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Advancements in the design of the DEMO driver blanket system during the EU DEMO Pre-Conceptual Design Phase: Overview, Challenges and Opportunities

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KIT Karlsruher Institut für Technologie

Breeding Blanket Project

CCFE Ciemat cea ENEA IPP KIT Wigner

32nd SOFT 2022

32nd SYMPOSIUM ON FUSION TECHNOLOGY

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Outline

1. **Introduction**
2. The BB System and high level requirements during PCD
3. The WCLL concept and the WCLL TER
4. WCLL main performance achievements
5. The HCPB concept and the HCPB TER
6. HCPB main performance achievements
7. Challenges in system design and plant integration
8. Opportunities
9. Summary and outlook

1. Introduction

- WPBB constituted in 2014 inside PPPT in EUROfusion (H2020)
  - Major goal: achieve design for BB and TER at PCD level, compatible with PPPT DEMO plant requirem. and interfaces
  - After recommendation of Fusion Roadmap, 4 BBs: HCPB, HCLL, WCLL, DCLL
- Critical re-evaluation of BB design strategy in 2017-2018
  - Assessment of EU DEMO BB and EU ITER TBM by independent expert panel
    - Revision of programs to streamline them
    - Considering time left to reach maturity levels: DEMO shall only consider BB designs requiring limited tech extrapolations
  - Identification of most mature BB designs: WCLL and HCPB, remaining gaps with R&D
  - Choice offers least uncertainties/extrapolations, allows testing 2 coolants and 2 functional materials in 2 EU TBMs
- New strategy after re-evaluation included in latest EU Fusion Roadmap, several new aspects
  - DEMO as Component Test Facility for the BB
    - „driver“ BB allowing for TBR and P_{el} + „advanced“ BB that can cover requirements for FoaK commercial FPP (CoE, >100 dpa)
  - Staged design approach concluded by Gate reviews (milestones, findings, achievements, guidance further phases)
    - PCD phase, G1 (2014-2020): SE approach, design solutions prioritizing TRL, industrialization and ↓cost
    - CD phase, G2 (2021-2024) + G3 (2025-2027): WPBB prepare work for BB driver selection in G2 and concept validation in G3
    - After successful G3, way paved for ED phase from 2030 onwards

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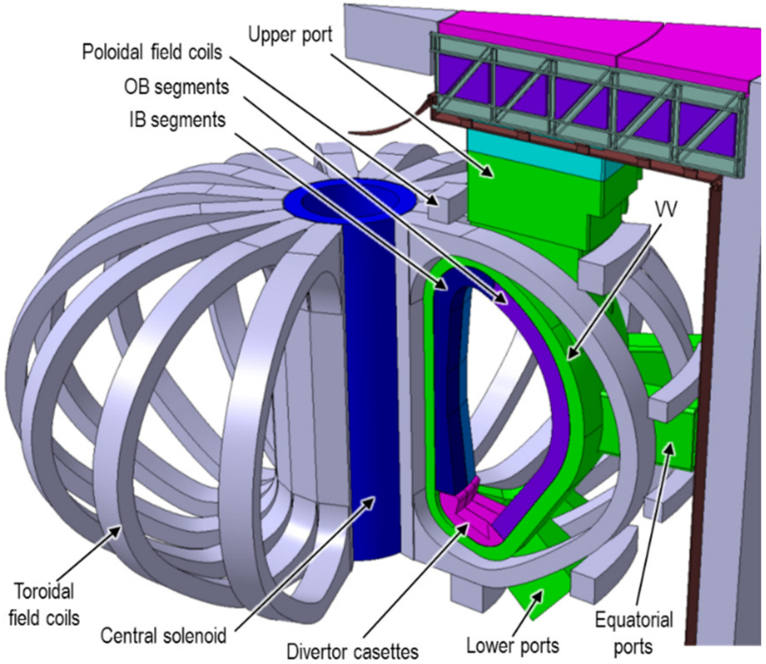
1. The BB System and high level requirements



- DEMO baseline 2017, main stakeholder requirements
  - Single-null, P_{fus}=1998 MW, P_{el}≈500 MW
  - 16 TF coils =>16 sectors, NWL ≈1 MW/m², t_{burn}=2 h, t_{dwell}<600s
  - 1 sector: BB split in single module segments: 3 OB + 2 IB
  - BB vertical maintenance through upper ports
  - BB supported on VV through BB attachment system transfers EM and weight loads to VV
  - BB feeding pipes upper port, eventually few in lower port also
  - TBR_{req}=1.05 (fuel cycle), TBR_{target}=1.15 (fuel cycle + modeling)
  - Progressive BB operation:
    - "starter blanket" ≈2fpy
    - "second blanket" ≈ 5fpy
- Main BB interfaces
  - Main interfaces: LIM, H/CD, FLs, PHTS, RM, VV, VVPSS and TER
  - Candidate driver BB concepts: WCLL and HCPB

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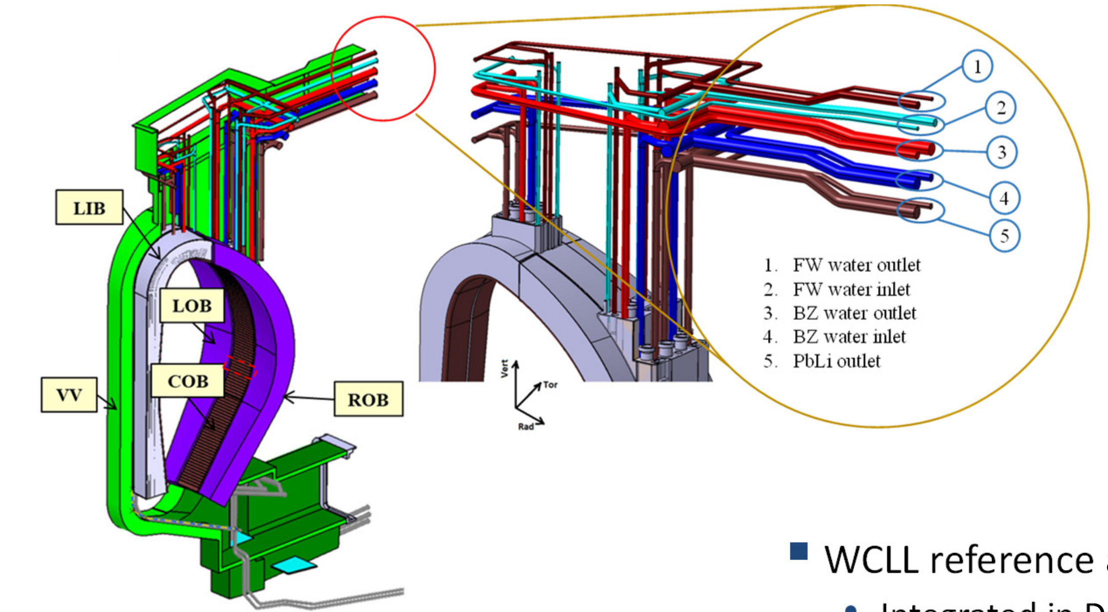
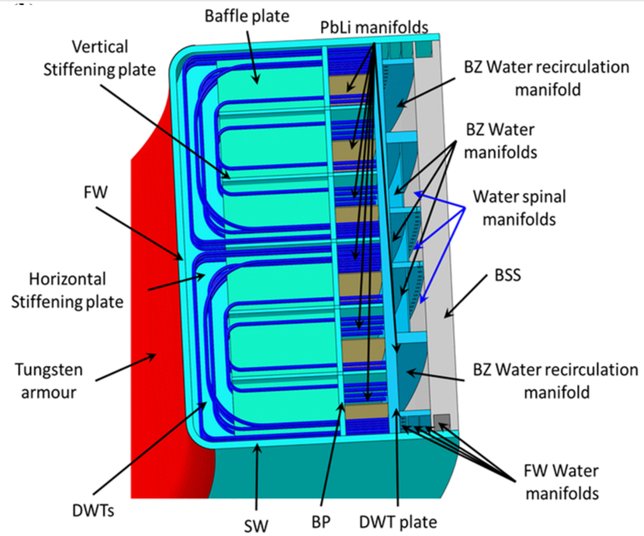
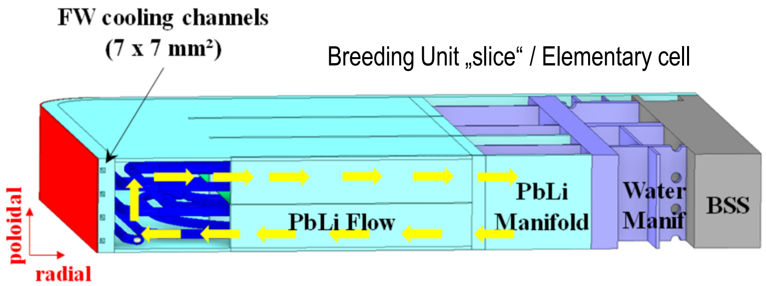
3. The WCLL Concept

P. Arena, P-1.259





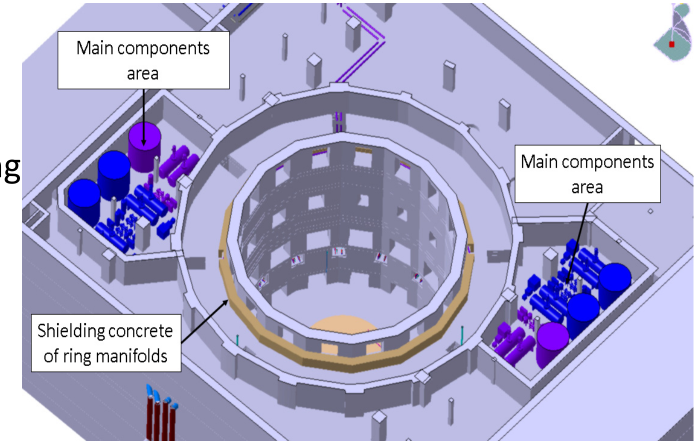


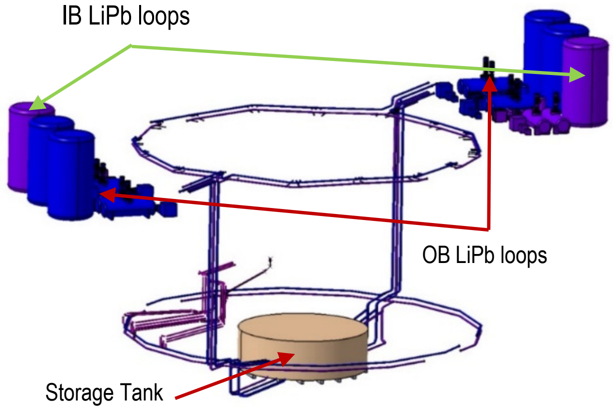
- WCLL reference architecture description
  - Integrated in DEMO BL2017, design result after iterations in PCD
  - Water coolant in PWR conditions: 15.5 MPa, 295-328°C
  - 2 parallel, separated cooling loops per segment: 1xFW, 1xBZ
  - Pb-15.7%Li as n-multiplier (Pb), T-breeder (^{6}Li 90%) & T-carrier
  - EUROFER97 RAFM as structural material

3. The WCLL TER

M. Utili, P-2.93

- 4xOB + 2xIB loops, 3.5 km piping (TER-BBS-ST), 1400 m^3 PbLi
- Loop Functions:
  - T extraction and removal from PbLi, heating, purification & rad. shielding
- Each WCLL TER loop:
  - Pumping System: PbLi circulation, mechanical pumping (min. leakages)
  - Purification System: He removal system + ACP removal system
  - Tritium Extraction Unit (TEU)
- TEU technologies being investigated
  - Gas Liquid Contactor
  - Permeator Against Vacuum
  - Liquid Vacuum Contactor
- Mock-ups of 3 TEU technologies being tested in TRIEX-II (ENEA) and CLIPPER (CIEMAT), extensive R&D to reduce uncertainties in T transport parameters and structural materials





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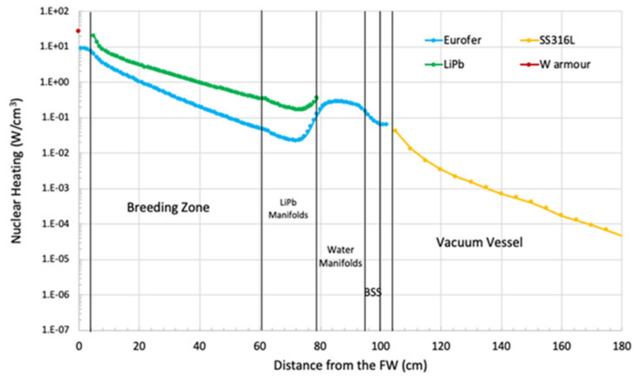
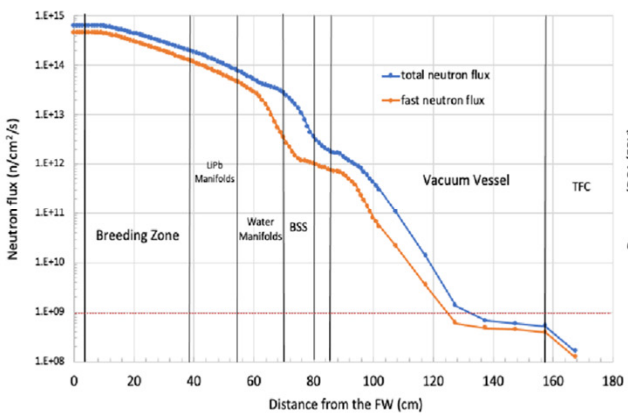
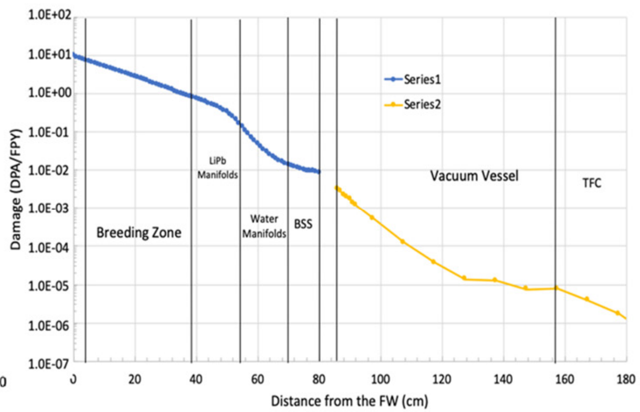
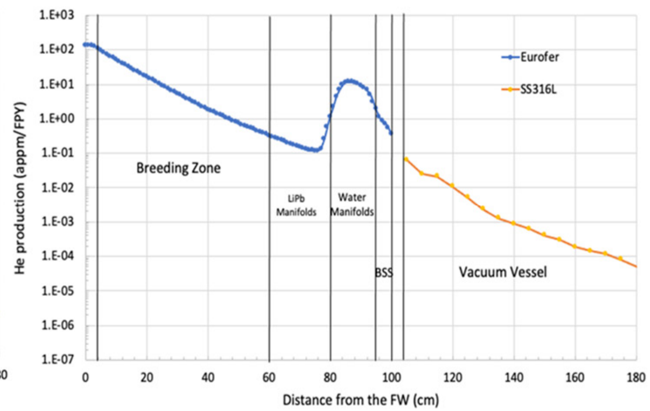
4. WCLL main performance achievements

- Neutronics
  - Fully heterogeneous MCNP neutronics model (MCNP5 v1.6, JEFF 3.3)
  - Tritium Breeding Ratio, TBR=1.14, marginally lower than TBR_{target}=1.15
    - Newer TH iterations have led to larger #DWT and FW channels in to divertor region
  - Excellent shielding performance towards the VV and TF coils
    - Fast neutron flux ≈ $4 \cdot 10^8 < 10^9$ n/cm²s
    - Integrated radiation damage in VV ≈ 0.02 <2.75 dpa in 6 fpy
    - Integrated He production in VV ≈ 0.6 <1 appm in 6 fpy





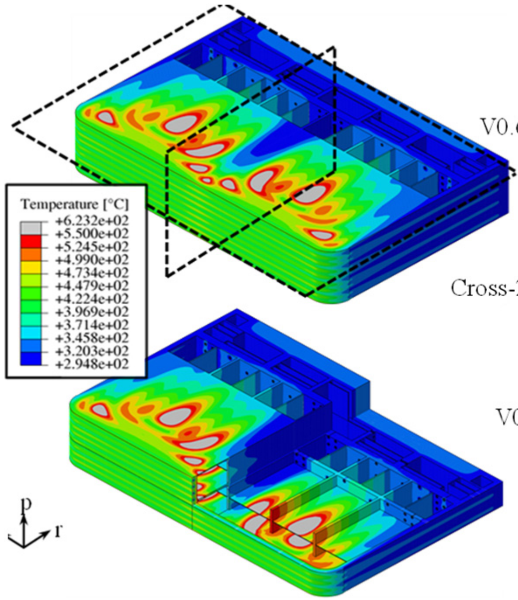


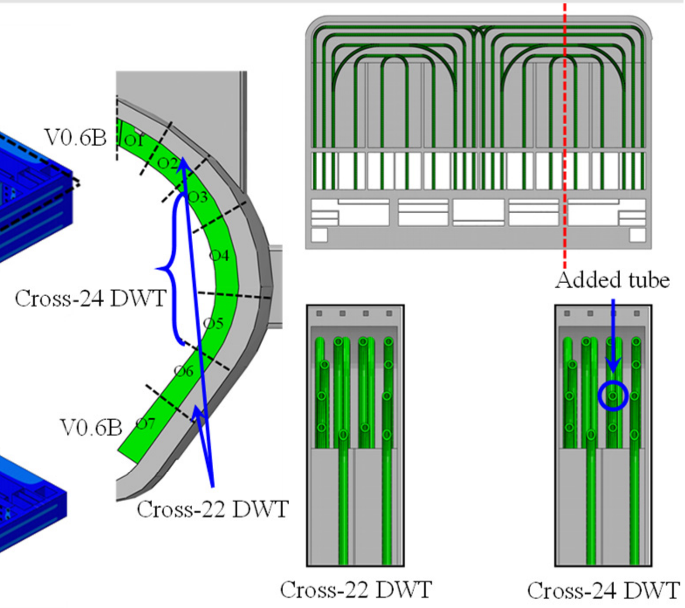


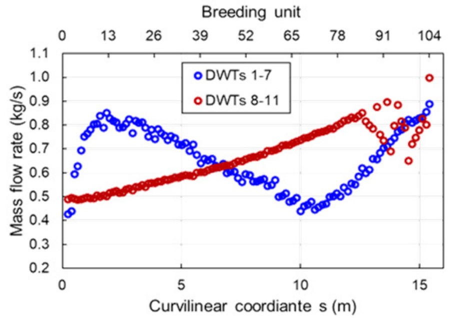
4. WCLL main performance achievements

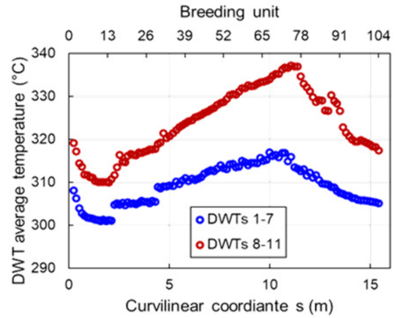
- Thermo-hydraulics
  - Optimization of FW and DWT layout in OB
    - Power density not unif. poloidaly => segment subdiv. in 7 regions, identif. of DWT layout for each
    - Heat flux non uniform density => FW channel shaping subdivision and identification of layout
    - FW layout: 4 channels per unit cell enough to remove heat flux from plasma in 5/7 regions, 6 channels needed in O6 and O7
    - DWT layout: O1 & O7 => original layout; O2 & O6 => cross-22 DWT; O4 & O3 => cross-24 DWT
  - Optimization of FW and DWT in IB ongoing
    - Preliminary result: #DWT from 20 to 22
  - BZ water manifold flow distribution
    - Important difference in $\dot{m}$ and T_{out} along segment
    - Need for orifice distribution if manifold is kept

L. Melchiorri, P-1.224





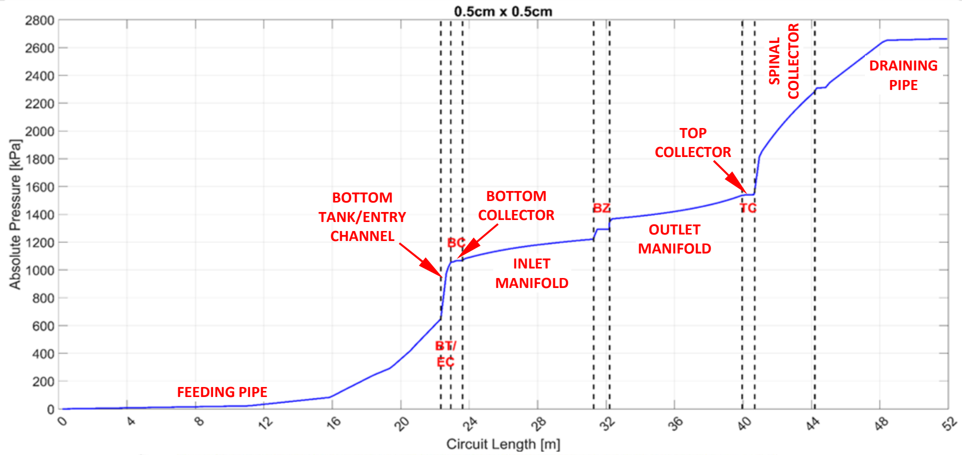


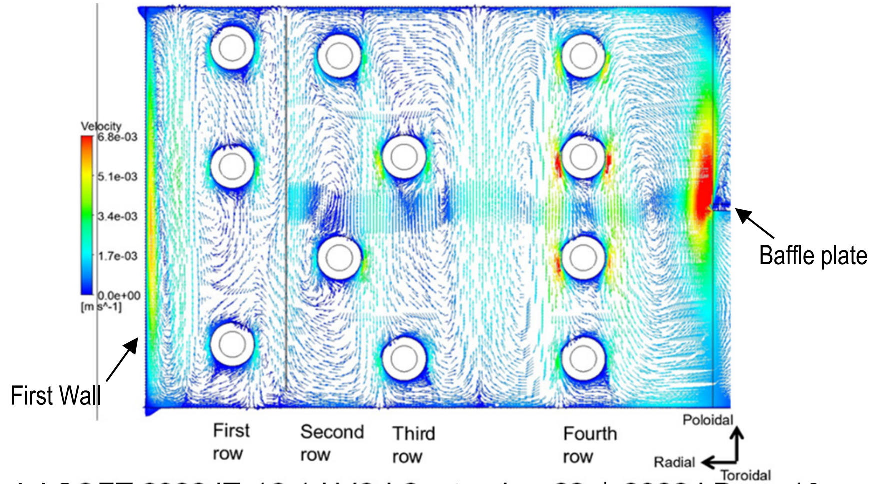


4. WCLL main performance achievements

- Magnetohydrodynamics (MHD)
  - Methods developed to study coupled effects MHD-TH
  - Hydraulic behaviour of PbLi flow in in-VV piping
    - Pressure evolution of COB + feeding & draining pipes
    - Main Δp: feeding & draining pipes (crossing of mag. field) and entry channel and spinal collector
    - $\Delta p_{total,OB}$ = 2.6 MPa >2.0 MPa design limit for pumping system
    - Magnetic fields in IB side higher => higher $\Delta p_{total,IB}$ expected
  - Heat transfer and flow behaviour at BZ unit cell in presence of poloidal + toroidal magnetic field
    - Medium size vortices develop between rows of DWT
    - If only tor. mag. field => larger vortices around entire rows
    - No significant differences in thermal field (high magnetic field tends to suppress convective heat transfer in BZ)

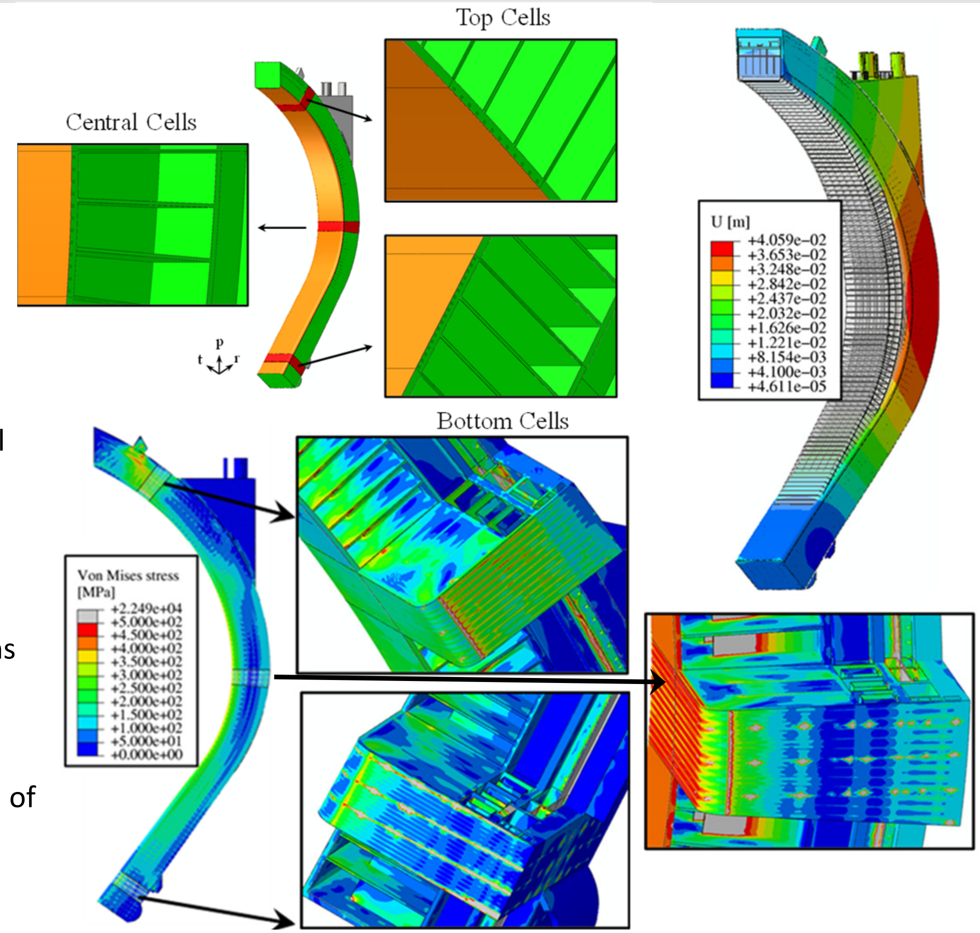
C. Mistrangelo, P-2.18 | S. Siriano, P-1.221





4. WCLL main performance achievements

- Thermo-mechanics
  - Load combinations (LCs) assessed against RCC-MRx
    - Normal operation (NO) – Level A (Cat I)
    - Up-VDE – Level C (Cat III)
    - Over-pressurization (OP)/in-box LOCA – Level D (Cat IV)
  - Thermo-mechanical analyses (OB) in 2 steps:
    - Thermal, gravity, pressure, restraints, (EM) fields in global model => identification of high stressed fields => sub-model
    - Thermal field interpolated to entire COB segment, 3 areas identified for local analyses by sub-modelling, LCs applied
  - Assessment through stress linearization:
    - Good global behaviour in NO, yet IPFL fails at some locations
    - Most critical region: equatorial, due to constrained thermal expansion of the segment under effect of BB attachment
    - Thermal stress of segments seems the driver: deep revision of the BB attachment is needed to ease thermal expansion



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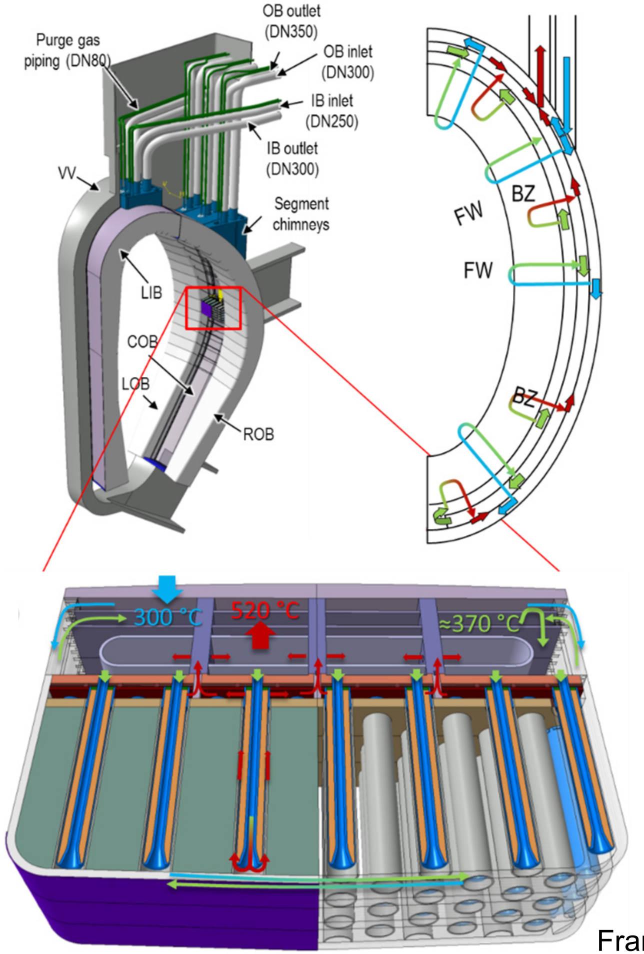
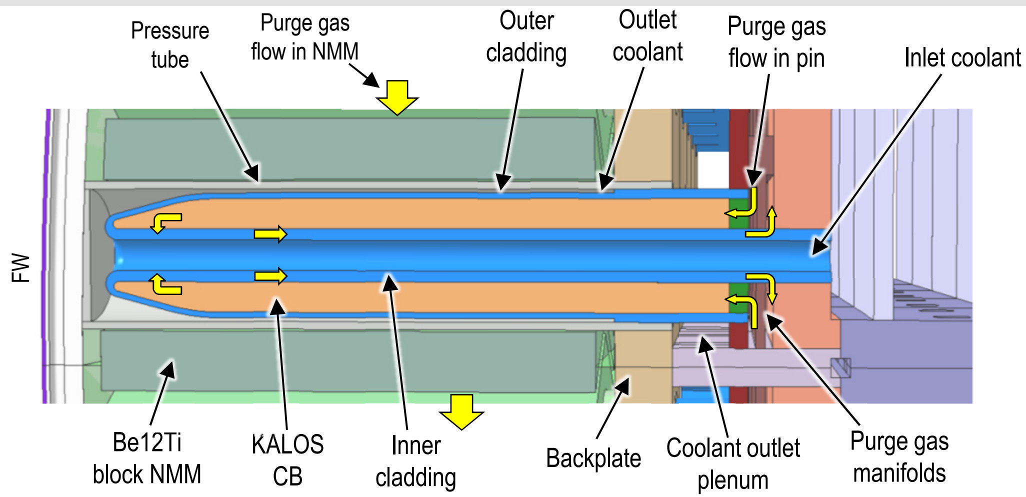


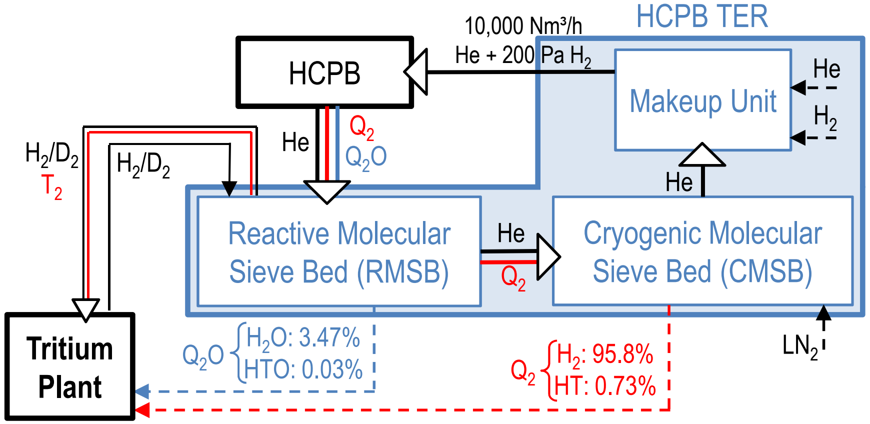


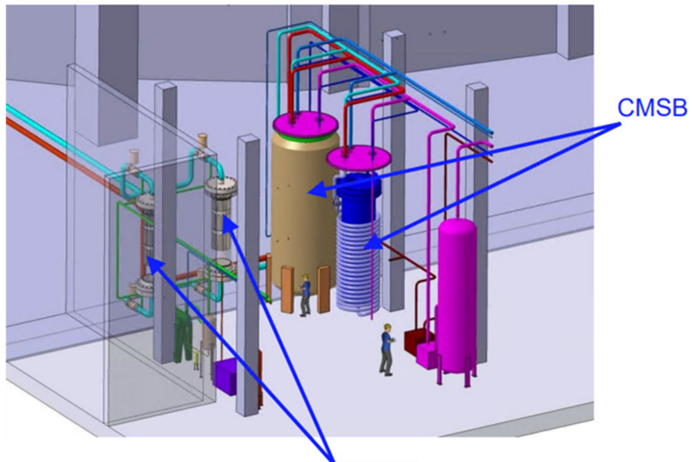
- HCPB reference architecture description
  - Integrated in DEMO BL2017, design result after iterations during PCD
  - Helium coolant: 8 MPa, 300-520°C, 1 single loop: FW and BZ in series
  - ACB pebbles (Li_4SiO_4 + 35%mol Li_2TiO_3) as tritium breeder (^6Li 60%)
  - $Be_{12}Ti$ hexagonal prismatic blocks as neutron multiplier
  - EUROFER97 RAFM as structural material
  - Purge gas: He + 0.1vol% H_2/H_2O @0.2 MPa

5. The HCPB TER

G. Ana, P-2.253

- 1 loop, He+200Pa H_2 purge gas 0.2 MPa, 10 000m³/h
- Loop Functions:
  - T removal from purge gas & purge gas conditioning
- HCPB TER loop:
  - Reactive Molecular Sieve Bed (RMSB, trapping/adsorption Q_2O) + Cryogenic Molecular Sieve Bed (CMSB, Q_2 adsorption at 77 K) + Circulator + Makeup Unit
- Reference purge gas: Q_2 species => T permeation issue
  - He + H_2 + H_2O ("wet") purge gas, may allow full Q_2 oxidation (i.e. TER only with RMSB), but corrosion issue M. Draghia, P-2.260
- Getter Bed as alternative to CMSB under study
  - No need for LN_2, TiH/ZrH considered, attention to residual T
- HCPB reliability issue: 8 MPa purge gas operation option
  - LN_2 consumption with 8 MPa purge gas prohibitive => Getter Bed instead of CMSB required





Getter Bed (alternative to CMSB)

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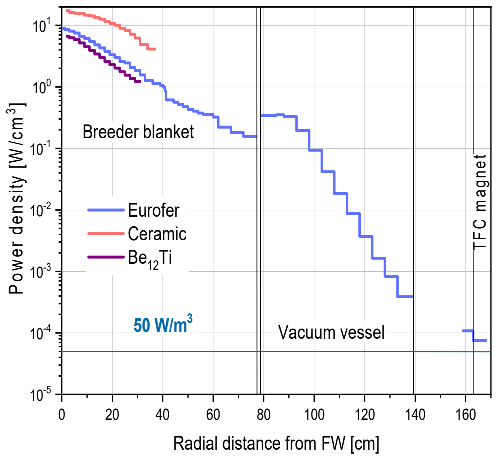
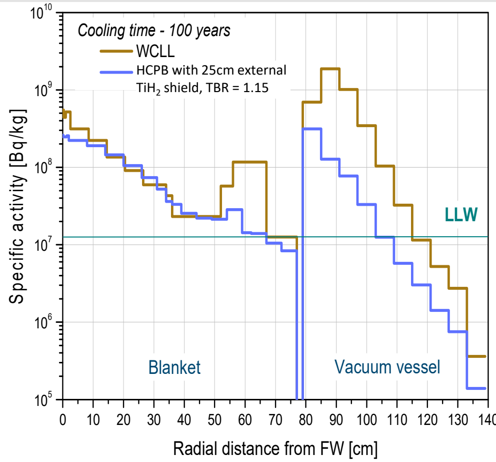
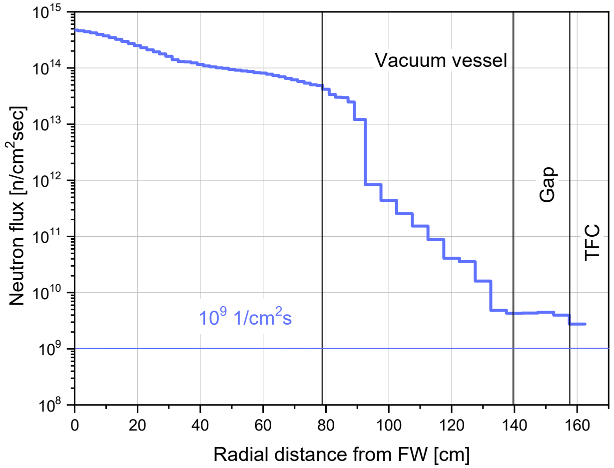
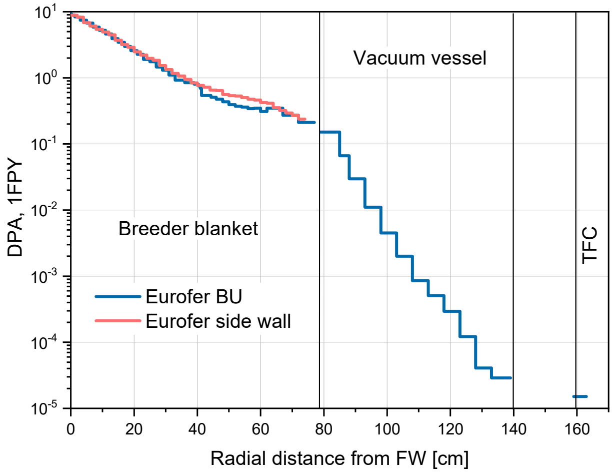
6. HCPB main performance achievements

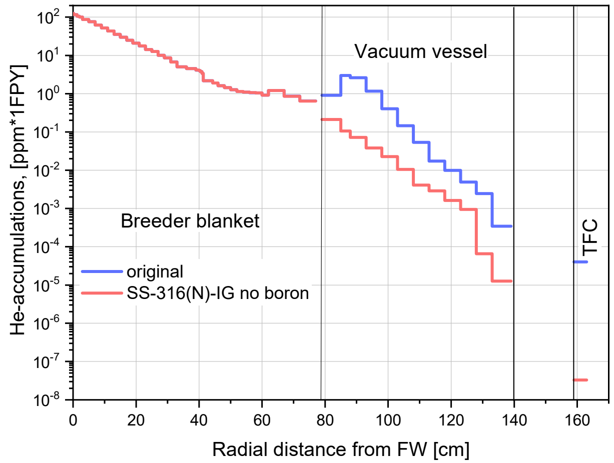
- Neutronics
  - Neutronics on fully heterogeneous model
  - ^{6}Li 60%: TBR ≈ 1.20, ^{6}Li 40%: TBR ≈ 1.16
    - Margins can deal with modeling uncertainties (±3%, 2σ)
  - Shielding performance marginally below the limits
  - Concern of VV activation: studies on a n-shield
    - dpa in VV ≈ 0.130dpa/fpy (WCLL ≈ 1/10 HCPB)
    - Best mats.: TiH_2, $ZrH_{1.6}$, $YH_{1.75}$, WC, B_4C (also int/ext)





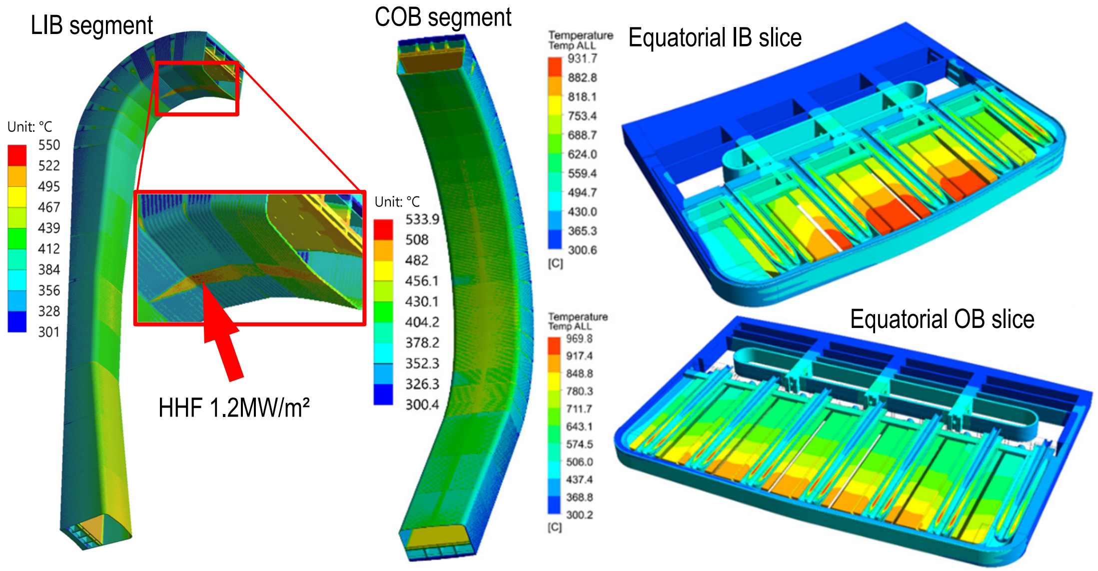


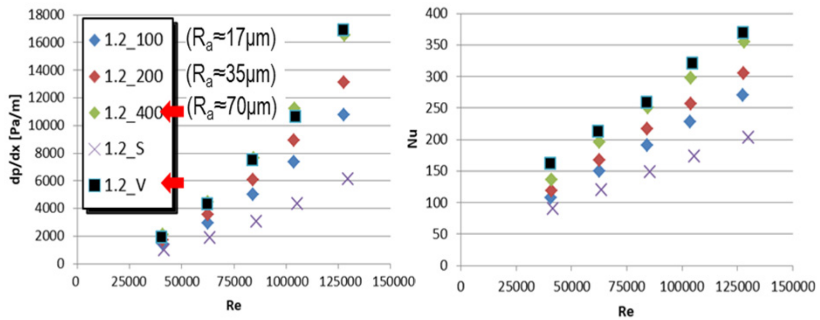




6. HCPB main performance achievements

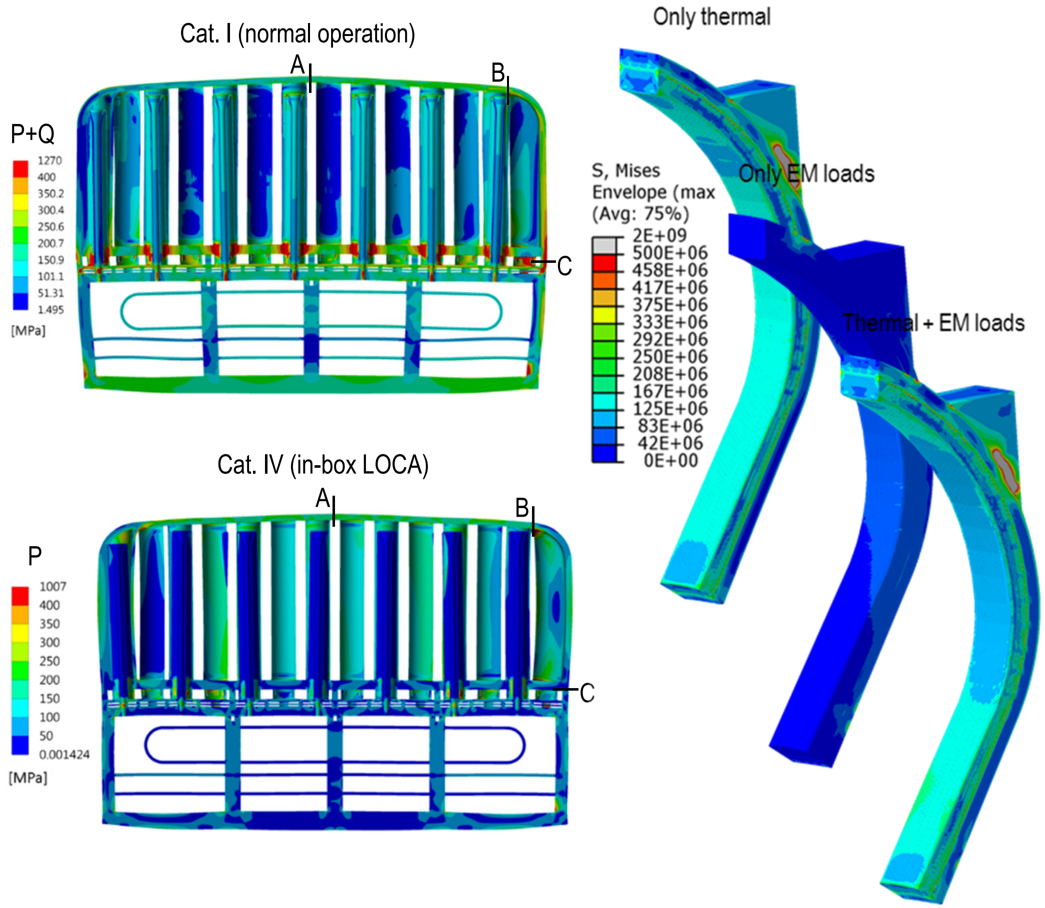
- Thermo-hydraulics
  - Global simplified FEM and CFD analyses
    - FEM analyses: check adequacy of FW design (geometry, $\dot{m}$ settings, turbulence promoters) against inhomogeneous plasma and BZ heat fluxes
    - Full segment CFD isothermal analysis: understanding Δp in segment and $\dot{m}$ distribution
      - ✓ $\dot{m}$ distrib. in FW & BZ ≈homogeneous (±15%)
      - ✓ Δp_{IB}≈0.55 bar, Δp_{OB}≈0.8 bar => P_{circ}≈90 MW
      - ✓ Δp_{FW}=50%, $\Delta p_{out\text{-}to\text{-}COB}$=13%, $\Delta p_{COB\text{-}to\text{-}out}$=30%
  - Local CFD analyses
    - Thermal field in equatorial region (most loaded section): globally fulfilling design limits, local peaks in ACB and low stress regions of EUROFER97
    - Analyses to understand limits of high heat flux capability: up to 1.2 MW/m² Δp < 0.64 bar





6. HCPB main performance achievements

- Thermo-mechanics
  - LCs assessed against RCC-MRx
    - Normal operation (NO) – Level A (Cat I)
    - Up-VDE – Level C (Cat III)
    - In-box LOCA – Level D (Cat IV)
  - Normal operation (Cat I, Level A):
    - Slice models in eq. OB, good global behaviour except for backplate location due to large Q stress
  - Up-VDE (Cat III, Level C):
    - Qualitative steady state global analyses at 2 up-VDE timesteps where resultant F and M peaks
    - Stress from EM loads low, thermal stress driver, need to revise attachment and flow strategy in manifold
  - In-box LOCA (Cat IV, Level D):
    - Good global behaviour except IPFL mode, however, nearly fulfilment with inelastic analysis route



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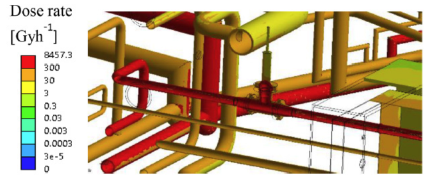
7. Challenges in system design

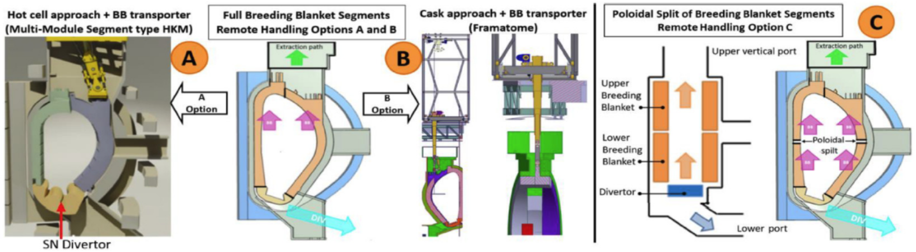
- General risks:
  - **Low reliability**: Number of welds against in-box and in-VV LOCA drivers T. Pinna, FED 161 (2020)
  - **Low readiness of manufacturing tech. for BB segments, W-armour and C&S and costs**
  - **EUROFER97 embrittlement during operation:** DBTT shift in EUROFER97when irradiated <400°C
  - **High T permeation rates and low reliability of T transport analyses**
  - **High cost of ^{6}Li enrichment**
- Specific risks in WCLL:
  - **Uncertainties in pressure transients:** due to water-PbLi interaction M. Eboli, Energies 14 (2021) M. Eboli, IT-3C.1
  - **Low TBR margin:** marginally meets current criteria
  - **Influence of MHD in thermohydraulics of PbLi**
  - **Uncertain efficiency of PbLi draining:** due to helium production, ^{6}Li(n,T)^{4}He, and accumulation
- Specific risks in HCPB:
  - **Be_{12}Ti and ACB:** thermomechanical behavior under thermal cycling and irradiation R. Gaisin, IT-4C.2
  - **Low TRL and lack of irradiation data of Be_{12}Ti and ACB**
  - **Pressure drops:** still moderate, could still jeopardize plant layout feasibility
  - **Low neutron shielding margin:** marginally meets current criteria

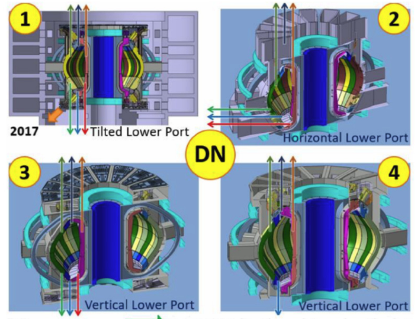
7. Challenges in plant integration

- Three main design & integration cross fields identified and studied: G.A. Spagnuolo, FED 173 112933 & 171 112573 (2021)



  - **Radiation protection in BB and ancillary systems**
    - Studies for options to improve shielding capabilities of the HCPB
    - Impact of H_2O activation (spacial distrib. of ^{16}N, ^{17}N dose rates, especially isolation valves)
  - **Definition of the T management working points (extraction, inventories and releases)**
    - T permeation problem => T transport analyses with global T balance in the different systems:
      - ✓ Focus on T permeation rate and inventory in coolant: key parameters for feasibility assessment and tech. selection for CPS
      - ✓ Control of T conc. and inventories: work to ↓T release with perm. barriers/guard pipes in TER and need to ↑ CPS performance
  - **Remote maintenance of BB** D. Chauvin, FED 173 (2021) 112941
    - Vertical maintenance: studies with full and split segments, DN, upper or lower port maintenance
    - Current space in VV and ports too constrained, no viable solution found, trade-off needed





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8. Opportunities

- RAMI:
  - **WCLL**: generally speaking, reduction of number of elements in BZ => ↓ welds => ↑ RAMI
    - Further design effort to reduce number of DWT in reference design
    - Revisit poloidal water tube configuration to drastically reduce BZ elements P. Pereslavtsev, P-1.262
  - **HCPB**: coolant and purge gas equalization => in-box LOCA will not exist => internal welds lesser relevant
    - Drawback: CMSB part of TER not feasible (too much LN_2 consumption): a Getter Bed instead is mandatory
- T permeation:
  - **WCLL**: poloidal config. => ↓ #BZ elements => ↓ interface surface PbLi-water => ↓ permeation
  - **HCPB**: adding H_2O in purge gas and adding of H_2 in coolant can reduce permeation by 1/5 G.A Spagnuolo, FED 173 (2021)
- Alternative configurations: Review of options for T-breeder and NMM F.A. Hernández, FED 137, (2018)
  - **For water:** Water cooled Lead and Ceramic Breeder (WLCB) G.Zhou, FED 168A (2021)
  - **For helium:** Helium cooled Lead and Ceramic Breeder (HLCB) G.Zhou, FED 146A (2019)
- Alternative coolants
  - **CO_2 instead of helium:** same NK, TH, TM. Missing: CO_2 radiolysis and consequences S.Wang, FED 138 (2019), 146B (2019)
- R&D program in WPBB
  - L.V. Boccaccini, FED 179 (2022)

T. Hernández, IT-5A.2 | B.E. Ghidersa, IT-3C.2 | R. Marinari, O-4C.2 | O. Leys, O-4C.4 | S. Pérez-Martin, O-4C.5
D. Horsley, P-2.161 | C. Köhly, P-2.214 | G. Bulubasa, P-2.256 | G. Zhou, P-2.94 | J. Leys, P-1.214 | A. Del Nevo, P-1.265
M. Utili, P-2.93 | A. Abou-Sena, P-2.71 | I. Cristescu, P-2.64 | P. Maccari, P-2.127

Outline

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2. The BB System and high level requirements during PCD
3. The WCLL concept and the WCLL TER
4. WCLL main performance achievements
5. The HCPB concept and the HCPB TER
6. HCPB main performance achievements
7. Challenges in system design and plant integration
8. Opportunities
9. **Summary and outlook**

9. Summary and outlook

- WPBB successfully developed the WCLL and HCPB as DEMO driver BBs at PCD level during 2017-2020
- Both blankets have been integrated in the DEMO plant following SE approach
- Major achievements for both BBs:
  - First set of baseline documentation with comprehensive set of analyses for design justification
  - Robust, consistent design globaly meeting key plant requirements and most design criteria
- Despite major achievements, risks (some critical) have been identified:
  - Reliability, EUROFER97 DBTT, T permeation rates and low readiness of manufacturing as key common risks
- Opportunities have been also spotted, being explored from beginning of CD phase
  - Reducing BZ elements/Revisiting poloidal config (WCLL), high pressure purge gas (HCPB)
  - Molten Lead Ceramic Breeder (water or helium cooled version)
- Comprehensive R&D program going together with design to bridge gaps

Q & A