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

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Introduction

- **University of Palermo** and **Karlsruhe Institute of Technology** (KIT) are involved in R&D activity on nuclear fusion technology.
- The realization of the **DEMO** fusion reactor represents a milestone within the European Roadmap to the Realisation of Fusion Energy.
- In this framework, KIT is dedicating several efforts to the development of a **multi-physics analysis tool** allowing the characterization of DEMO breeding blanket design points.
- One of the multi-physics analysis procedures developed at KIT is characterized by the implementation of **analysis software only**. The purpose of the procedure is to set up a **fast and efficient analysis tool** capable to address the breeding blanket **preliminary** design.

Introduction

A cooperation between **KIT** and **University of Palermo** has allowed to perform a preliminary step for the **validation** of such a procedure using a theoretical - computational approach on a dedicated model of the **DEMO 2015 Helium Cooled Pebble Bed (HCPB) Breeding Blanket (BB) 4th outboard module**.

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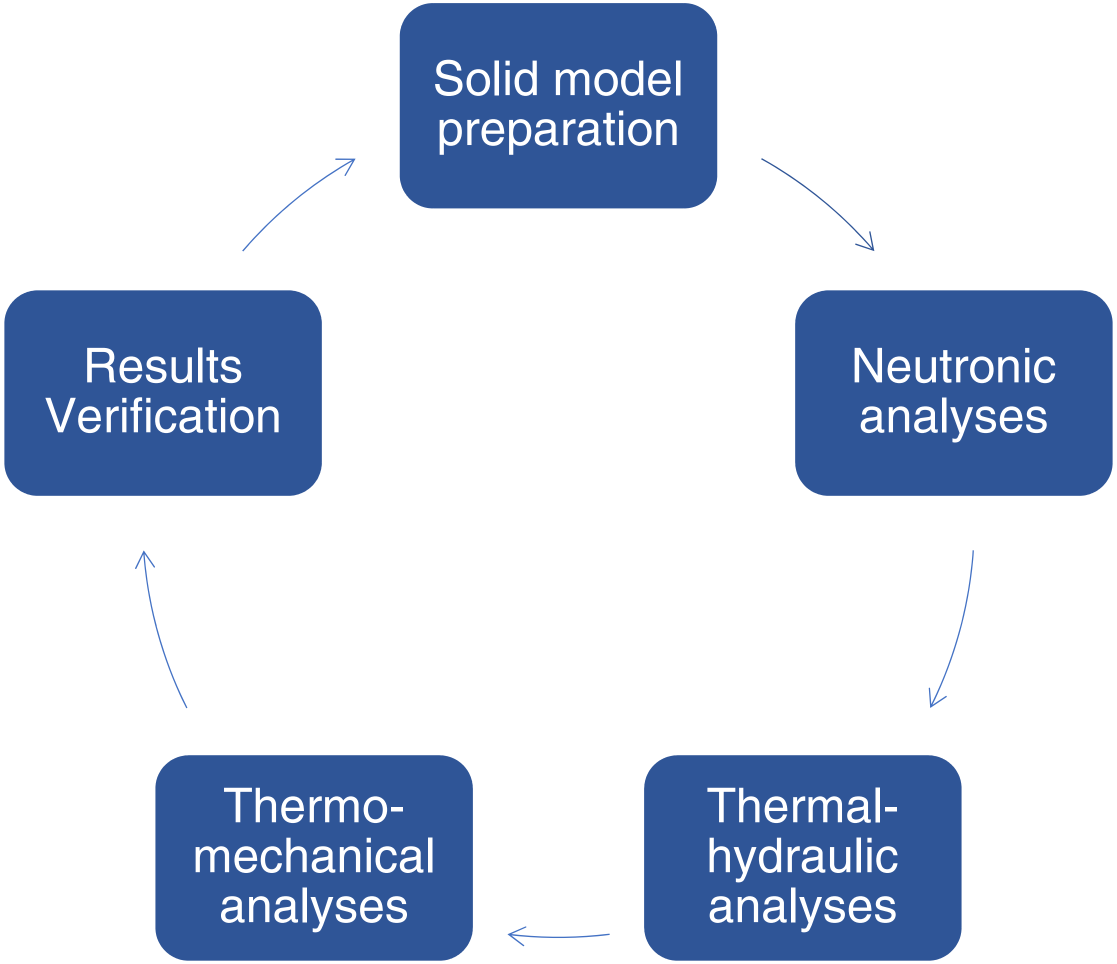
Multi-physics Analysis Cycle



Multi-physics Analysis Cycle

Main issues of a multi-physics analysis cycle:

1. **Incompatibility** between the CAD generated solid model (*Boundary representation method*) and the neutronics-suitable solid model (*Constructive Solid Geometry representation method*).
2. **Demanding computational requirements** if the analyses are performed on a DEMO global solid model.

Proposed solutions:

1. **Use ANSYS Design Modeler's legacy MCNP conversion capability** to produce a neutronics-suitable model from a CAD generated solid model.
2. **Circumscribe a local solid model** (i.e. a slice) for the analysis of the breeding blanket response.

Multi-physics Analysis Cycle

Solid Models Incompatibility

A major issue related to multi-physics analyses is due to the different solid model representation methods used by design codes.

Constructive Solid Geometry Representation (CSG)

- Used for **Neutronic Analyses**
- Primitive surfaces are instantiated and combined using boolean operations
- Design is **not user-friendly**

Boundary Representation (Brep)

- Used for **Thermal-hydraulic** and **Thermo-mechanical** analyses
- The solid model is described by a set of non overlapping surfaces
- **User-friendly** design with CAD software

Multi-physics Analysis Cycle

Computational Requirements

- The **reduction of computational requirements** is of primary importance to obtain a fast analysis tool.
- The set-up of a **local circumscribed model**, together with a proper definition of a local source and boundary conditions, could allow to achieve a sufficiently reliable estimate of the breeding blanket response with a significantly reduced computational effort.

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Validation Procedure

Two **local** models of the HCPB BB have been set-up, analyzed and compared with a **global** model of the HCPB BB inserted in 2015 MCNP DEMO generic model.

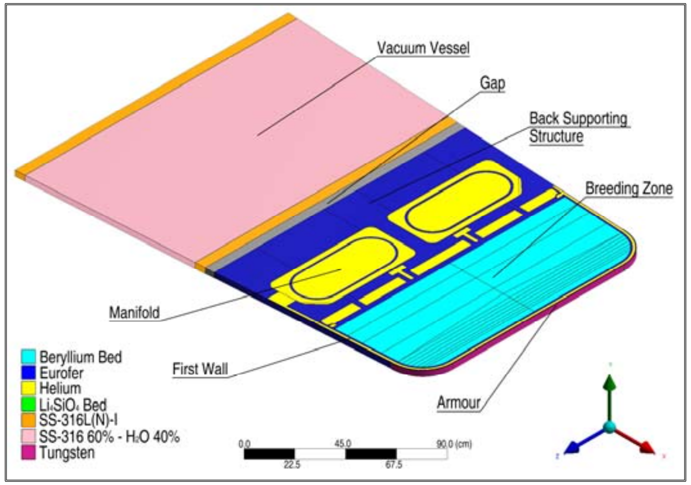
1. First of all, **volumes comparisons** between the BRep solid models and the CSG solid models obtained after the conversion have been performed to assess the reliability of the conversion approach.

2. Then, comparisons of **nuclear power deposition** together with its **volumetric density** data on the different models have been performed to validate the analysis method.

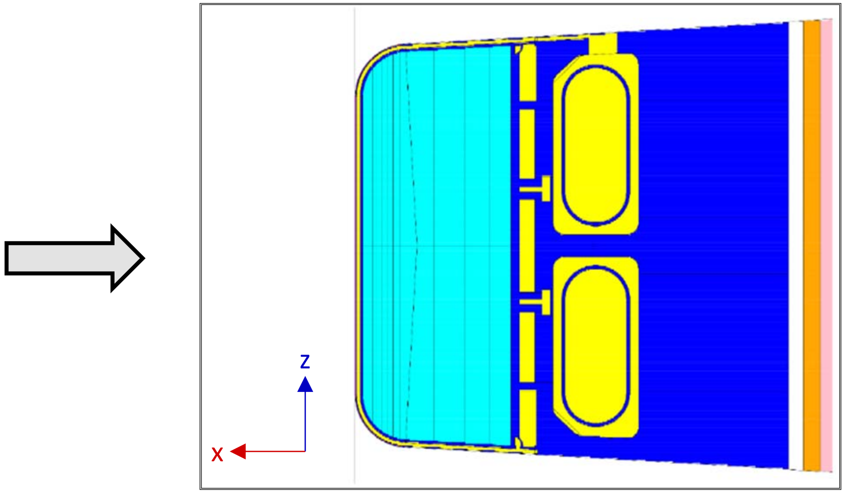
HCPB BB SLICE Local Solid Model

- A solid model of a slice extracted from the DEMO HCPB OB4 module has been imported in ANSYS Design Modeler and converted.
- The slice (i.e. the fundamental unit of the breeding zone of a module) is composed of half Be pebble bed, a cooling plate and half Li_4SiO_4 pebble bed.

BRep



CSG



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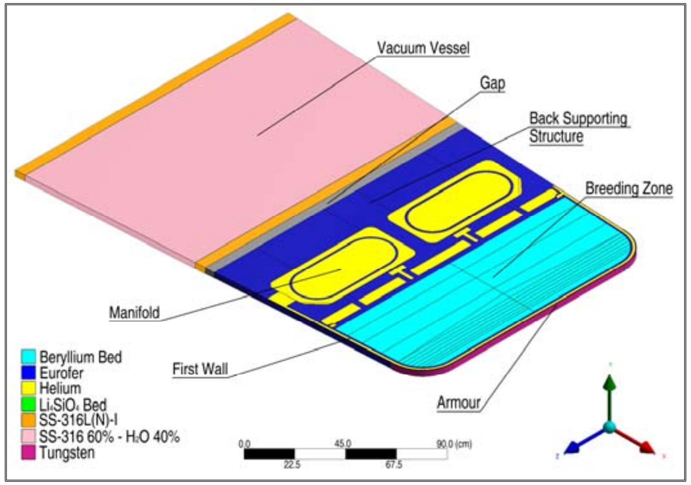
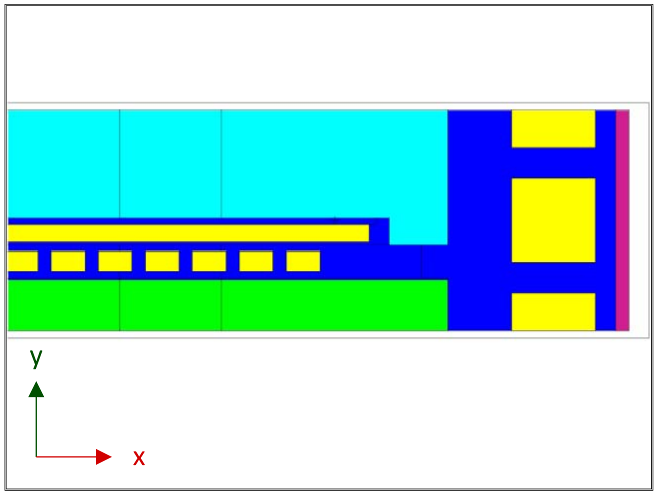


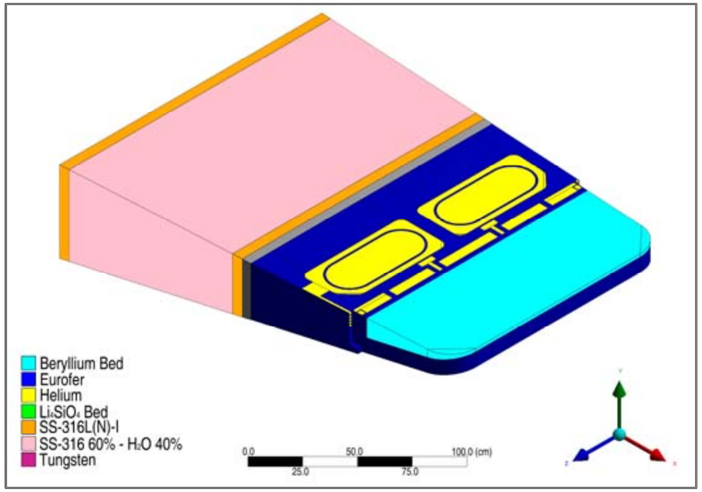
CSG



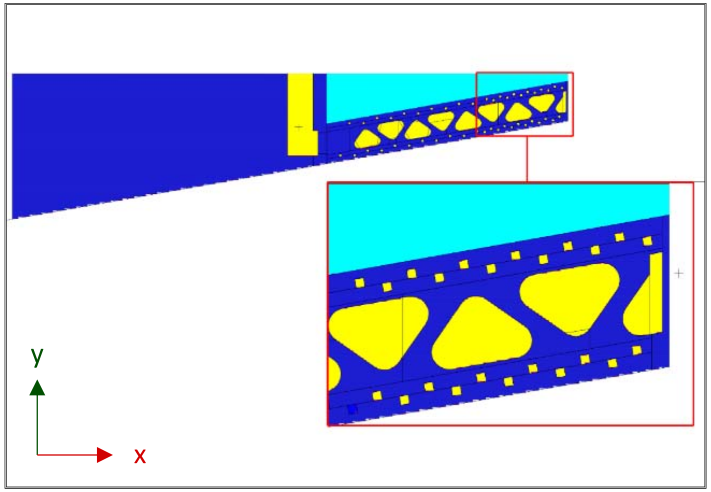
HCPB BB MODULE Local Solid Model

In order to set up a MCNP model of the whole HCPB OB4, a solid model of its cap has been imported in ANSYS Design Modeler and the described coupling approach application has been used to obtain a MCNP model of the cap itself.

BRep

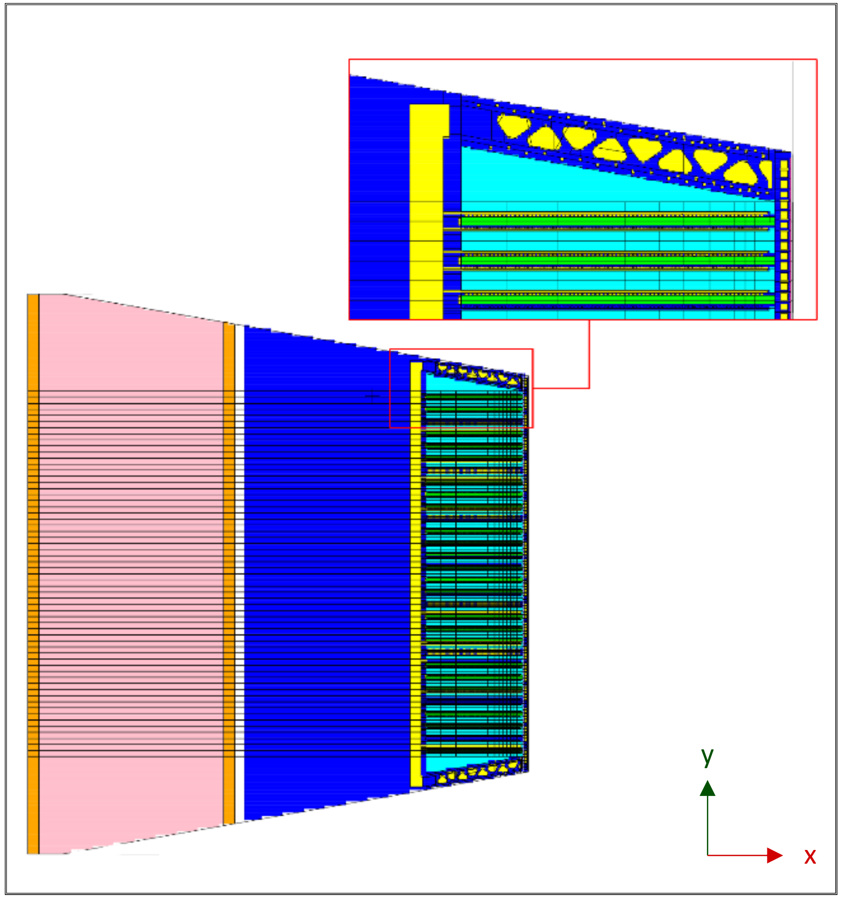


CSG



HCPB BB MODULE Local Solid Model

CAP and **SLICE** neutronic models have been **joined** together in order to build the solid model of **DEMO HCPB BB OB4 module**. The lattice features of MCNP have been used to generate the breeding zone, composed of a stack of 60 slice units piled in the poloidal direction. The universe features of MCNP have been used to re-create the two caps from the CAP solid model.



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Volumes Comparison

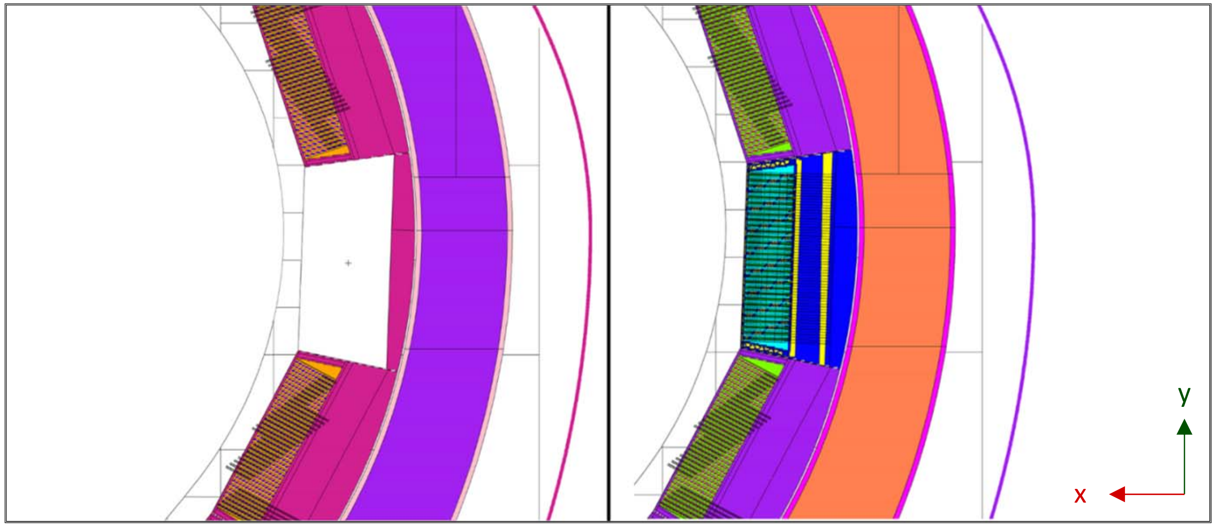
- The volumes of the bodies of the original BRep solid models have been compared with the corresponding volumes of the SLICE and CAP CSG models, which have been stochastically assessed using MCNP.
- The table shows the overall volumes differences between CSG and BRep models.

MODEL	Δ CSG-BRep [%]
SLICE	-0.01473%
CAP	-0.01025%

- An **excellent match** has been assessed, thus validating the geometric conversion procedure.

HCPB BB DEMO Global Solid Model

- The **MODULE** solid model has been joined with a **DEMO geometric model** taking into account a torus sector of 10°, in which the blanket has been implemented using repeated structures features with a semi-heterogeneous material composition.
- The **global DEMO model** has thus been obtained, which features a **fully heterogeneous OB4 module**.



Local Sources Definition

- In order to perform analyses on MODULE and SLICE local neutronic models, a **local source** has been defined for each model with the purpose to simulate DEMO radiation conditions.
- For each model, two **planar sources** (one for neutrons and one for photons) have been defined, with particles emission biased in **cosines** and **energies**.
- The emission probabilities for cosines and energies of each source have been defined starting from the results collected in an ad hoc analysis run with DEMO model.

Boundary Conditions For Local Models

Reflective boundary conditions have been imposed on the surfaces bounding the local models in poloidal and toroidal directions, thus simulating interactions in the corresponding adjacent structures in DEMO.

Nuclear power deposition calculation

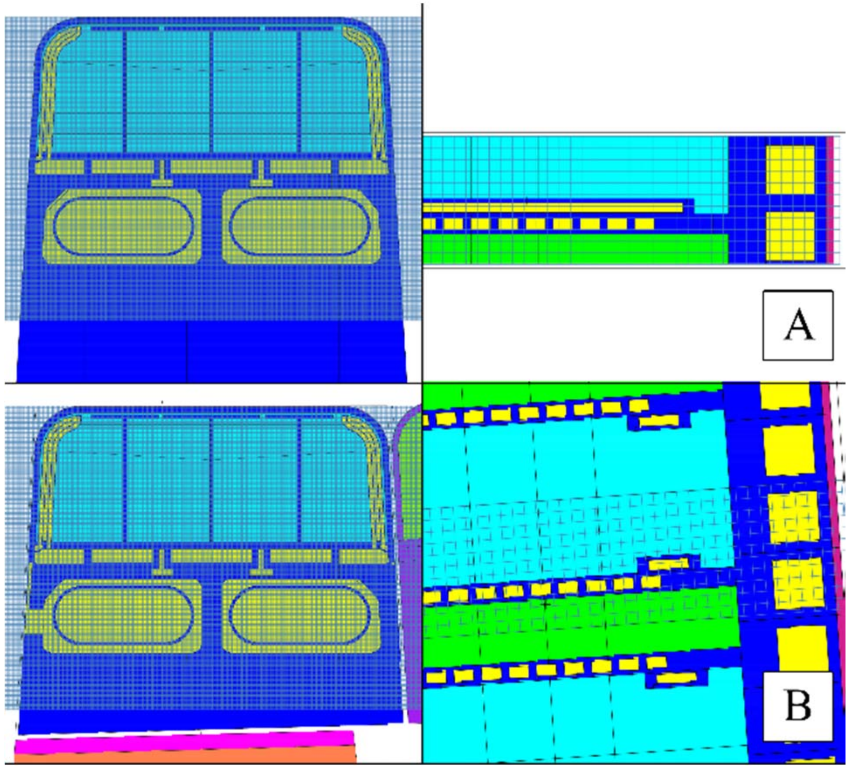
- **Power deposition** on corresponding cells of DEMO, MODULE and SLICE models has been calculated and compared to validate the local source definition procedure, the boundary conditions set-up and the coupling approach.
- Analyses have been performed considering a fusion power of 2037 MW.

	SLICE	MODULE	DEMO
Q_{dep} [W]	$7.7760 \cdot 10^4$	$7.6111 \cdot 10^4$	$7.5805 \cdot 10^4$
Δ_{DEMO} [%]	2.58%	0.40%	-

- The coupling approach application and the source sampling procedure have allowed to obtain a **reliable estimate of the overall deposited power on the local models**.

Nuclear power volumetric density distribution

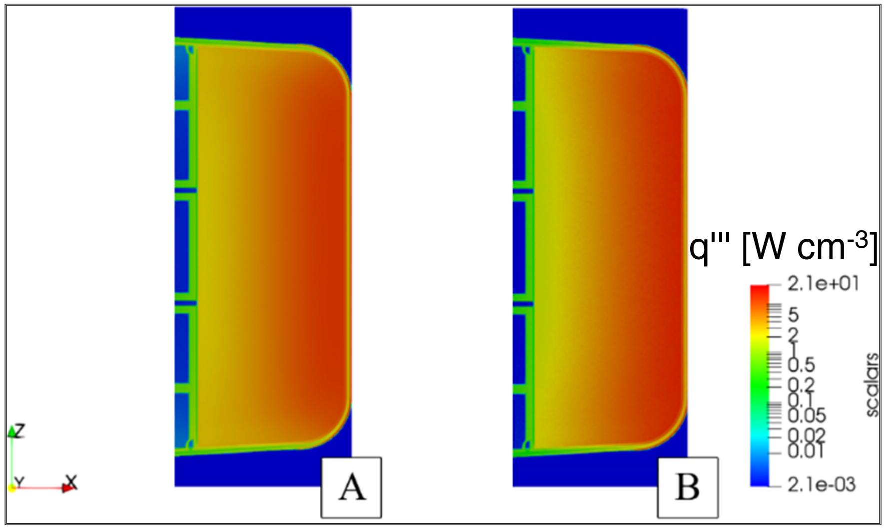
In order to score the **spatial distribution of the nuclear power volumetric density deposition** (q'''), a Cartesian mesh of *2557170* tetrahedral elements (corresponding to a mesh size of *0.3 cm* in all the directions) has been imposed to the SLICE model and in the corresponding region of the DEMO model.



A) SLICE
B) DEMO

Nuclear power volumetric density distribution

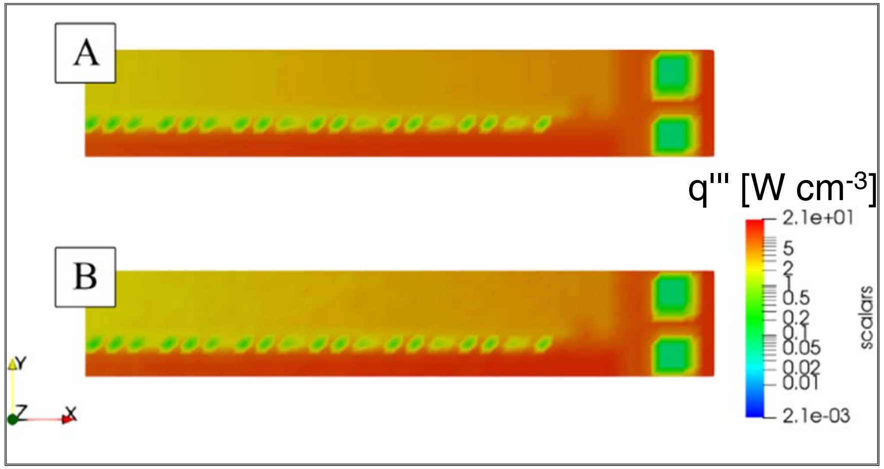
- Results have shown a **good agreement** between the models for what concerns the **overall power deposition** calculated from power density results.
- A power deposition of $7.6621 \cdot 10^4$ W has been achieved over the considered domain in DEMO, while the corresponding value in SLICE model is $7.7492 \cdot 10^4$ W, thus overestimated by **1.1376%**.



A) SLICE
B) DEMO

Nuclear power volumetric density distribution

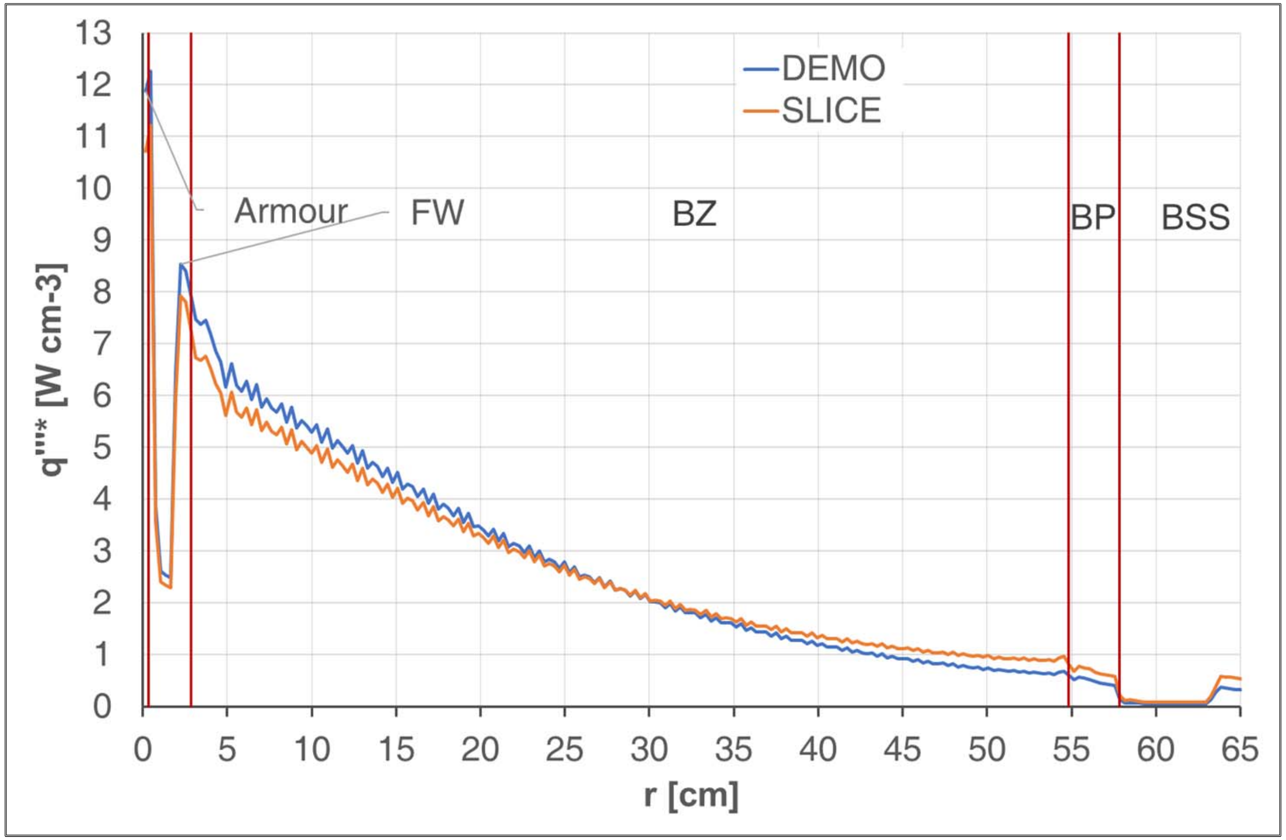
- Nuclear power volumetric density distribution shows a coincidence of the most stressed areas of the models, although a 16.4867% underestimation of the maximum power density value has been discovered in SLICE model.
- Further improvements of the statistical behaviour of the models and a more accurate source definition may result in a better matching of local power density deposition.



A) SLICE
B) DEMO

Radial profile of nuclear power density deposition

$$q'''^{*}(r) = \frac{1}{A_{pt}(r)} \int_{A_{pt}(r)} q'''(r,p,t)\,dA$$



Conclusions

- **University of Palermo** and **KIT** have cooperated with the aim to perform the **validation of the described direct coupling approach** to be implemented in a multi-physics analysis tool. With this purpose, the coupling approach has been applied to the 2015 concept of DEMO HCPB BB.
- Three reference neutronic models, namely **SLICE**, **MODULE** and **DEMO**, have been set-up and analysed.
- The conversion has proved to be effective with **negligible volume differences** between the original Brep solid models and the CSG models resulting from the conversion.

Conclusions

- As far as the **total nuclear power** is concerned, data obtained has shown a very **good agreement**. With regard to the **nuclear power volumetric density**, it has been observed that the response of the SLICE local model is **congruent** with the response of DEMO model as a consistent power density distribution has been obtained in the two models showing that **the most stressed areas are coincident**.
- The presence of some **local mismatch between results** makes necessary to further investigate the underlying neutronic and photonic phenomenology in order to define potentialities and limits of the coupling approach investigated.