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Overview of the HCPB Research Activities in EUROfusion

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Breeding Blanket Project

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Overview

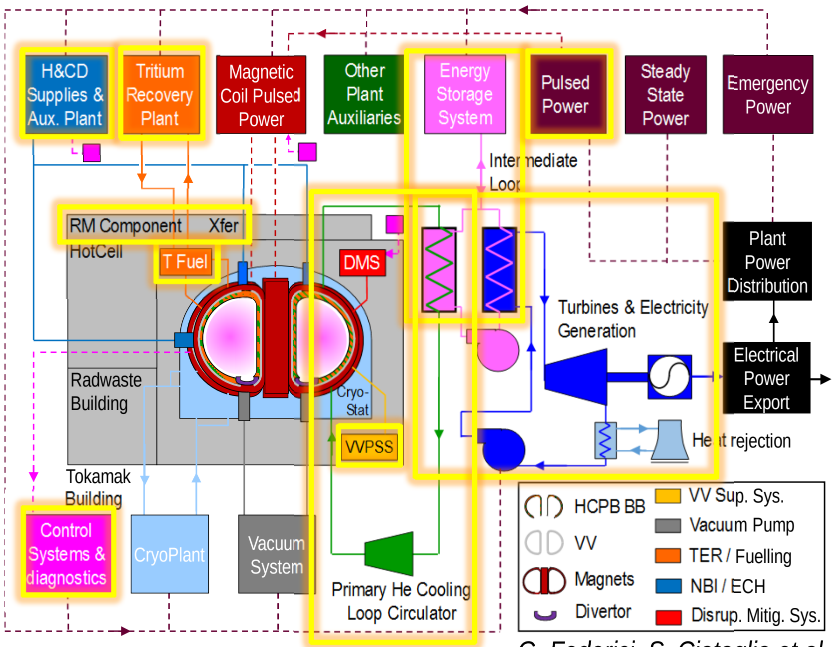
Introduction

- The EUROfusion’s Breeding Blanket (BB) Project
  - WP1-HCPB
  - WP2-HCLL
  - WP3-WCLL
  - WP4-DCLL

1. Concept definition and description
2. Design & Analyses
3. R&D functional materials

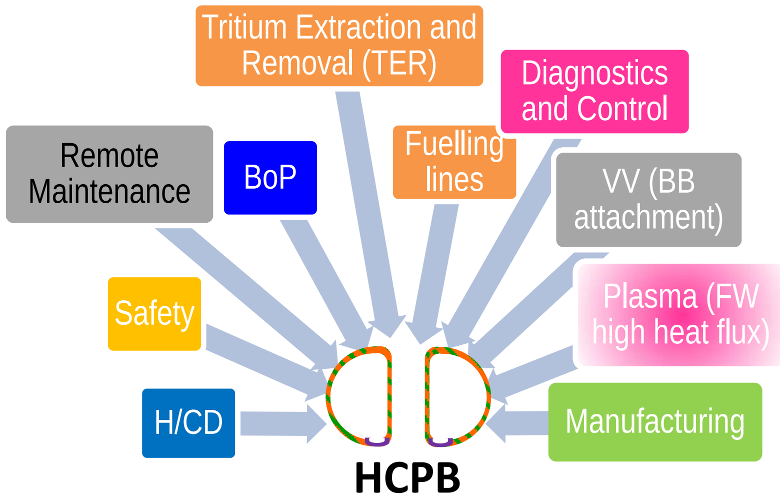
a. R&D Manufacturing & testing
b. R&D FW heat transfer augmentation
c. Systems integration activities
d. Key interfaces activities: BoP, Safety and TER

- Need for a holistic conceptual design!



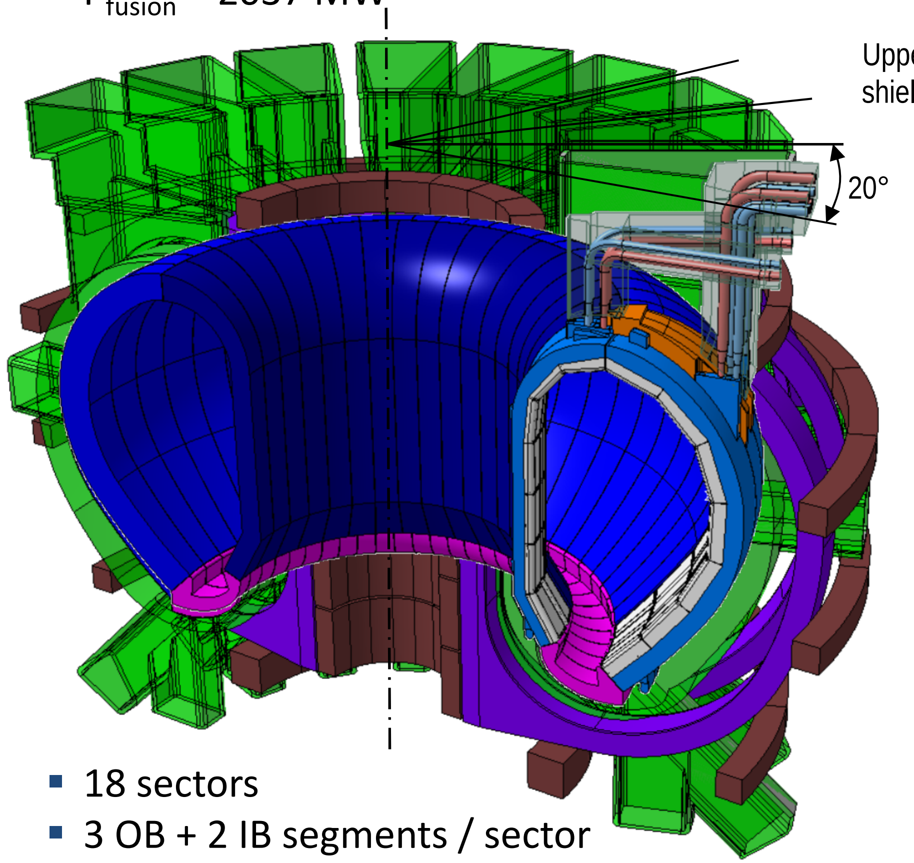
G. Federici, S. Ciataglia et al.

High degree of interactivity, BB design drivers!



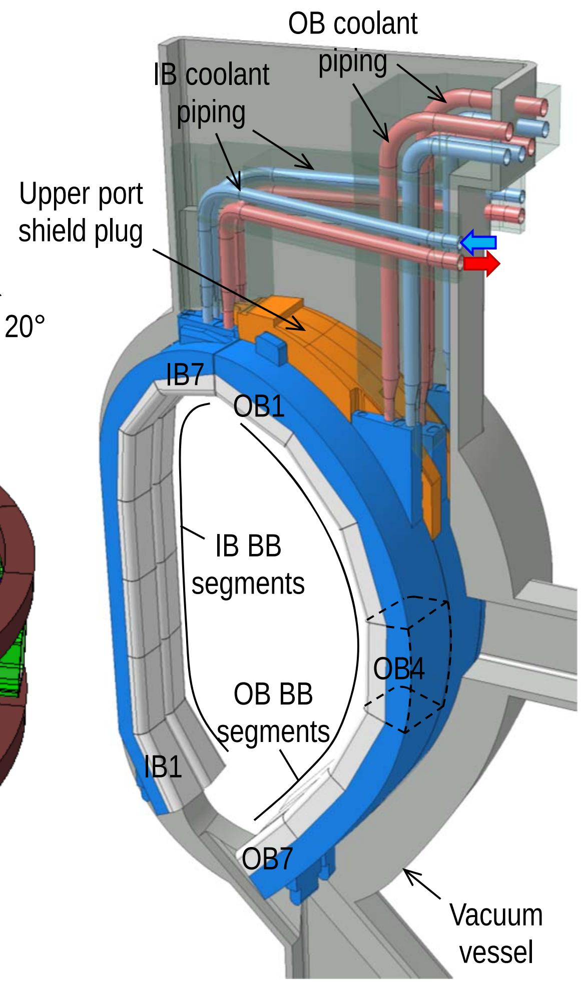
HCPB Design Description

- EU DEMO1 Tokamak baseline 2015
  - R_0 = 9.1m, a = 2.9m, A=3.1
  - Burn time = 2hr, dwell time 0.5hr
  - P_{fusion} = 2037 MW



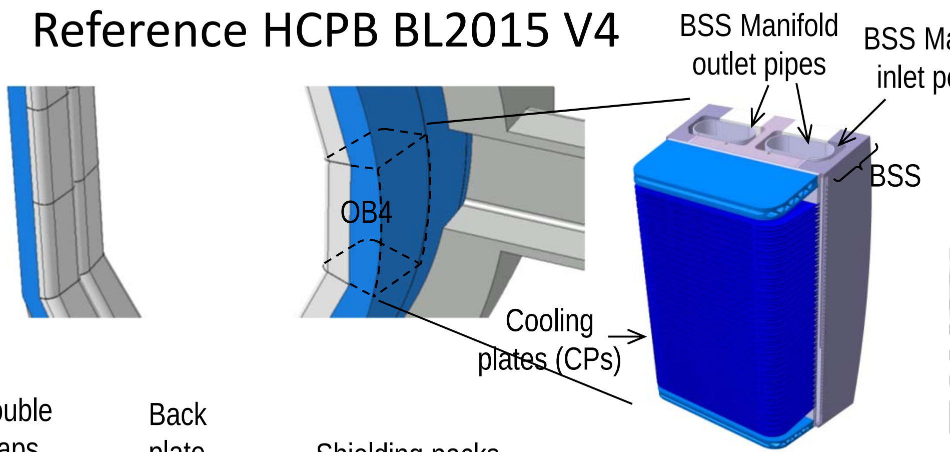
- 18 sectors
- 3 OB + 2 IB segments / sector

- Reference HCPB BL2015 V4

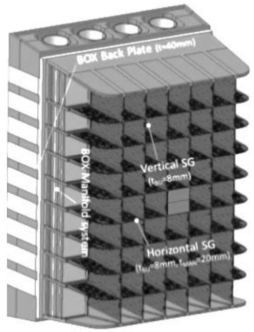


- 7 breeding blanket modules/segment
- Feedpipes through upper port
- OB inlet: DN300
- OB outlet: DN350
- IB inlet: DN250
- IB outlet: DN300
- Purge gas inlet/outlet: DN80

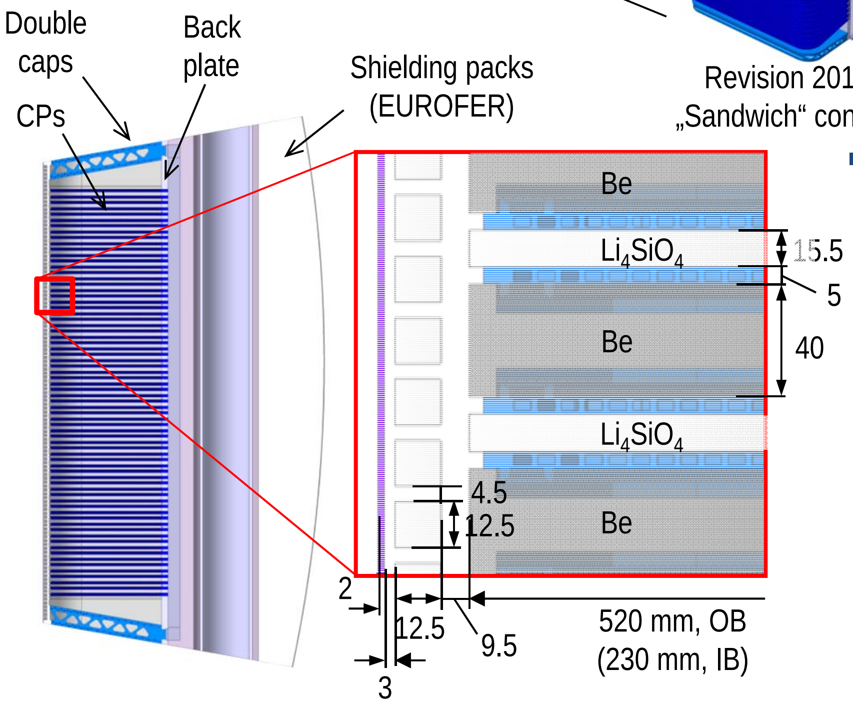
- Reference HCPB BL2015 V4



Revision 2015, „Sandwich" concept



Previously: „Bier-box", TBM-like



- Coolant:
  - Inert, transparent, 1-phase
  - He, 8 MPa, limit: Δp
  - T_{in} = 300°C, limit: DBTT
  - T_{out} = 500°C, limit: creep
- Purge gas:
  - He + 0.1vol% H_2
  - Alt.: He + 0.1vol% H_2O
- Materials:
  - Breeder: Li_4SiO_4 pebbles, Ø0.25-0.65mm (ref. TBM)
    - T_{max} ≈ 920 °C, limit: microstructure changes
    - T_{min} ≈ maximize (T-release rate)
  - Multiplier: Be pebbles Ø1mm (ref. TBM)
    - T_{max} ≈ 650 °C, limit: swelling, integrity
    - T_{min} ≈ maximize (T-release rate)
  - Steel: EUROFER97 / advanced EUROFER97
    - T_{max} ≈ 550 °C / 650 °C, limit: creep
    - T_{min} ≈ 350 °C / 350 °C, limit: DBTT

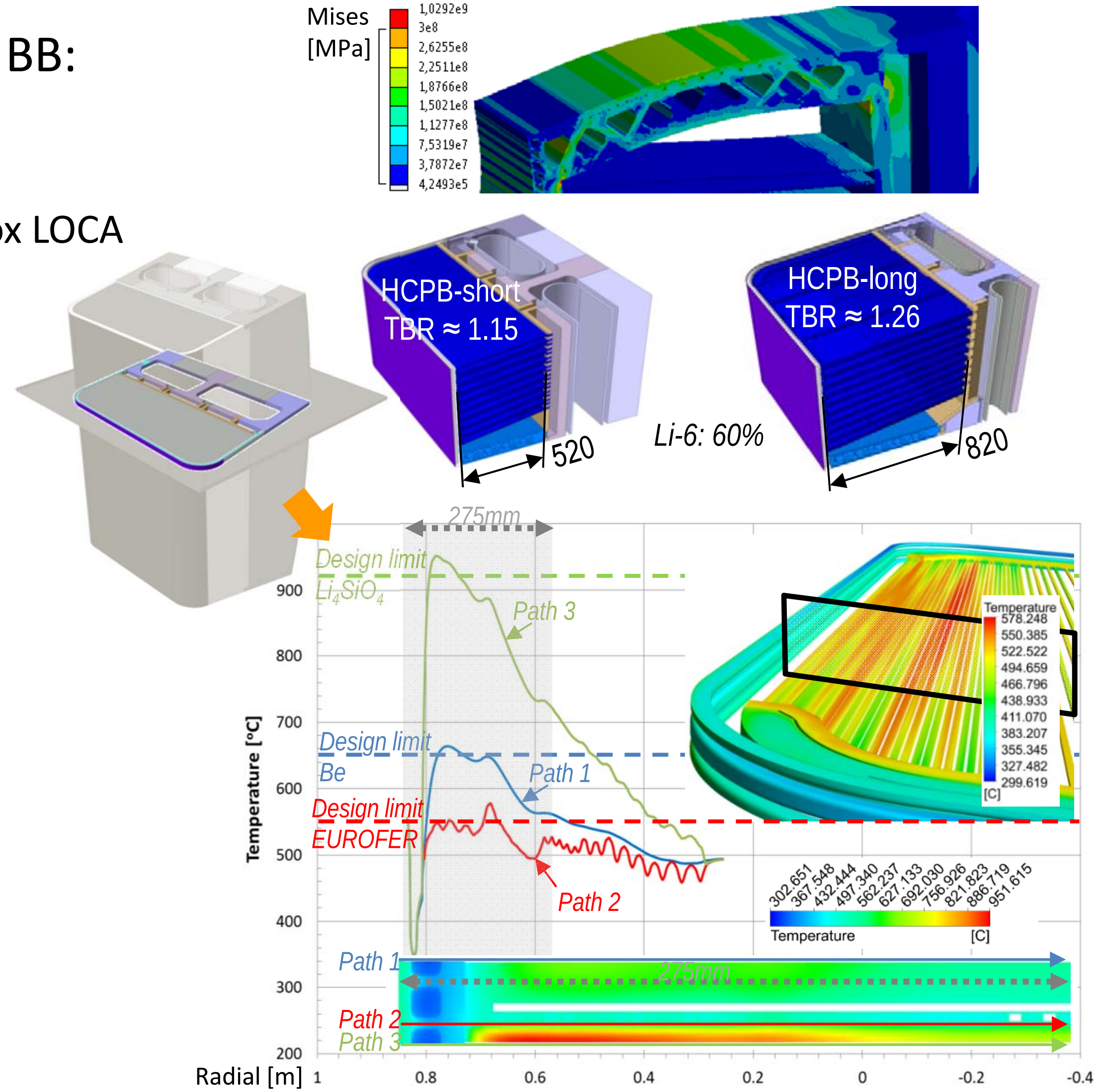
HCPB Design & Analysis Activities

- Design cycle of the DEMO HCPB BB:

Preliminary conceptual design

1. Thermomechanics (TM) under in-box LOCA
2. Neutronics
3. Thermohydraulics (TH)
4. TM normal/off-normal (disruptions) operation

Preliminary conceptual design



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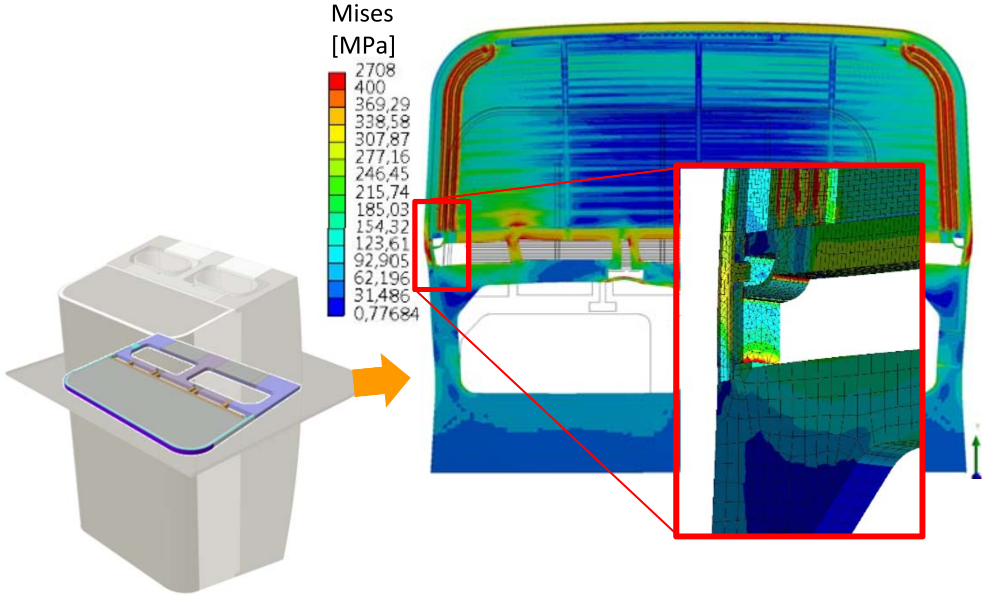
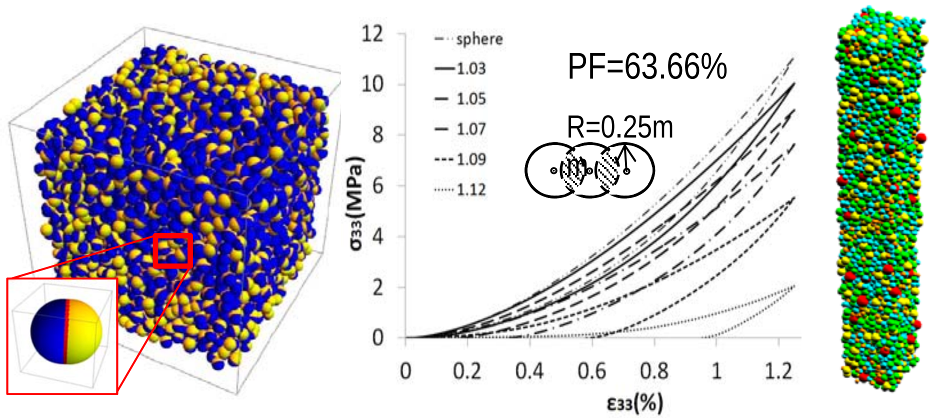
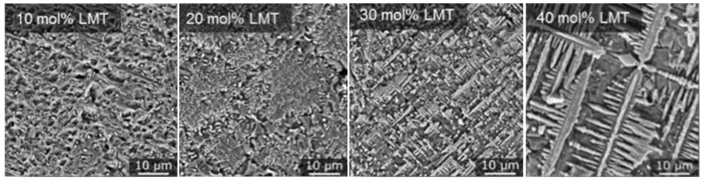


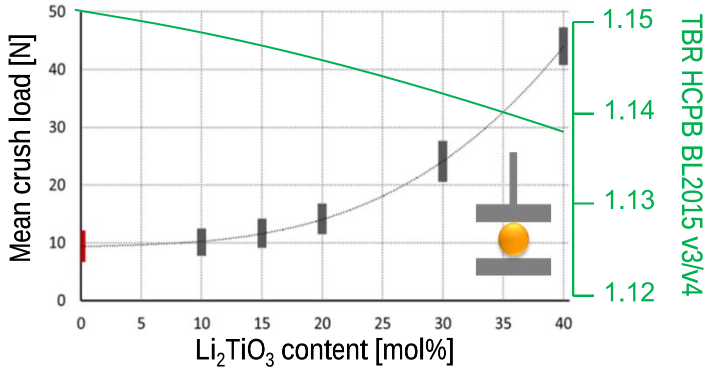
- Sequencial design cycle:
  - Difficulty to conciliate many aspects in each step: safety, manufacturing feasibility, nuclear + TH + TM, materials and costs
- Neutronics+TH+TM coupling studies
- Pebble beds thermomechanics: DEM



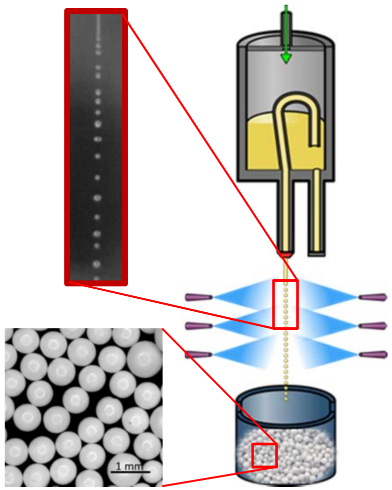
R&D Functional Materials: Ceramic Breeders

- Reference EU CB: Li_4SiO_4
- "Advanced CB": Li_4SiO_4 + additions of Li_2TiO_3
  - From eutectic (25mol% Li_2TiO_3), Li_2TiO_3 dominates
  - Li-Density↓, TBR↓, crush load↑↑





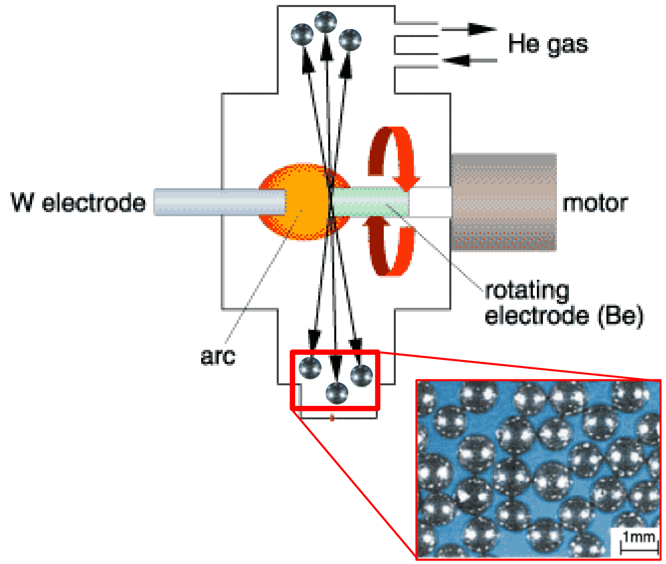
1. Production of Advanced Ceramic breeders (CBs)
   - The **KALOS** (**KA**rlsruhe **L**ithium **O**rtho**S**ilicate) Process
     - Melt processing at 1350 ÷ 1400 °C
     - Droplet generation by jet decay
     - Pebble solidification by liquid nitrogen spray
     - Optical monitoring by high-speed camera and image processing
     - Mean pebble size 650 µm, adjustable
     - Batch process (ca. 1kg), but straightforward scale-up



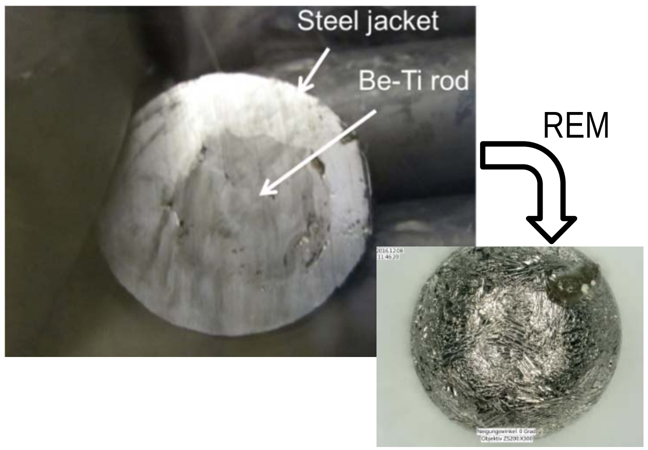
2. Qualification of advanced CBs
   - Composition, recycling, activation, conductivity, stability
   - Characterization unirradiated: corrosion, steel compatibility
   - Characterization irradiated: "T" (D) loading and release

R&D Functional Materials: Neutron Multiplier Materials (NMM)

- Reference EU NMM: Beryllium
- “Advanced Be-based NMM”: $Be_{12}Ti$, $Be_{12}Cr$…
  - Reduced content of Be: lower swelling, less water-reactive, increased upper temperature limit, but lower T-breeding



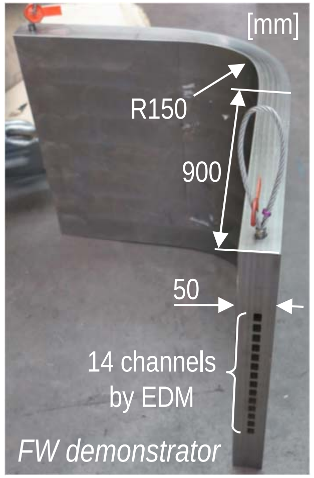
1. Production of Be NMM:
   - Reference EU: Rotating Electrode Method, REM (NGK, Japan)
     - ➢ Limited scalability to mass production, costly
   - Alternative cost-effective routes (under F&E contract):
     - ➢ Ball milling of Be-billets
     - ➢ Scrap from fluoride reduction method
2. Development of beryllides (KIT + TU Berlin)
   - Rod by hot extrusion Be-Ti powder mixtures + REM



3. Characterization
   - Unirradiated pebbles: T-release, oxidation, interactions…
   - Irradiated NGK pebbles: HIDOBE 01 & 02, <6000apm, <750°C
     - ➢ Creep, swelling,T-release, retention, activation…

R&D Manufacturing and Testing

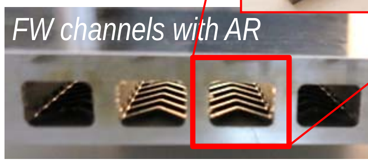
- Realization of key HCPB components:
  - Technology development and standardization
  - Mock-Ups (MU) qualification with codes & standards
  - Industrial contracts for long-term collaboration
- Main manufacturing and assembly routes:
  - Electrical Discharge Machining (EDM):
    - ➢ FW and CP cooling channels, with pilot hole
  - Cold forming for non-planar plates
  - E.g. ½ FW demonstrator: EDM + cold bending
  - Joining: Electron Beam welding
- Special manufacturing techniques
  - Selective Laser Syntering (SLS): complex parts
  - Hybrid assemblies: CNC + SLS + EB
  - FW artificial roughness (AR) with die sink EDM
- MU testing in He-loops (HELOKA, KATHELO)
  - Full-scale FW + sustained 1 MW/m² FW with AR



FW demonstrator


Hybrid manufacturing: CNC + SLS + EB

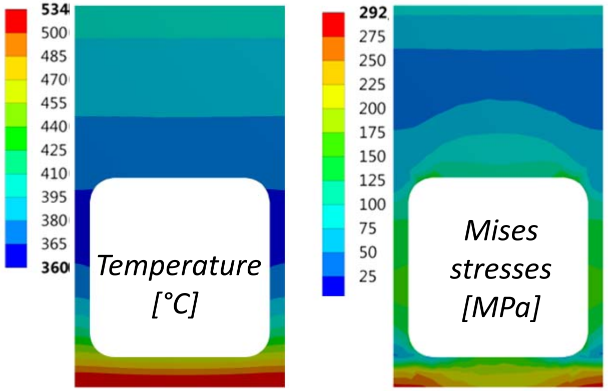
SLS multi-channel divertor module

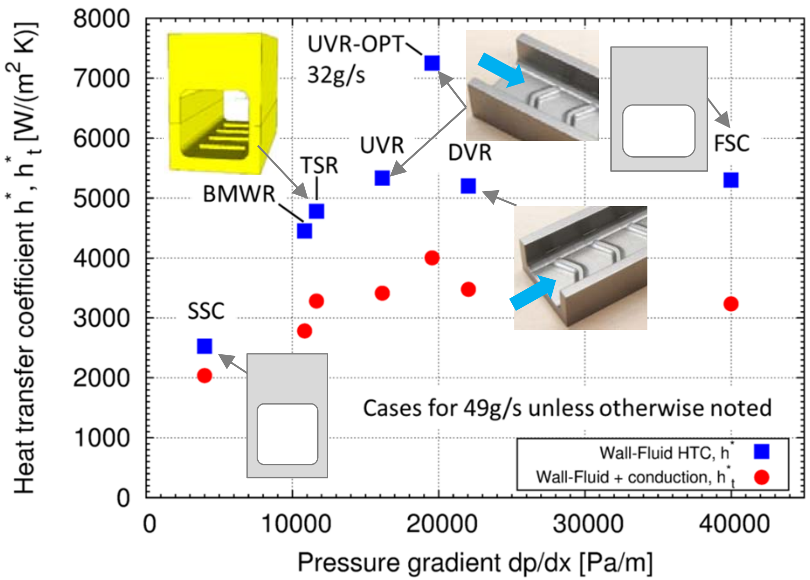

FW channels with AR

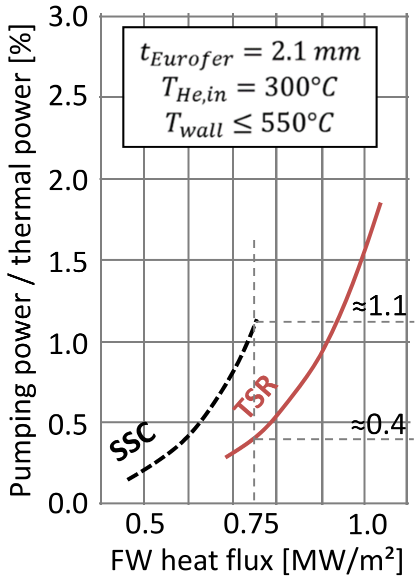

HElium-LOop KArlsruhe (HELOKA)

R&D FW Heat Transfer Augmentation

- Heat Transfer Augmentation by rib-roughening:
  - Motivation: HHF FW regions at upper and lower port
  - Ribs: HTC↑, but for same cooling, flow rate reduced $P_{pump} \propto \dot{m}^3$
  - Ribbed channels sustaining HHF for same P_{pump}!
- E.g. recent design point studies:
  - Squared channels of 12.5mm, 60 g/s channel (59 m/s)
  - Transversal ribs (TSR), HTC = 9500 W/(m²K), Δp = 0.52 bar/m



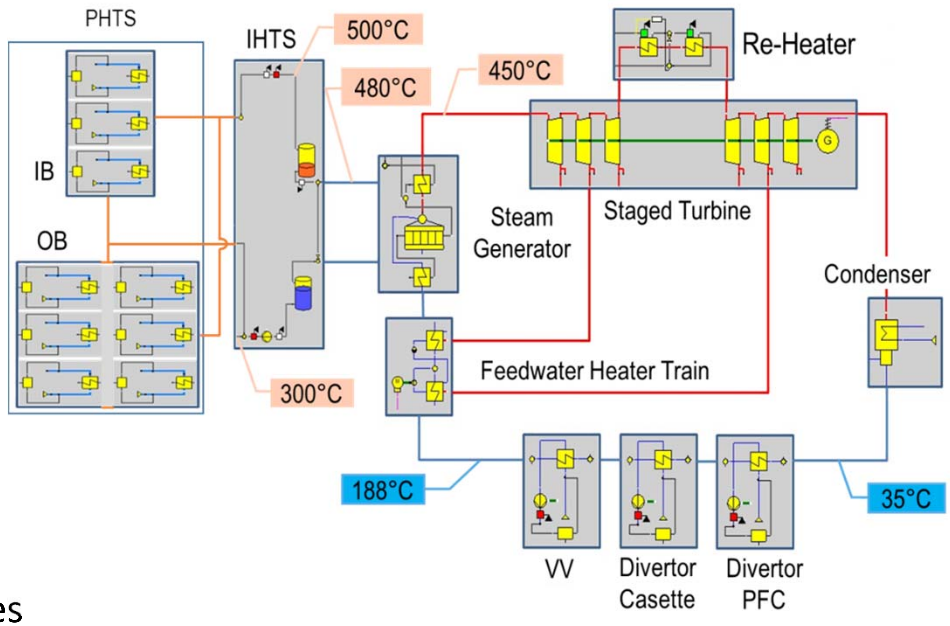




- Temps <550°C
- P stress ≈ 72 MPa ☺
- P+Q stress ≈ 393 MPa ☺
- 1 MW/m² can be sustained in a FW with TSR-ribbed He-cooled channels
- UVR HTC performance 1.15x better than TSR!

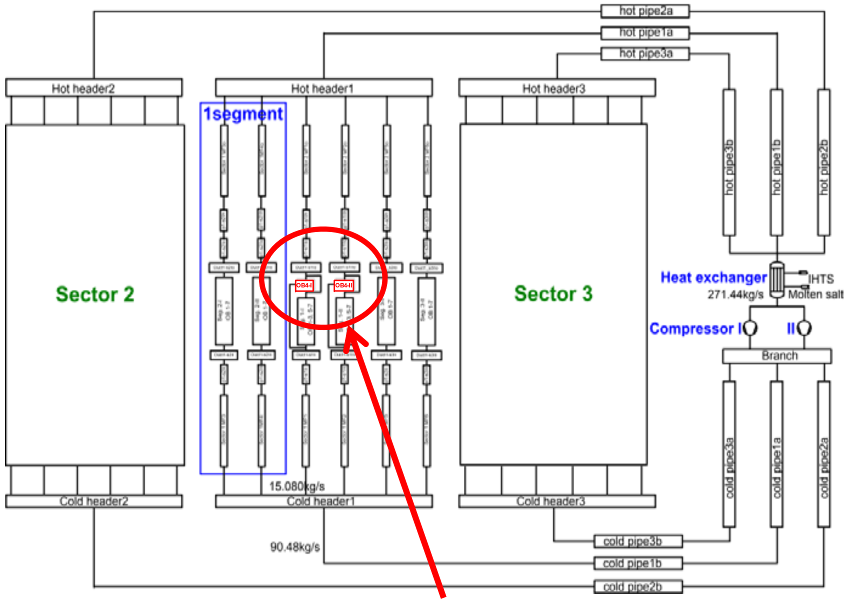
Key HCPB Interfaces Activities: BoP

- Integration of the HCPB BB into the BoP
- Currently, 3 cooling circuits:
  - PHTS: HCPB BB
  - IHTS: Energy Storage System (ESS) with molten salt (similarly as in Concentrated Solar Power)
  - PCS: Rankine cycle, water as working fluid



- Definition of components & loops characteristics:
  - 3 IB + 6 OB loops, 2 circulators / loop
  - 1 IHX / loop coupling PHTS loops with to ESS
  - Steam Generator coupling ESS with PCS
  - PCS: “conventional”, but with many heat sources
- Architecture of BoP
  - Credibility of a HCPB-DEMO depends on compatibility with state-of-the-art technology!
  - Some tech. extrapolation assumed for circulators: available 5-6MW, needed ≈8MW
  - η_{th}≈36%, high $T_{He,out}$ advantage shadowed due to particular DEMO features (ESS)
  - <u>Synergies at BB design level</u>: get closer to AGRs, GenIV-HTRs values: T_{out}↑, P_{circ}↓, *off-the-shelf* tech.

- FFMEA->PIEs->critical events (within DBA)
  - Loss of flow accident (LOFA) in FW
    - ➢ CFD model set-up for 1÷2 channels
    - ➢ RELAP5-3D for mitigating features (circuit / circulator redundancy, plasma shutdown)
    - ➢ Codes validation with LOFA experiment
  - Deterministic LOCAs with MELCOR186:
    - ➢ In-box LOCA (1 CP break), in-vessel (FW channels break), integrated in 1 OB loop PHTS

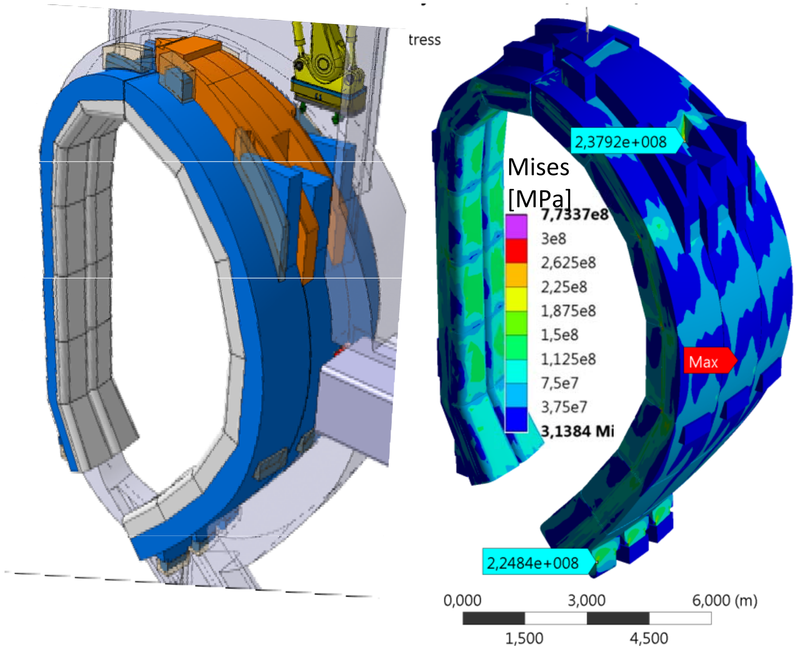


detailed 1x OB4 module

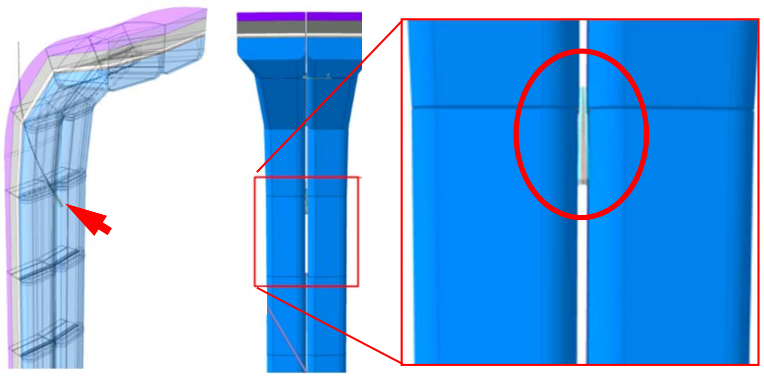
- He OB inventory: 9.5 ton ⇒
  - Combined VVPSS & EV concept, EV potentially reduced ≈80%
- Simulation of runaway e^- event
- Future work:
  - Analysis of ex-vessel LOCA
  - Modelling of the HCPB BB integrated into ist PHTS and auxiliary systems of BoP using RELAP5-3D
  - <u>Synergies at BB design level</u>: pipework upper port, study possibility to p_{He}↓ (HTRs, 6-7MPa)

Systems Integration Activities

- Development of a HCPB BB attachment
  - Key interfacing component between VV and BB
  - Attachment system
    - ➢ Defines segments kinematics (affects RM)
    - ➢ Affects segments internal stresses
  - EM analyses of disruptions events -> input EM forces
  - Analyses of full HCPB DEMO sectors with EM + thermal + gravity + coolant pressure loads



- Fueling lines integration:
  - Current baseline: 1 line between IB segments
  - Affected BB region: increased gap -> n streaming
  - Further work:
    - ➢ On cooling: passive or active
    - ➢ On fixation: VV or BB
    - ➢ Thermohydraulics + thermomechanics



Summary, Challenges and Future Plans

- HCPB R&D focused on BB specifics + key interfaces driving the design
- HCPB development achievements (with respect to former concepts):
  - Design simplification: thermohydraulics, assembly and manufacturing, pipework
  - HCPB actively working with interfaces to propose mitigating actions for a credible holistic solution!
  - Advanced CBs: significant gains in strength, up-scalable production
  - Be: alternative, cost-effective production routes
- Challenges:
  - EU Roadmap: "pragmatic approach" -> Reliability and Availability -> Mature technologies preferred
  - High uncertainties in DEMO architecture -> resilient, flexible BB designs
  - FW HHF cooling without penalizing Δp
- Future design and R&D plans
  - Redefine HCPB concept to reach figures with gas-cooled reactors (HTRs/AGRs): P_{circ}, p_{He} , ($T_{He,out}$)
  - Broadening palette of CB (for higher T breeding) and NMM (beryllides, Be alternatives)

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