a key component for the fusion reactor. Its major functions are:
  - To produce tritium (i.e. TBR>1.05);
  - To remove heat (neutronic/photonic power density and extreme high radiative fluxes);
  - To shield neutrons.

- Blanket concepts differ from compositions of breeder, neutron multiplier, coolant and structural materials.
  - Helium Cooled Pebble Bed (HCPB);
  - Water Cooled Lithium Lead (WCLL);
  - Helium Cooled Lithium Lead (HCLL);
  - Dual Coolant Lithium Lead (DCLL);

Conventional coupling procedure

- In the European BB DEMO project, several efforts are currently dedicated to the development of an integrated simulation-design tool able to carry out multi-physics analyses.
- This procedure may be time consuming and herald of errors.

Issues:
- different geometries used for each analysis;
- the changes are not always backwards.

CAD → Neutronic analysis → CFD analysis → Structural analysis

Motivation

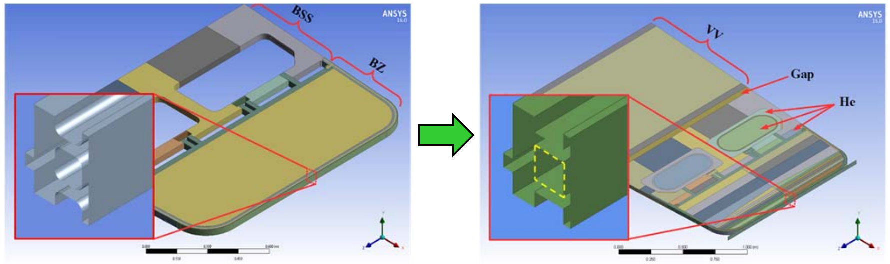
- The main objectives of the research project are:
  - to investigate and propose new methodologies aimed to improve the design of nuclear fusion components;
  - to outline a procedure for the coupling of neutronic, thermal-hydraulic and structural mechanical analysis for an integrated approach to the design of the tritium Breeding Blanket (BB) of DEMO reactor;
  - to apply this approach for the optimisation of BB design.

Coupling procedure

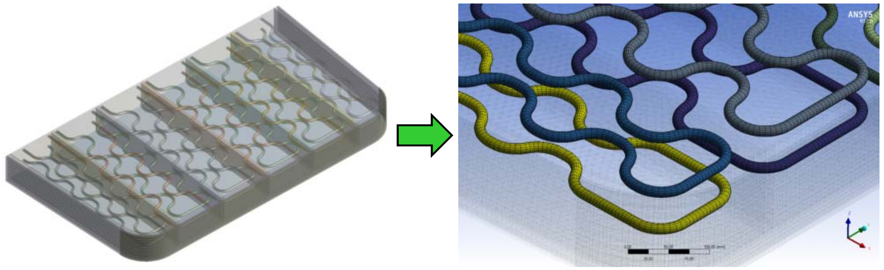
START
Import/create CAD geometry

GEOMETRY DECOMPOSITION AND CONVERSION

The reference geometry is imported from the CAD into ANSYS DesignModeler/Mesh, decomposed (slicing and reparation of sharp angles or meshed) and directly converted in a neutronic input for MCNP5/6.



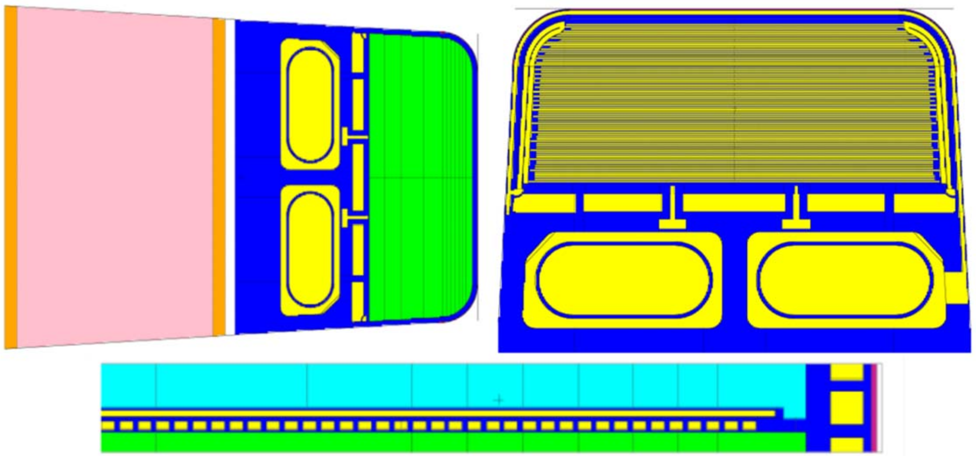
HCPB slice



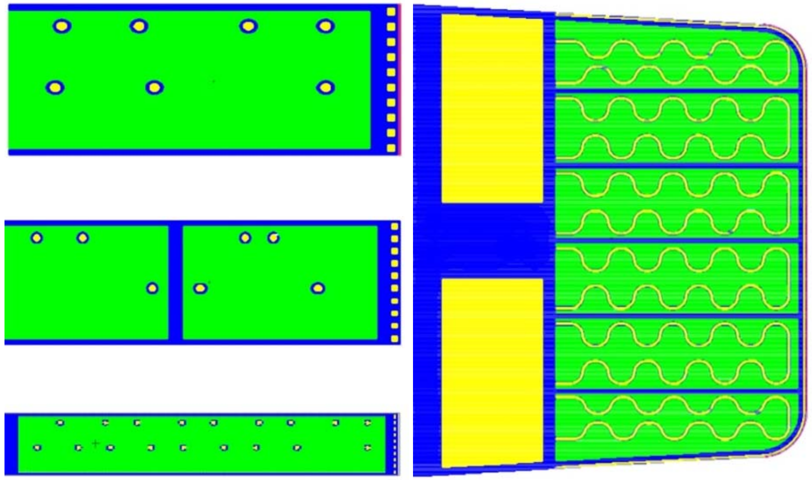
WCLL slice

Coupling procedure

NEUTRONIC ANALYSIS



Constructive Solid Geometry (CSG)



HYBRID Unstructure mesh (UM)

NEUTRONIC ANALYSIS

- The correct definition of the cells and the volumes conservation has been checked by means of the stochastic volume estimation based on the ray tracing technique in order to demonstrate that the neutronic models represent faithfully the real geometry;

	CSG	HYBRID	
Overall Error [%]	0.01%	Helical	-0.0035%
		Serpentine	-0.0005%

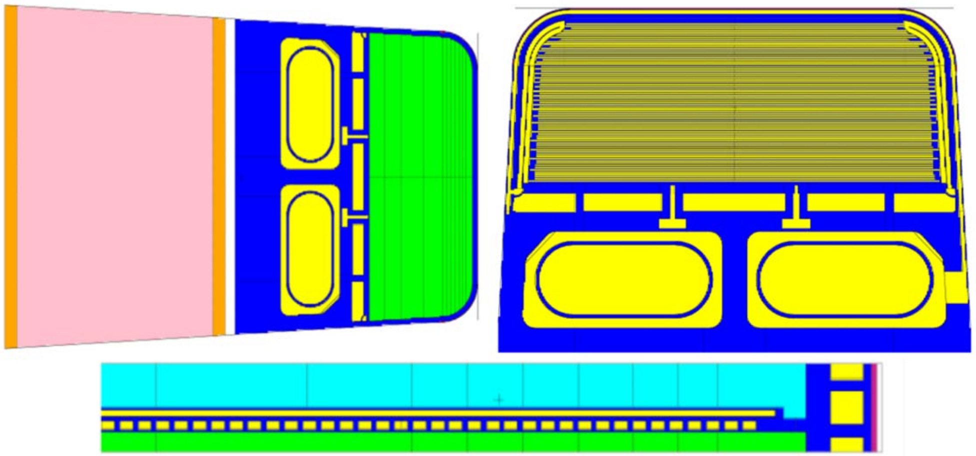
- reflecting boundary conditions have been imposed in the poloidal and toroidal direction, while, for the radial direction, the VV has been included;

- a dedicated global neutron source model has been developed to simulate the actual neutron volumetric source of a fusion reactor. It has been identified the surface corresponding to the outboard equatorial module where neutrons and photons are biased in cosine and energy. The cosine distribution has been ranged in 10 subdivisions while:

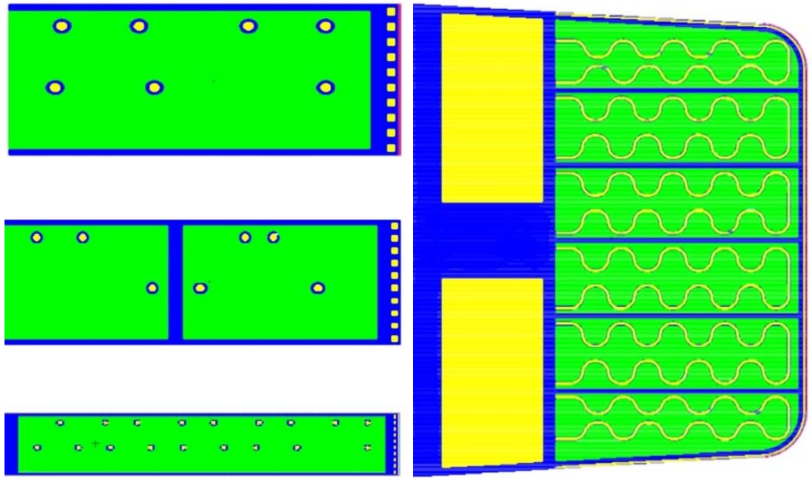
  - the neutron energy has been sampled from 0.111 MeV to 14.2 MeV subdivided in 98 energy bins;
  - the photon energy has been sampled from 0.001 MeV to 50.0 MeV subdivided in 43 energy bins.

Coupling procedure

NEUTRONIC ANALYSIS



Constructive Solid Geometry (CSG)



HYBRID Unstructure mesh (UM)

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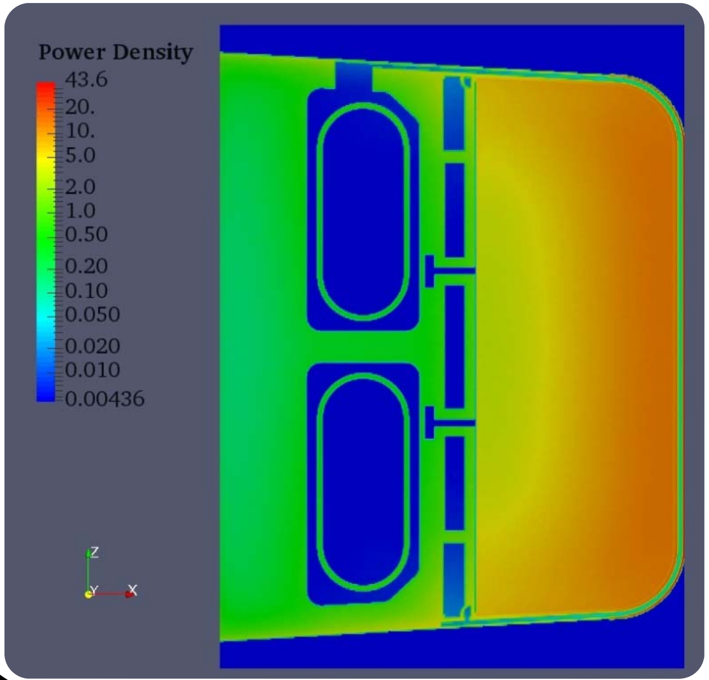
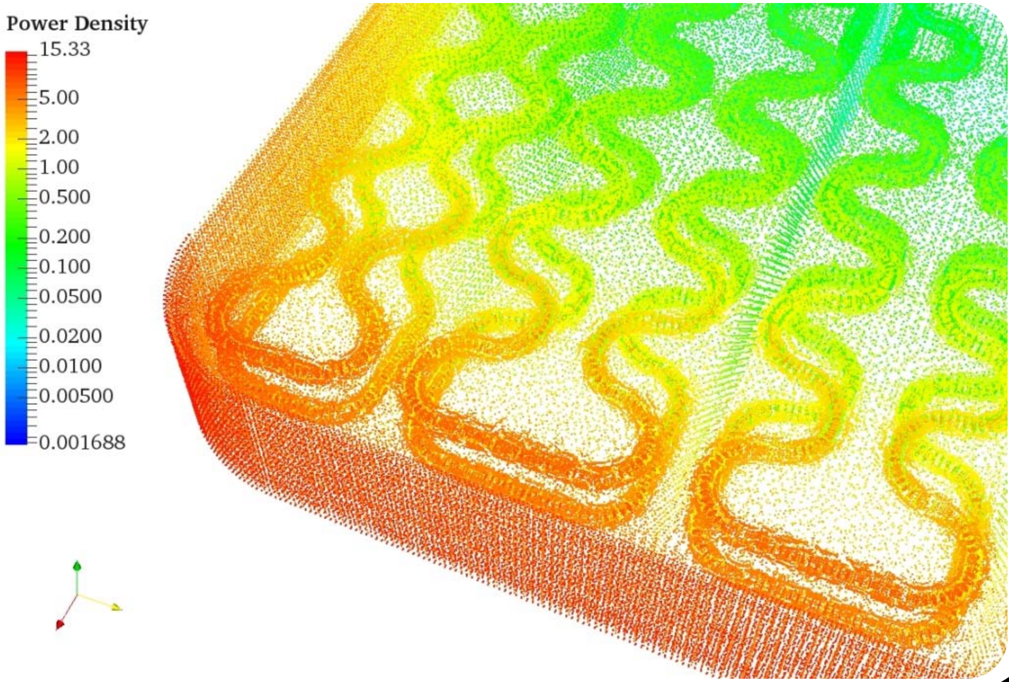
Coupling procedure

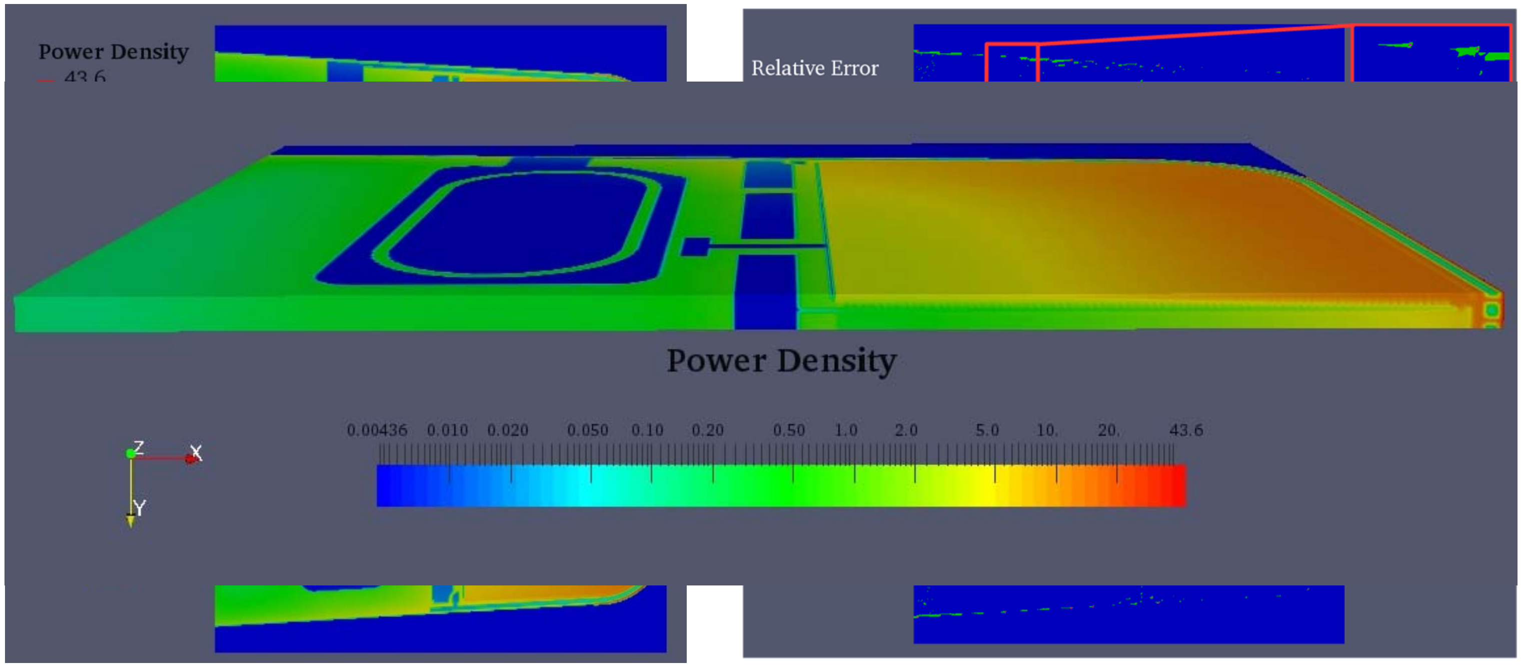
3D POWER DENSITY PROFILE CALCULATION





Results – Neutronics (CSG)

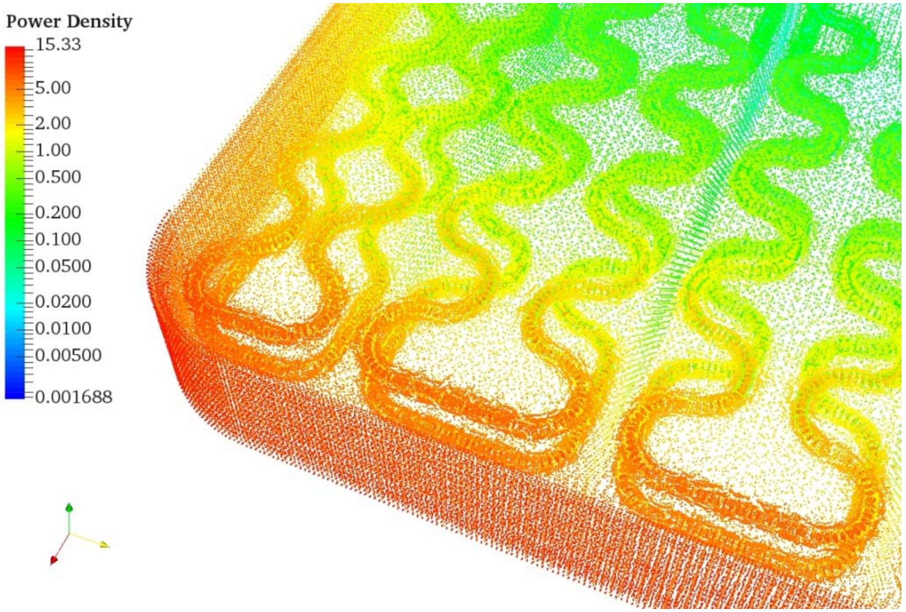
- The neutronic Monte Carlo calculation has been performed with MCNP5 code running a statistically-relevant number particle histories (~ 100M). Run time ~ 20h;
- the power density deposition has been calculated on a superimposed mesh of ~ 2M voxel with a resolution lower than 3 mm in x, y and z direction;
- the 99.13% of mesh elements have a relative error lower than 5%, 0.82% between 5 and 10%, and only 0.05% greater than the 10%.



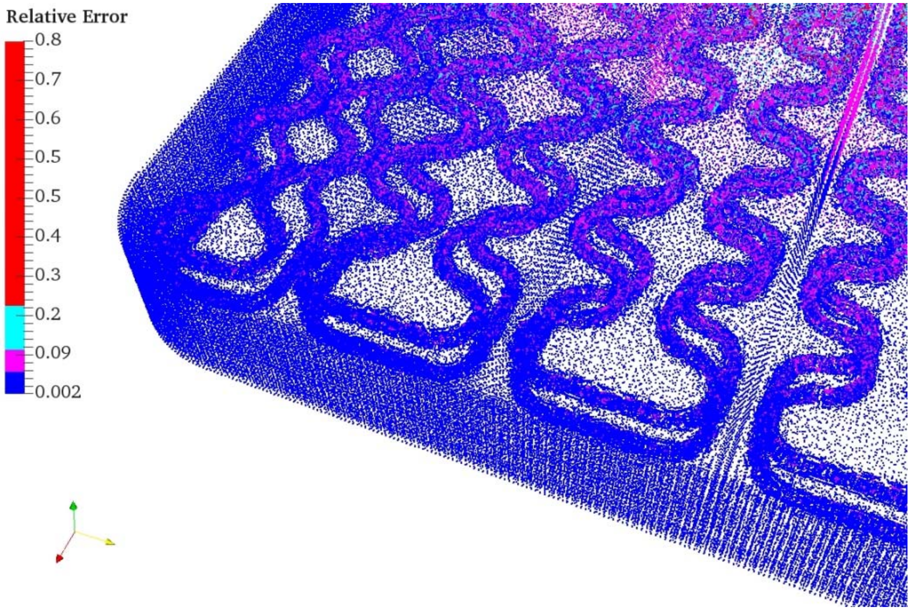
Results – Neutronics (HYBRID)

- The neutronic Monte Carlo calculation has been performed with MCNP6 code running a statistically-relevant number particle histories (~ 100M). Run time ~ 11h;
- between the 86.9% and the 89.42% of the mesh elements have a relative error lower than 10%, 8.03-10.33% between 10 and 20%, and 2.56-2.78% with an error greater than 10%;
- for these preliminary analyses, no variance reduction technique has been used.

3D power density profile – Serpentine tube configuration

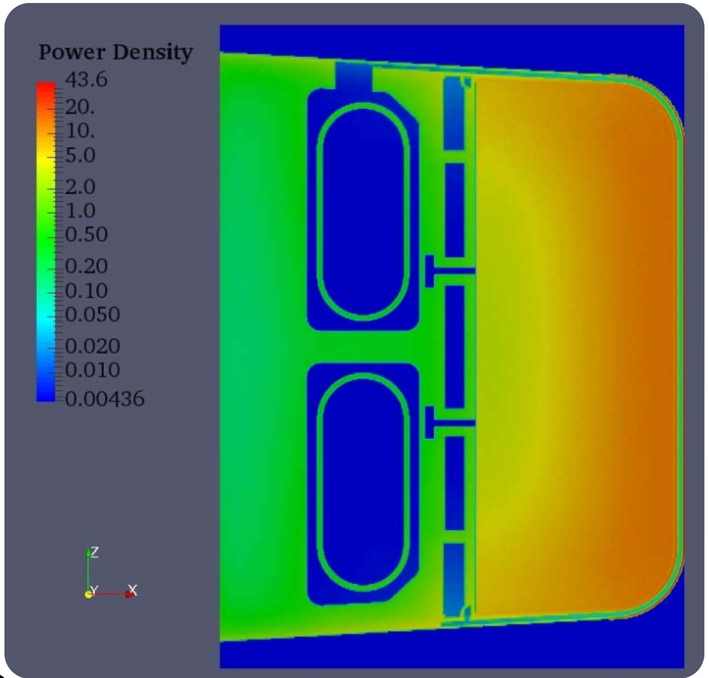


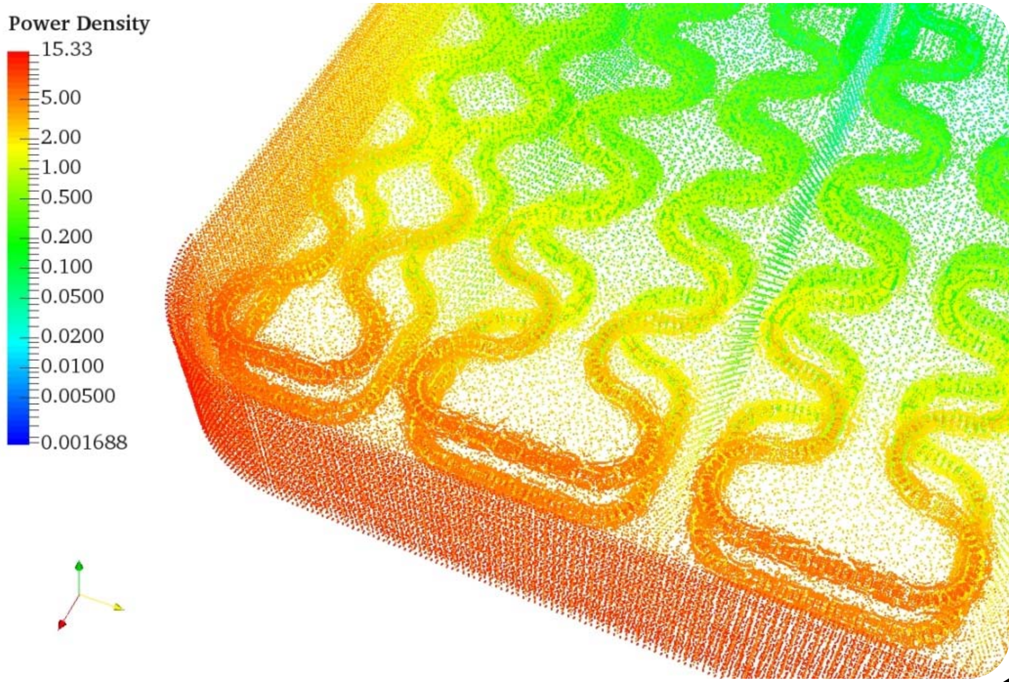
3D relative error profile – Serpentine tube configuration



Coupling procedure

3D POWER DENSITY PROFILE CALCULATION

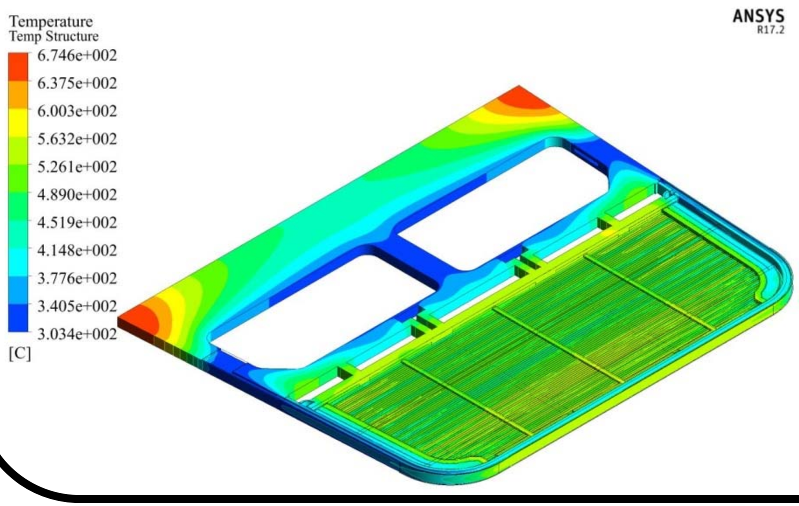


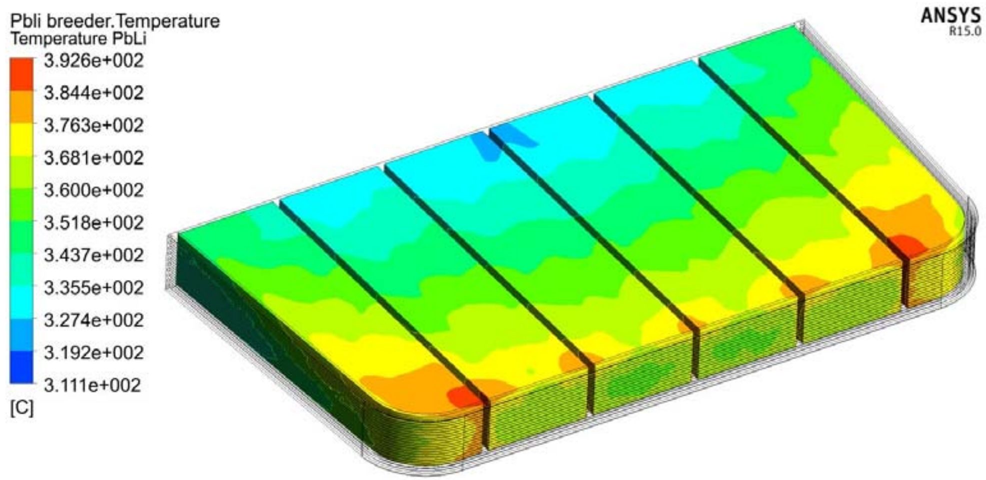


Coupling procedure

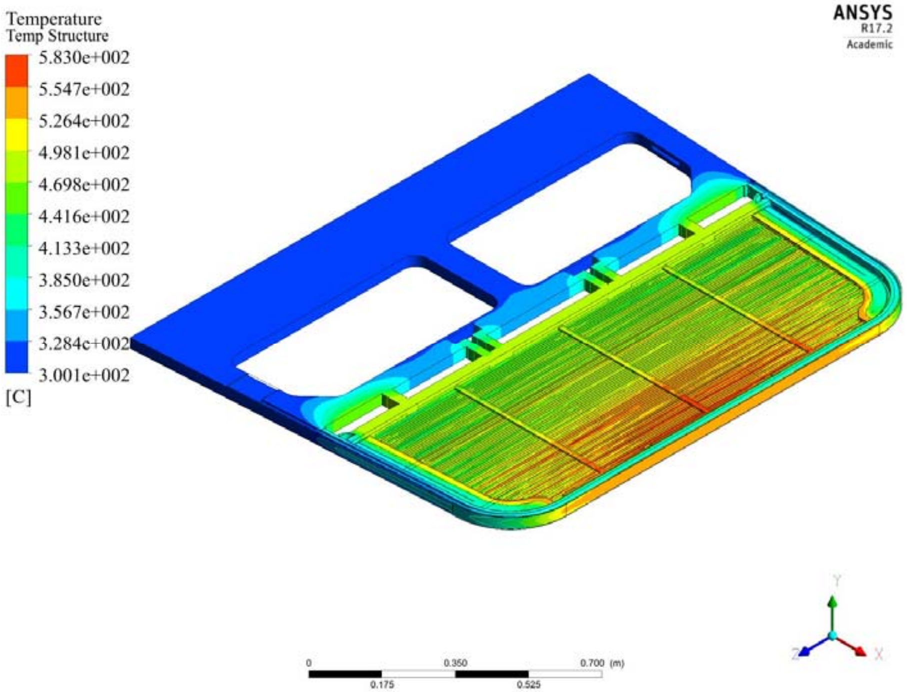
Mapping of 3D power density into CFX

CFD ANALYSIS

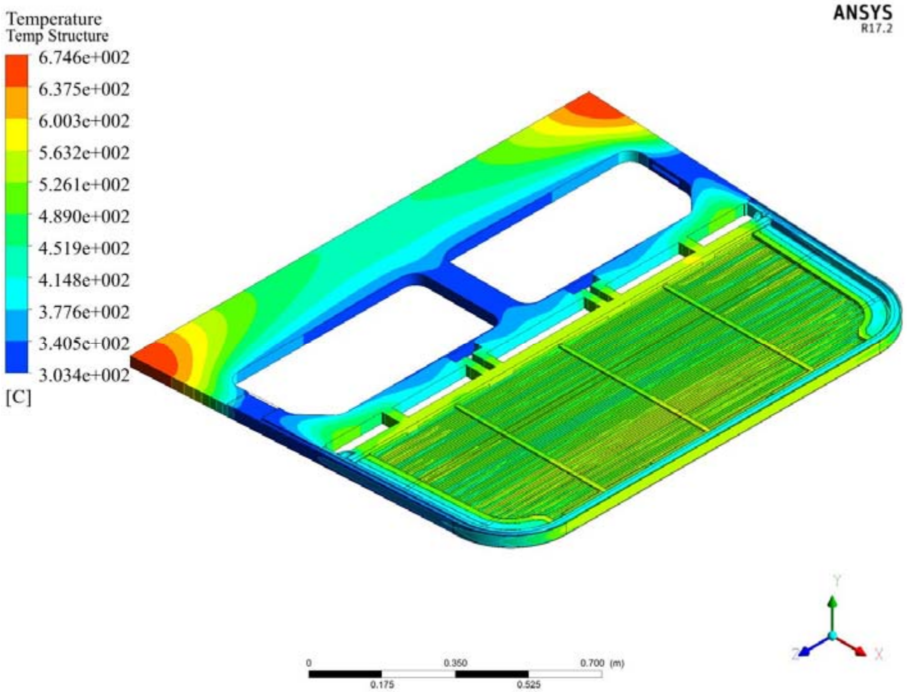




Results – Thermal-hydraulics (CSG)

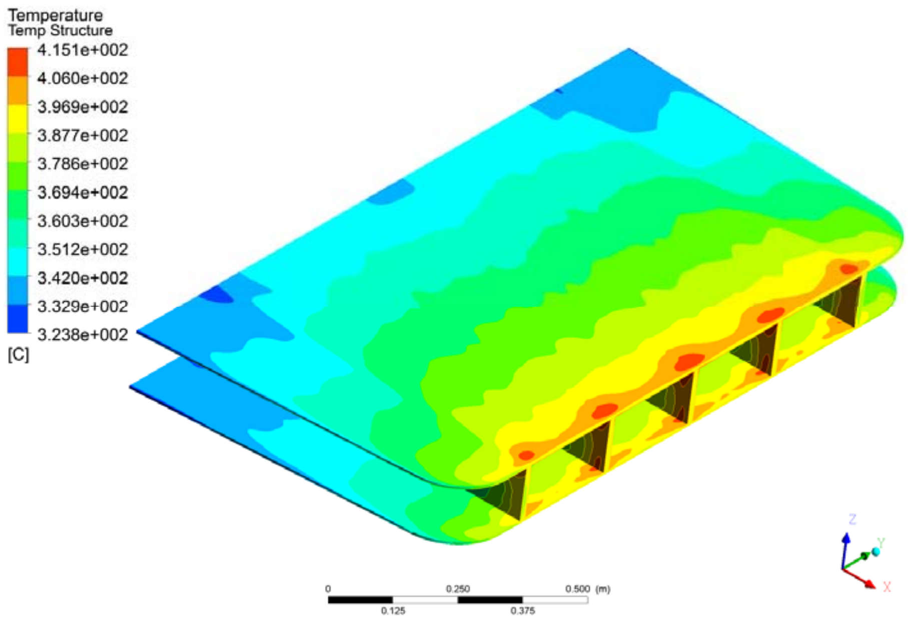


B. Kiss (BME-NTI-HAS, BUTE),
HCPB Design Report 2015, 2MNBH9,
radial power density profile

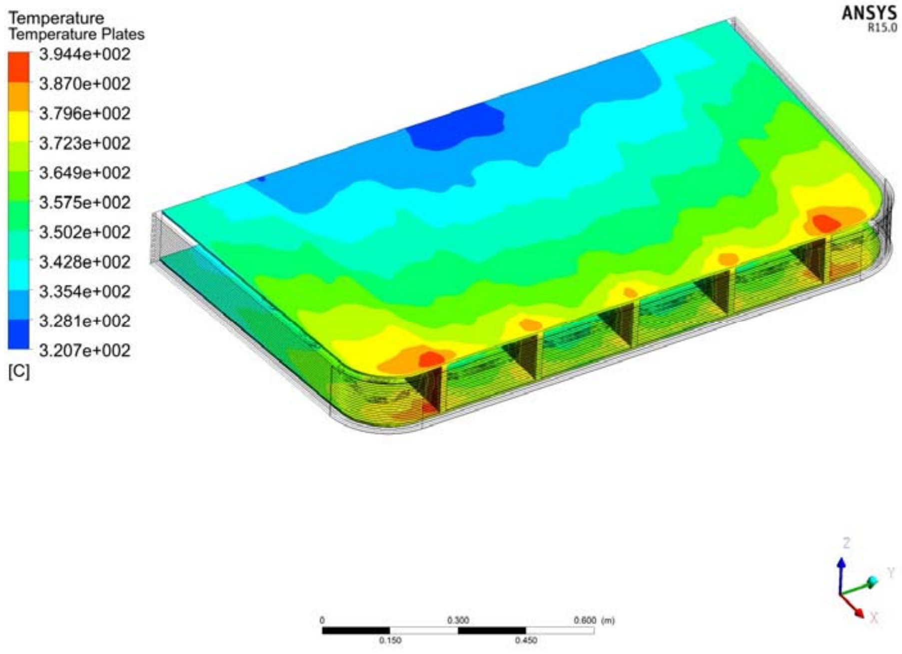


G.A. Spagnuolo (KIT),
3D power density profile

Results – Thermal-hydraulics (HYBRID)



Temperature calculated using a radial power density profile



Temperature calculated using a 3D power density profile

Coupling procedure

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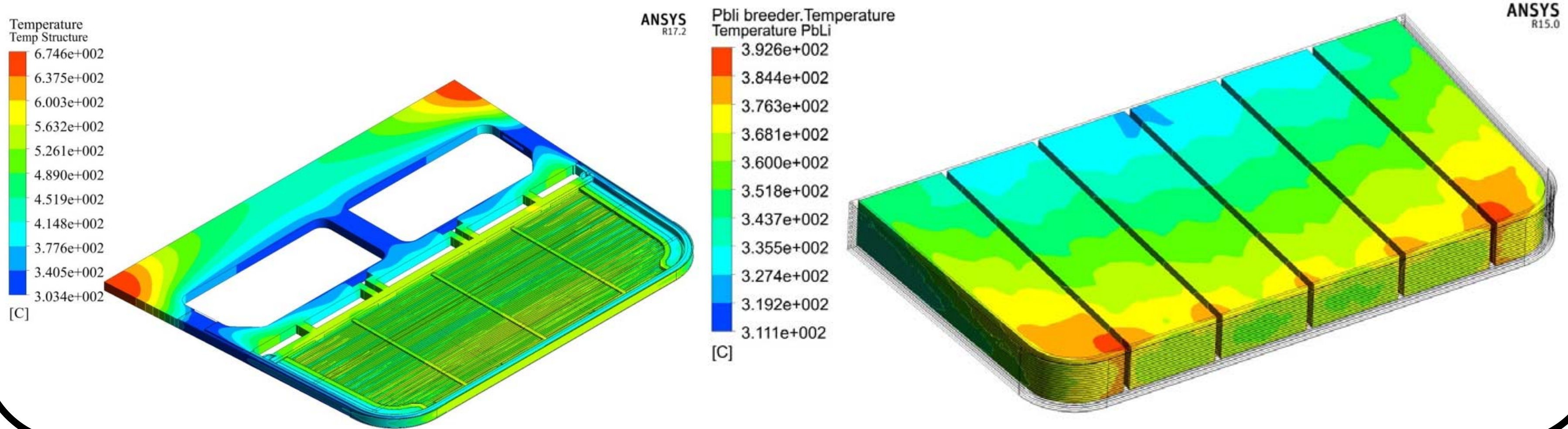
CFD ANALYSIS



Δp, T_{out}, T_{struc} whitin the limits?

No → Geometry modifications

Yes

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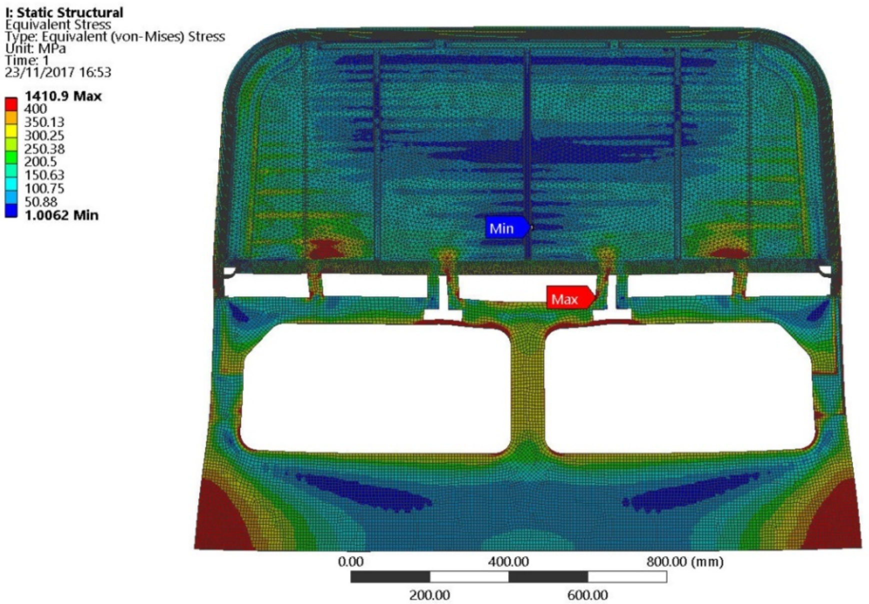
Coupling procedure

Mapping of 3D temperature field

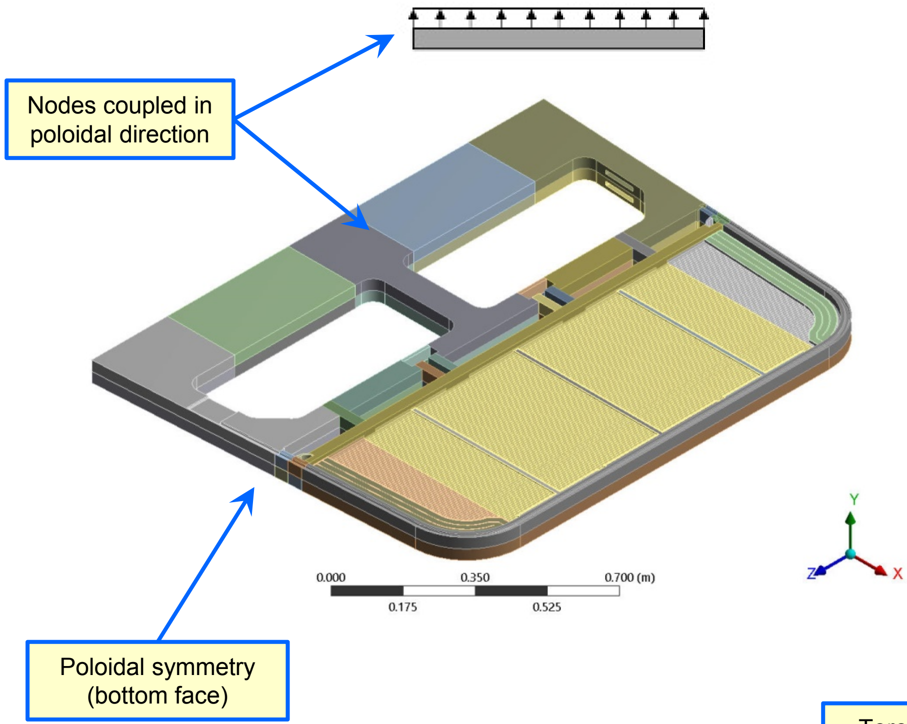
- T_{struc}

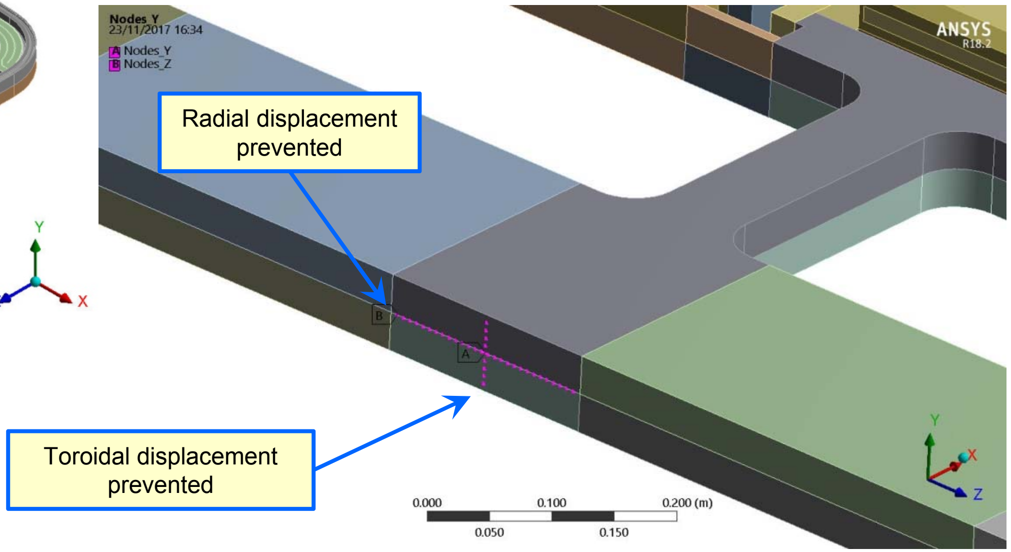
THERMO-MECHANICAL ANALYSIS



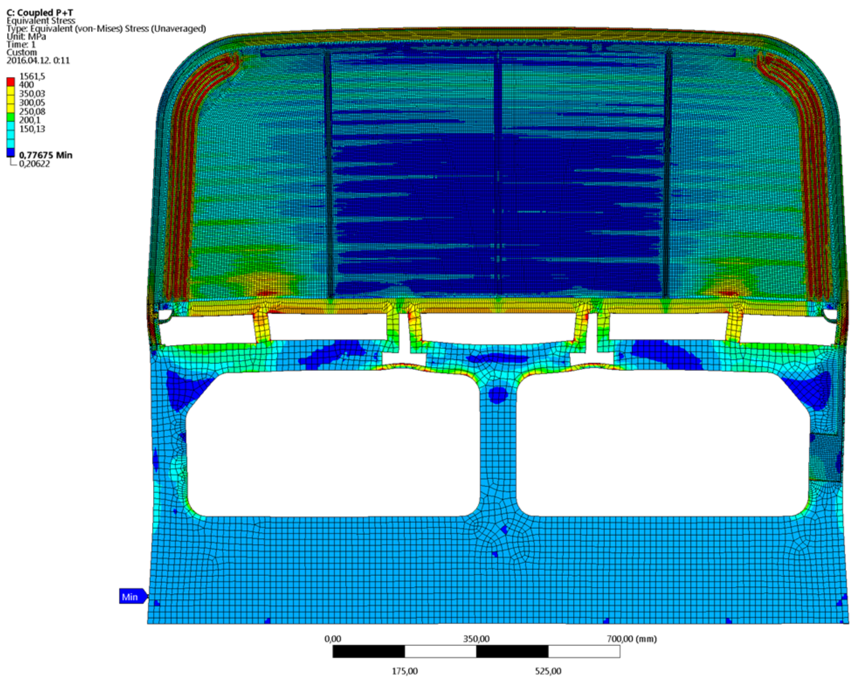
Analysis – Mechanics (CSG)

- Boundary conditions in normal operation (static)
  - The following set of mechanical boundary conditions along radial (x), toroidal (z) and poloidal (y) directions has been imposed to simulate the presence of the rest of the module as well as the attachment mechanical action.

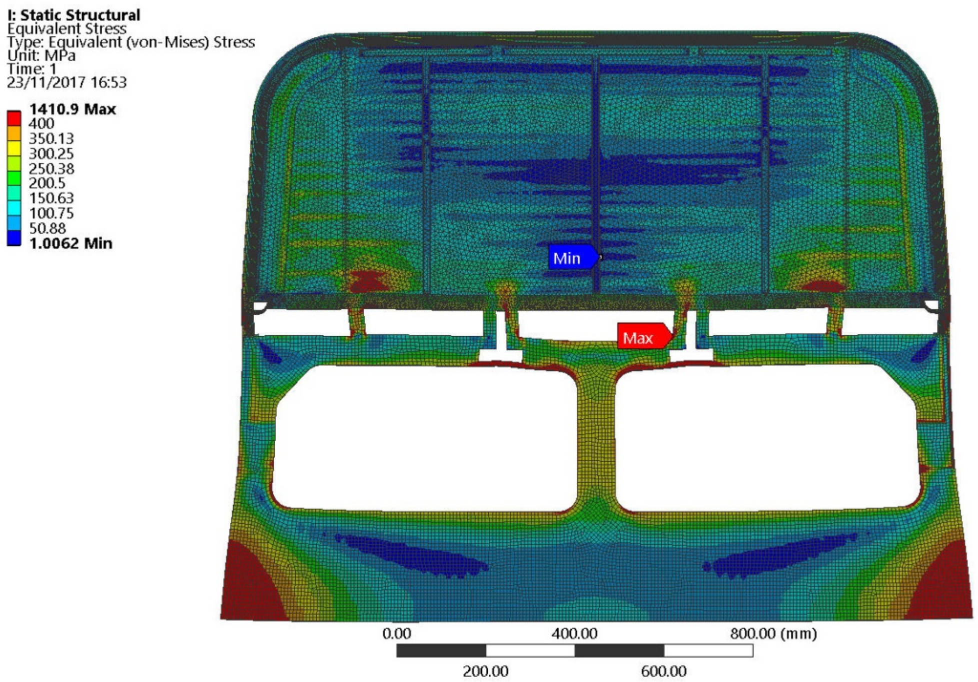




Results – Mechanics (CSG)



G. Nádasi (Wigner RCP),
HCPB Design Report 2015, <u>2MNBH9</u>



G.A. Spagnuolo (KIT),
3D power density profile

<u>Gandolfo Alessandro Spagnuolo</u>, Pierluigi Chiovaro, Pietro Alessandro Di Maio, Riccardo Favetti

Coupling procedure

Mapping of 3D temperature field

- T_{struc}

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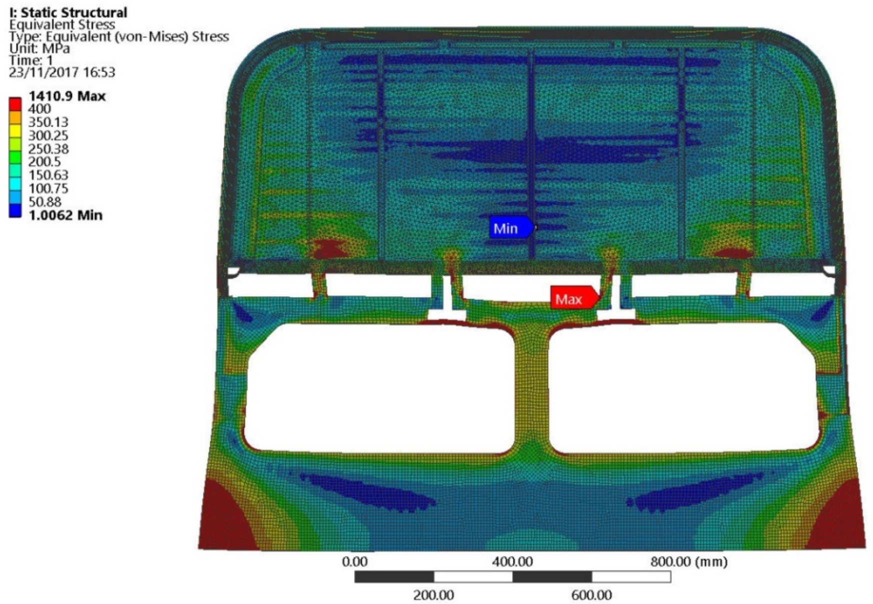
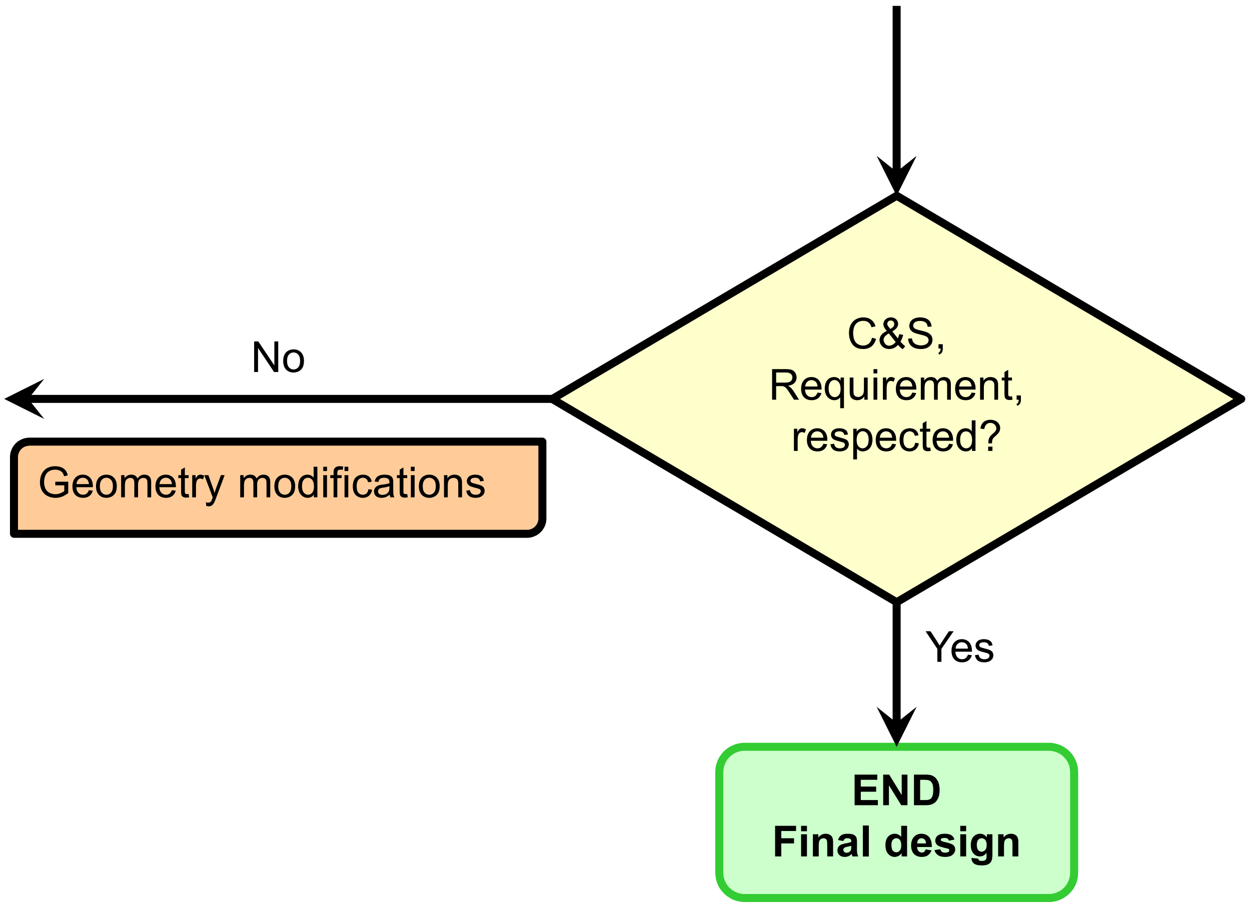


Coupling procedure



Open points & future developments

- Geometry parametrisation for multi-physics scoping analysis aimed to optimise the BB design;
- Application of the procedure for water activation analysis with direct coupling with CFD for the calculation of the asymptotic Nitrogen concentration C_{N_2};
- Component-level hydrogen transport analysis with OpenFOAM model (i.e. T-Map) or directly implementing the governing equations in CFD;
- Study of possible connection with systems code (i.e. MIRA) for updating BB input parameters.

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Development and verification of a component-level hydrogen transport model for a DEMO-like HCPB breeder unit with OpenFOAM

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HCPB

ABSTRACT

This work describes the development of a numerical model to simulate transient tritium transport on the breeder unit (BU) level for the EU helium cooled pebble bed (HCPB) concept for DEMO. The key output quantities of the model are the tritium concentration in the purge gas and in the coolant and the tritium inventory inside the BU structure. The model capabilities should cover normal operation as well as accident conditions.

The Open Source Field Operation And Manipulation framework OpenFOAM serves as the basis for the model. Equations and boundary conditions required for hydrogen isotopes transport are implemented. Realistic properties data as diffusion constants and Sieverts constants are required, too. A key model issue is solid-fluid interface mass transfer. Two correlations that (1) approaches Sieverts equilibrium in the diffusion limit and (2) a rate dependent correlation that includes the diffusion limit for very high ad-/desorption rate constants are introduced. A two species interface mass transfer correlation based on the single species rate dependent correlation is developed, too. First verification calculations are compared to analytic solutions and TMAP calculations.

1. Introduction

Tritium as one of the two necessary fuels for the currently technically pursued D-T fusion process will have to be produced inside the fusion plant blanket itself e.g. starting from lithium making use of the fusion neutrons. For the so called breeding of tritium, one European concept for DEMO called HCPB (helium cooled pebble bed) uses pebble beds of lithium orthosilicate (OSI) and beryllium. Beryllium is foreseen as a neutron multiplier to gain the required breeding neutrons at suitable energies to breed tritium in the neighboring OSI bed. High pressure helium serves as coolant; a separated stream of low pressure helium, usually called the purge gas, is used to transport the bred tritium out of the breeder to the tritium extraction system (TES). Usually a small amount of hydrogen is added to the purge gas to support tritium extraction. A breeder blanket typically is build-on of several identical or at least very similar breeder units (BUs). These BUs represent a practicable level for Computational Fluid Dynamics (CFD) modeling.

The attenuation of nuclear interaction processes with increasing distance from the first wall (FW) and the cooling configuration will result in considerable temperature spreads, tritium generation profiles and different grades of radiation damage to the structure material (Eurofer-97) as well as to the breeder ceramics (OSI) and neutron multiplier material (Be) inside a BU. Transport parameters and tritium retention properties are known to depend considerably on these quantities.

The design of a BU has to take into account these parameters with regard to the breeding efficiency and the self-sufficiency of the reactor with fuel. The tritium inventory in the components plays a role with regard to safety and decommissioning requirements.

The above conditions obviously ask for multiple physics capabilities when analyses are to be done. Thermomechanical analyses of a BU by the designers with commercial CFD and FEM codes are standard proceeding. However simulation options for tritium release and transport are still incomplete. Available tritium transport modeling codes typically operate at the system level or at a microscopic level. A publication [1] indicates the awareness of the EU fusion community responsibles of the need for a component level model closing the gap between the well-known TMAP code [2] and the diverse system level codes. Notably a component level model is expected to improve the accuracy of the answers on questions related to safety (such as tritium inventory, tritium retention and contamination of the coolant flows) and to the TES design.

At KIT first efforts with ANSYS [3] have not been further developed. Instead the (system level) FUS-TPC code has been adapted for a

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Conclusion

- The capability of ANSYS to generate inputs based on CSG and UM representations suitable for neutronic analysis has been demonstrated;
- the coupling procedure between neutronic, thermal-hydraulic and structural calculations has been developed and carried out;
- the developed methodologies allow an extremely precise estimation of the power density profile providing important inputs to be used for the BB design;

ID3282: Validation of multi-physics integrated procedure for the HCPB breeding blanket

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Karlsruhe Institute of Technology

THANKS FOR YOUR ATTENTION!

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