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An Enhanced, Near-term HCPB Design as Driver Blanket for the EU-DEMO

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Breeding Blanket Project

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The views and opinions expressed herein do not necessarily reflect those of the European Commission.

Overview

1. Current Reference EU-DEMO HCPB
2. Achievements & Key Issues
3. Enhanced HCPB Design
4. Performance Figures
5. Primary Heat Transfer System Integration
6. Be-free blanket? An alternative solution
7. Conclusions & Outlook

Overview

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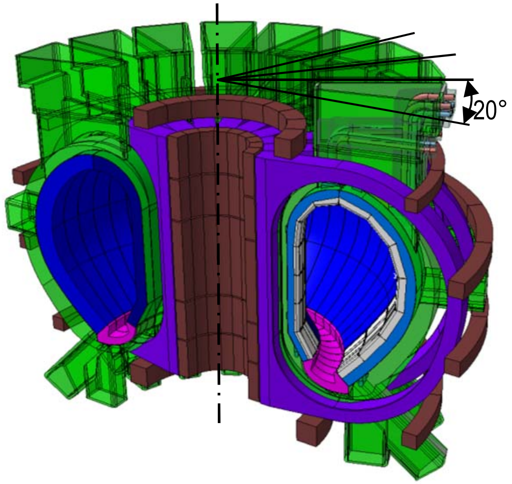
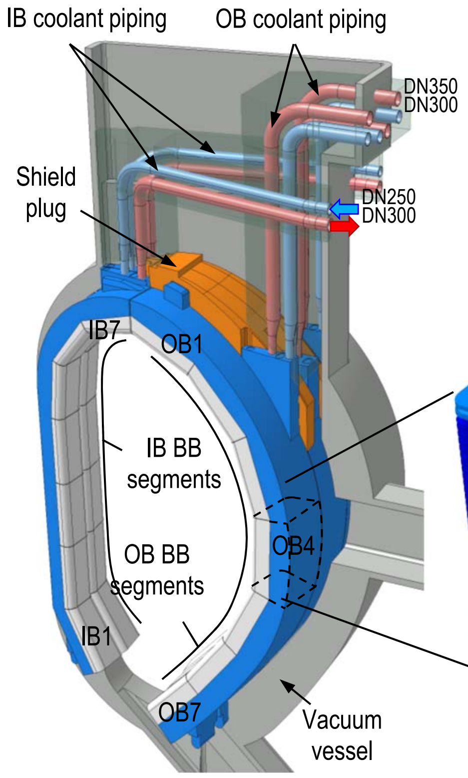
1. Current Reference EU-DEMO HCPB

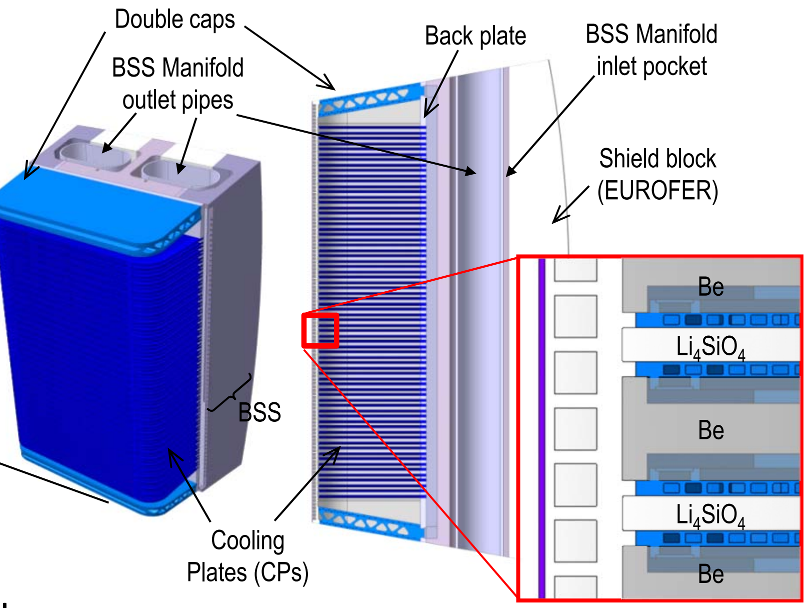
- EU DEMO1 Tokamak BL2015
  - R_0 = 9.1m, a = 2.9m, A=3.1
  - Burn time = 2hr
  - **Dwell time 30 min**
  - P_{fusion} = 2037 MW
  - **18 sectors**
  - 3 OB + 2 IB segments / sector
  - **OB thickness ≈1300mm**



- Coolant:
  - He gas, neutronically inert,
  - He, 8 MPa, T_{in} = 300°C, T_{out} = 500°C
- Purge gas:
  - He + 0.1vol% H_2; alternative: He + (tbd)vol% H_2O



- Reference HCPB BL2015 V4
  - Multi Module Segment (MMS)
    - 7 BB modules/segment
  - Feedpipes: upper port



- Materials:
  - Breeder: Li_4SiO_4 pebbles, ^6Li 60%, Ø0.25-0.65mm (ref. TBM)
    - T_{max} ≈ 920 °C, maximize T_{min}
  - Multiplier: Be pebbles Ø1mm (ref. TBM)
    - T_{max} ≈ 650 °C, maximize T_{min}
  - Steel: EUROFER97 / advanced HT EUROFER97
    - T_{max} ≈ 550 °C / 650 °C
    - T_{min} ≈ 350 °C / 350 °C

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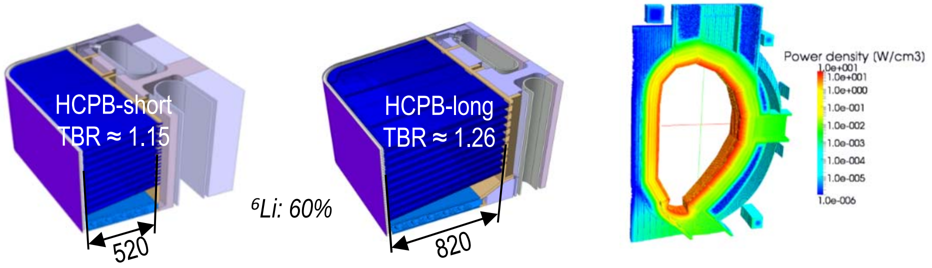
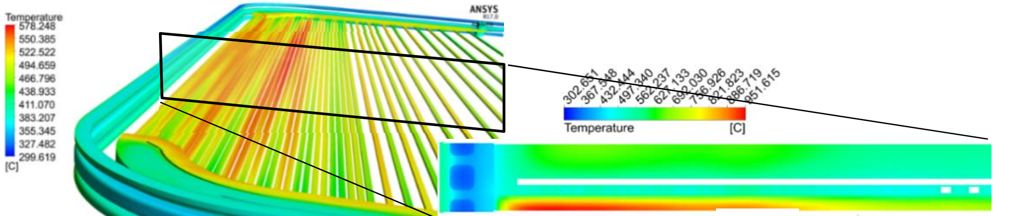
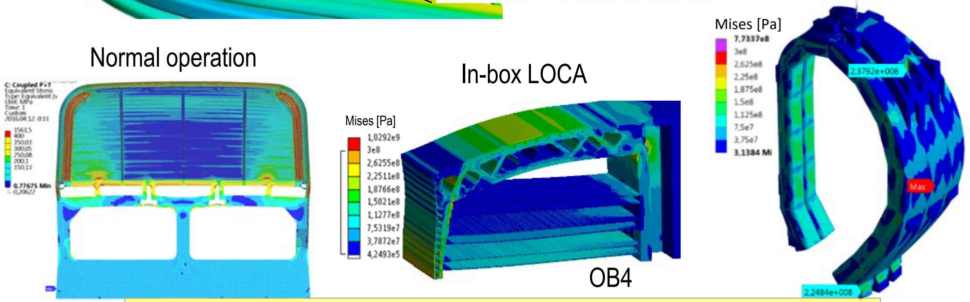
2. Achievements…

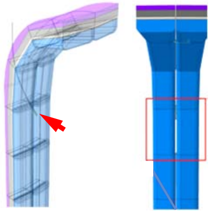
- Achievements:
  - Neutronics:
    - Fair TBR margin: 1.15 („HCPB-short“, reference), up to 1.26 („HCPB-long“, for worst-case scenario)
    - Many scoping studies: radial thickness, breeder and multiplier materials, shielding…
  - Thermohydraulics:
    - FW & BZ: 50% „redundant“ cooling scheme
    - Old TBM-like design „beer-box“ (stiffening plates + BUs) simplified to CP sandwich with integrated manifolds
    - Temperatures globaly under limits, several hot spots in eurofer and functional materials
  - Thermomechanics:
    - Full RCC-MRx assessment for normal operation
    - Innovative design of caps to withstand level C in-box LOCA without need of vertical stiffening grids
    - Full sector analyses under CDE and ex-vessel LOCA + CDE
  - Integration:
    - Blanket attachment studies
    - Primary Heat Transfer System (PHTS)
    - Global thermohydraulic studies
    - Integration of fuel lines
    - Safety studies (LOCAs, LOFAs…)

X.Z. Jin et al., P1.224









F. A. Hernández et al, Fusion Eng. Des. 124 (2017) 882-886

F. A. Hernández et al, IEEE Trans. Plasma Sci. 46(6) (2018) 2247-2261

P. Pereslavtsev et al, Fus. Eng. Des. 124 (2017) 910-914

G. Zhou, Fus. Eng. Des. (doi.org/10.1016/j.fusengdes.2017.12.017)

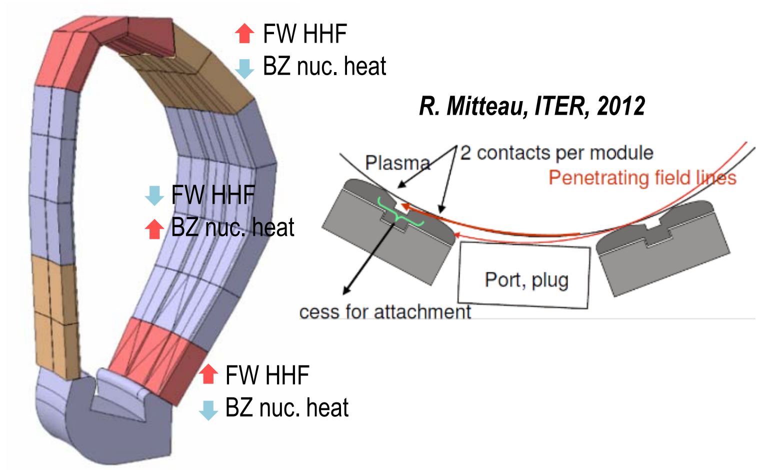
C. Zeile et al, Fus. Eng. Des. (doi.org/10.1016/j.fusengdes.2018.02.024)

E. Bubelis et al., Fus. Eng. Des. (doi.org/10.1016/j.fusengdes.2018.02.40)

A. Froio et al., IEEE Trans. Plasma Sci. 46(5) (2018) 1436-1445

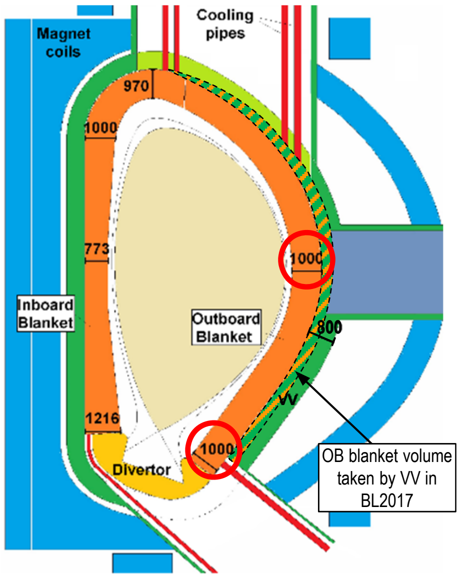
2. … & Key Issues

- … however, key issues:
  - FW heat flux issue
    - FW & BZ needs opposite: need sequenciality
    - ITER-like FW rooftop shaping found to be essential to shadow leading edges => TBR↓



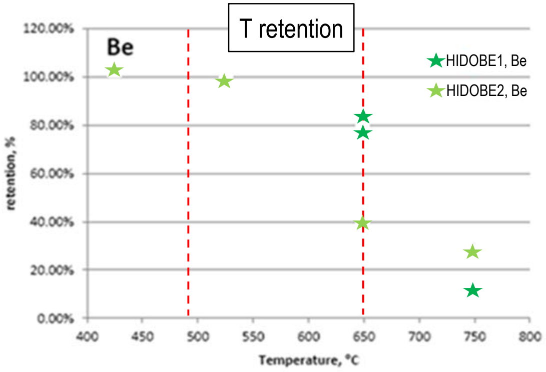
R. Mitteau, ITER, 2012

  - Flow complexity (high DP)
    - Coolant redundancy too complex for PHTS
    - Δp in BB still large, (large $W_{circ,total}$) => TRL of HCPB PHTS compromised
  - CP with many mm-sized channels
    - Complex manufacturing & high costs
    - Compromised RAMI
    - Risk of thermal bukling of CPs
  - New DEMO 1 tokamak baseline 2017
    - R_0 = 9.0m, a = 2.9m, A=3.1
    - Burn time = 2hr
    - **Dwell time 10 min**
    - $P_{fusion} \approx 2000$ MW
    - **16 sectors**
    - 3 OB + 2 IB segments / sector
    - **OB thickness ≈1000mm** (to mitigate key plasma stability problem with BL2015)



OB blanket volume taken by VV in BL2017

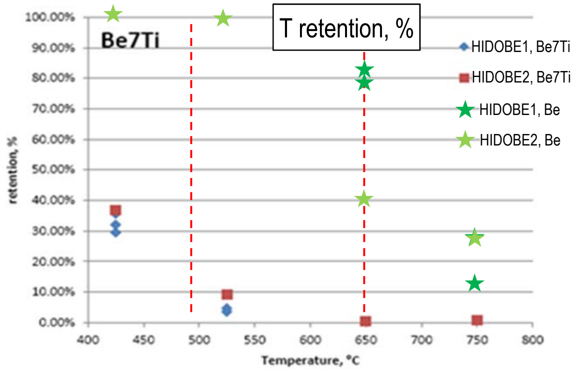
    - MMS arrangement seems not feasible: BSS judged to be too thin to withstand EM-loads after disruption
    - Significantly thiner blanket => TBR↓
  - The Be issue
    - Be retention at 650°C still 40%! => several kg of T inventory in Be expected => key safety issue for DEMO (less for ITER)
    - High water & air reactivity
    - Toxicity
    - Recyclability (U impurities => Pu)
    - Limited resources
    - Mass production and costs

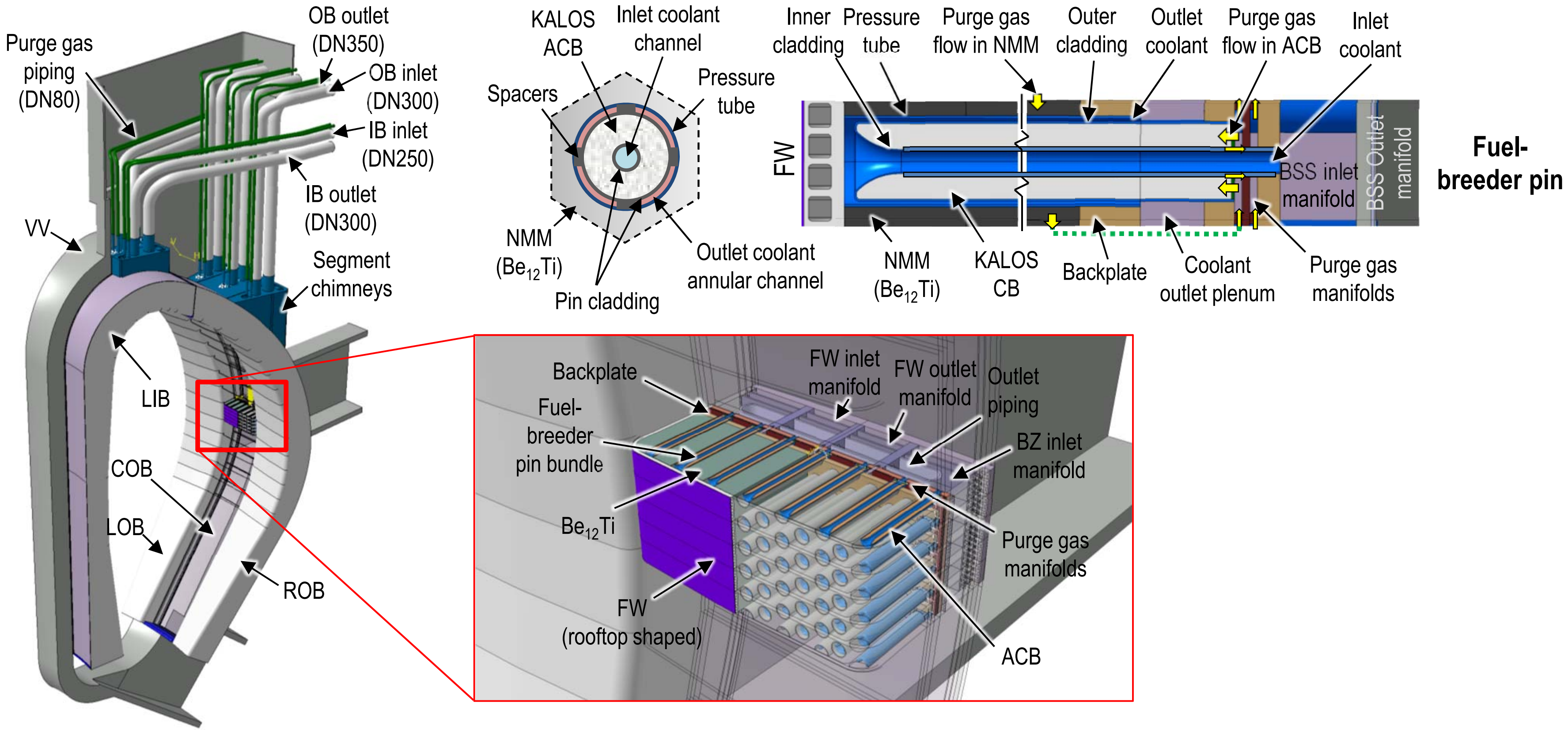


Overview

3. Enhanced HCPB Design

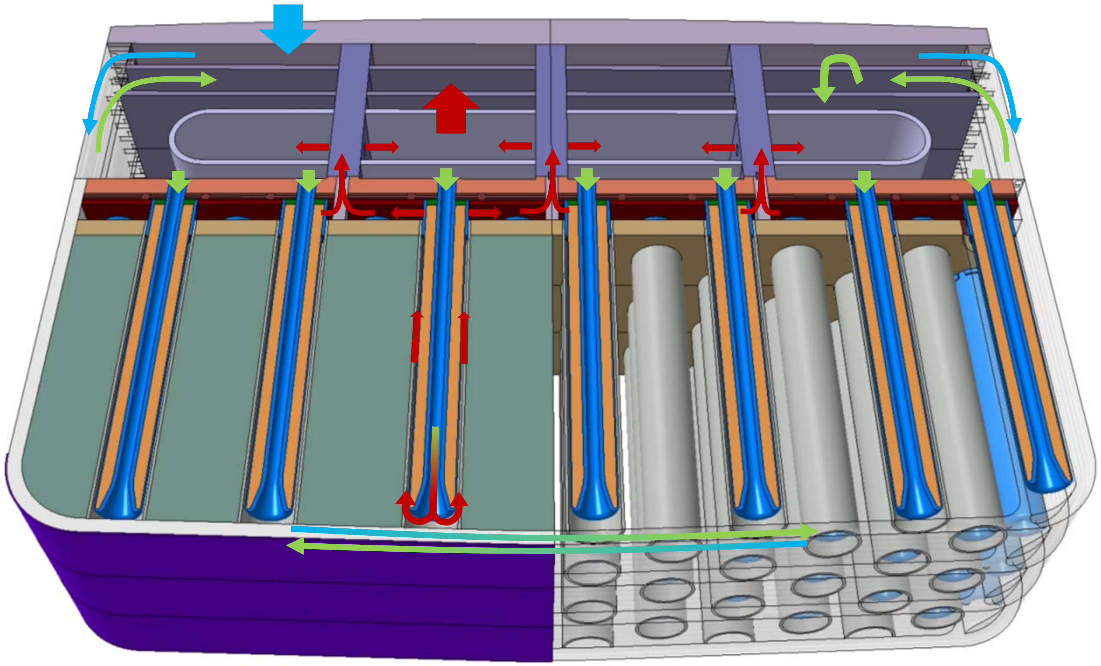
- Design highlights:
  - Introduction of SMS architecture and rooftop shaped FW
  - Elimination of coolant redundancy (too complex PHTS) => BZ flexibility
  - Simplest „core“: fission-like „fuel“-pin elements
  - Introduction of advanced functional materials:
    - Advanced Be NMM: $Be_{12}Ti$, lower retention, lower reactivity, lower swelling…
    - Advanced CB „KALOS“: Li_4SiO_4 + 25%mol Li_2TiO_3 (strength ≈2x, ΔTBR<-1% w.r.t. Li_4SiO_4)

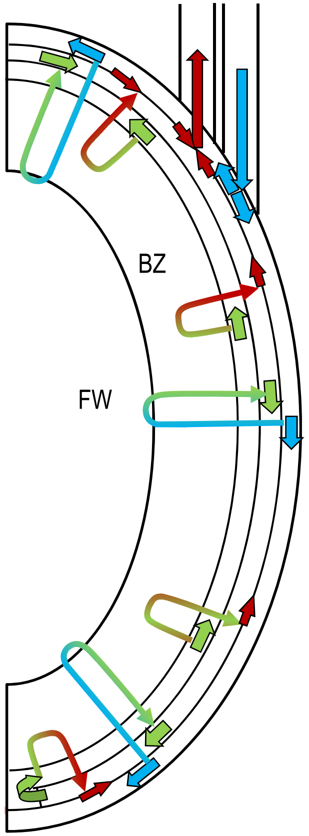




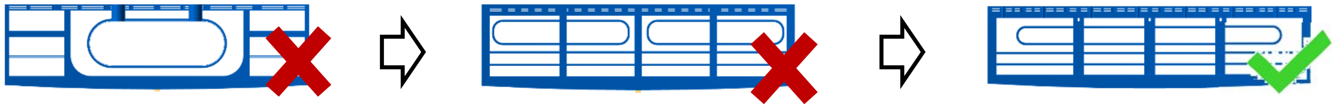
3. Enhanced HCPB Design

- Design highlights:
  - FW and BZ work decoupled but in series
    - Heat in FW integrated into PHTS
    - Robustness against poloidal variability in FW heat flux: mixed temp. at FW outlet known ≈370°C
    - Better control inlet temp. for BZ (≈370°C)





  - Manifold design: result of a design iteration



  - Coolant: He, 8 MPa, T_{in} = 300°C, **T_{out} = 520°C => key advantage for PHTS**

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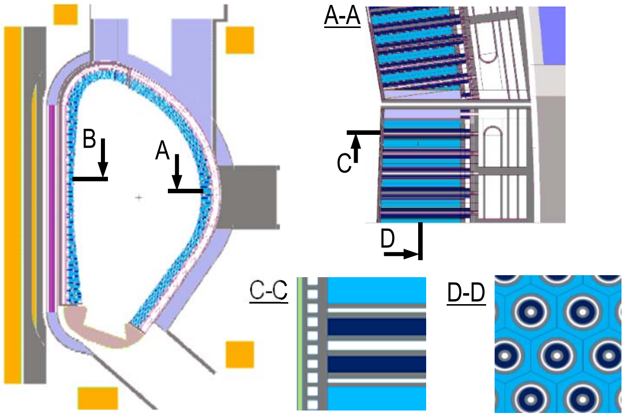
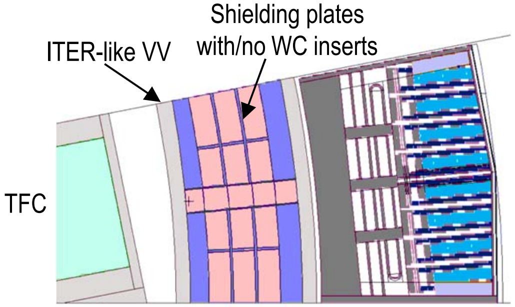
4. Performance Figures: Neutronics

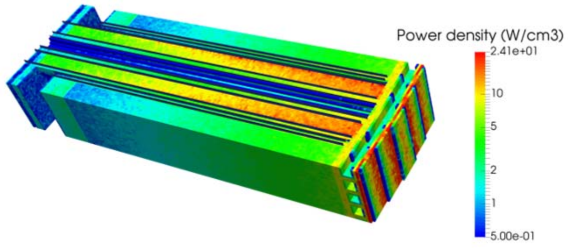
- Neutronics campaign:
  - MCNP5-1.60, data from JEFF-3.2
- Tritium breeding performance:
  - TBR = 1.16, not worse than reference HCPB design (1.15), and…
  - Heterogeneity: key driver for neutronic performances
    - Effect of rooftop shape FW: ΔTBR ≈ -0.03
    - Effect of heterogeneous FW: ΔTBR ≈ -0.01
    - Effect of heterogeneous BZ: ΔTBR ≈ -0.01
    - Effect of FW bending radii: ΔTBR ≈ -0.01

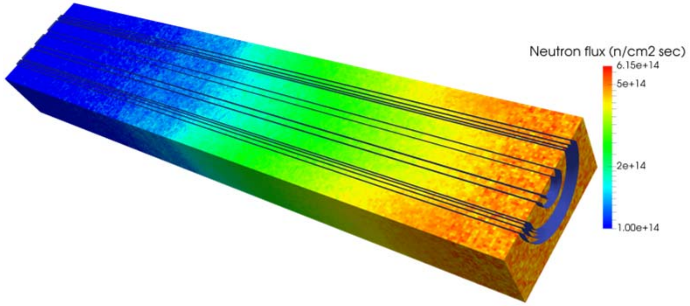
If not taken into account: (virtual) TBR ≈ 1.21!

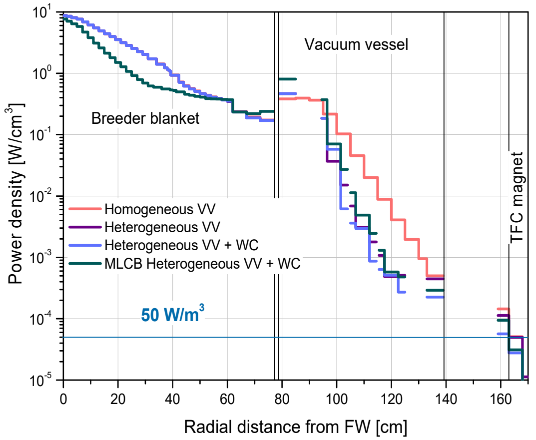


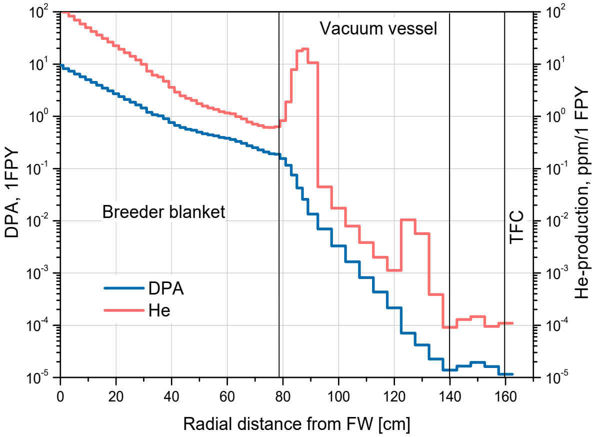
- Shielding, dpa damage, He production:
  - PD limit 50 W/m³ in TFC ok, but low margin
  - WC inserts in VV can reduce PD ≈50%
  - Streaming in BZ ok despite the radial channels in pins
    - Streaming through multiplier highest









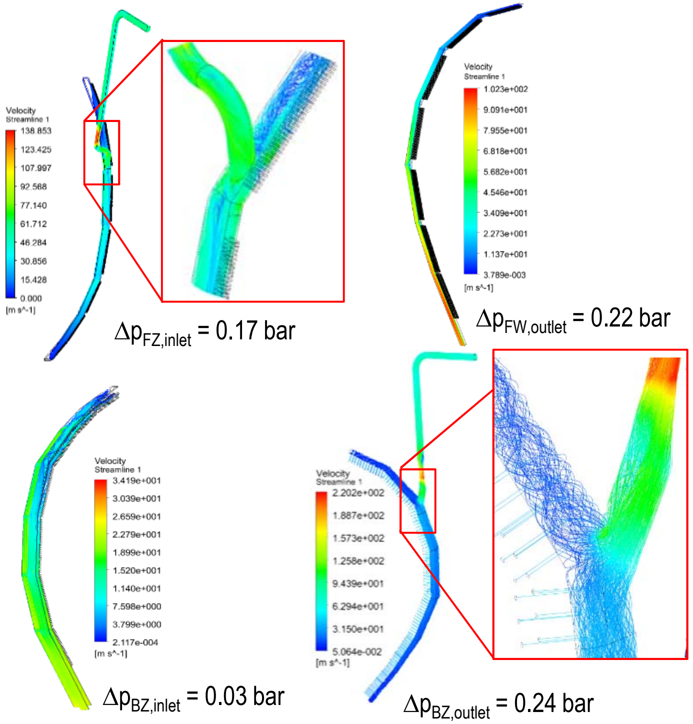


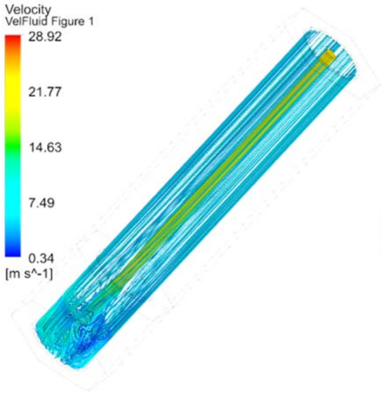
P. Pereslavtsev et al., P1.175

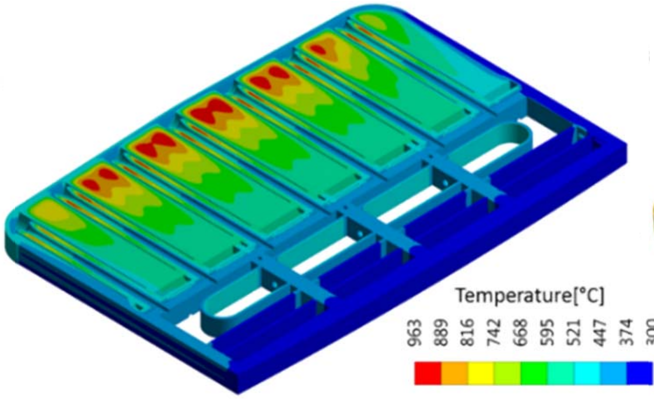
4. Performance Figures: Thermohydraulics

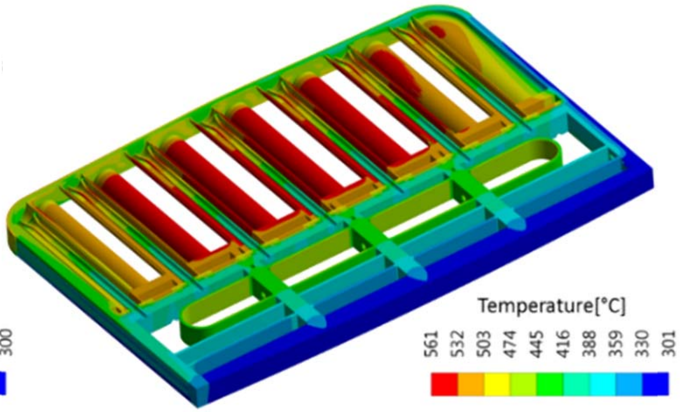
- TH models:
  1. CFD thermohydraulic analyses of 1 fuel-breeder pin
  2. FE thermal analysis of unit slice of equatorial OB BZ region
  3. Global hydraulic analyses of OB and IB BSS for Δp
  4. CFD FW high heat flux analyses
- TH results highlights:
  - BB outlet temperature pushed to 520 °C
  - Temperatures of materials globaly under limits
    - Localized peaks in ACB and eurofer
    - Virtually no max. temp. design limit for $Be_{12}Ti$, but kept ≈950 °C
  - Δp in fuel-breeder pin <0.05 bar!
    - Δp in CPs for reference HCPB ≈1 bar
  - BSS manif. TH yet to be updated and optimized, preliminarily
    - $\Delta p_{BBS,IB} \approx 0.91$ bar
    - $\Delta p_{BBS,OB} \approx 0.66$ bar

$\}$ 30-40% come from (unnecessary) cross section changes and „hard“ turns



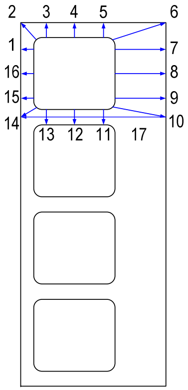




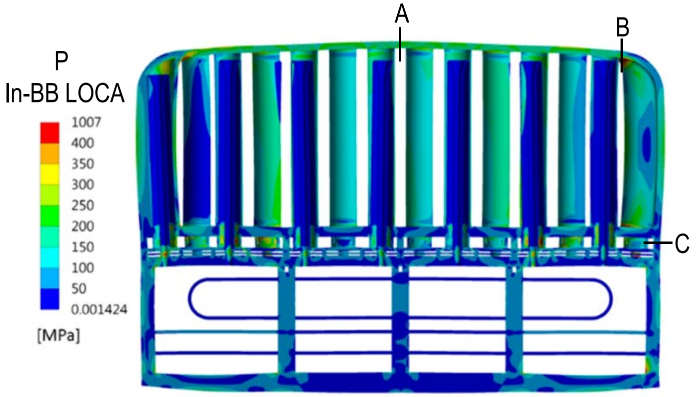


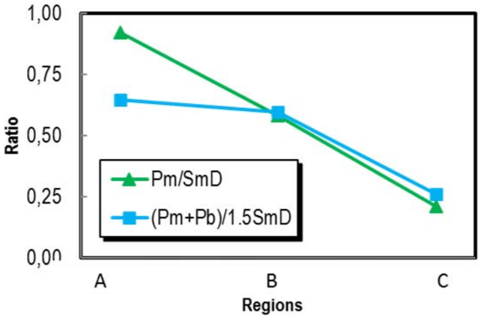
4. Performance Figures: Thermomechanics

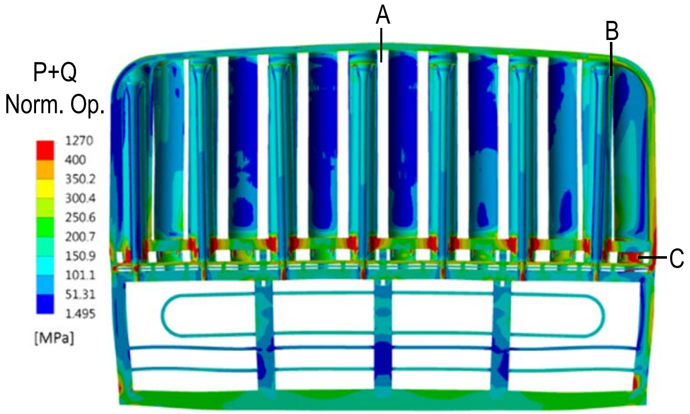
- TH models:
  1. FE TM analysis of unit slice of equatorial OB BZ region under in-box LOCA (level D)
  2. FE TM analysis of unit slice of equatorial OB BZ region under normal operation (level A)
- TM results highlights:
  - In-box LOCA stress assessment (P-loads): level D, globaly ok
  - Normal operation (monotonic modes): level A, globaly ok
    - Further work on design optimization needed for local peak stresses
    - Observation: revision of IPFL mode needed, over-conservative

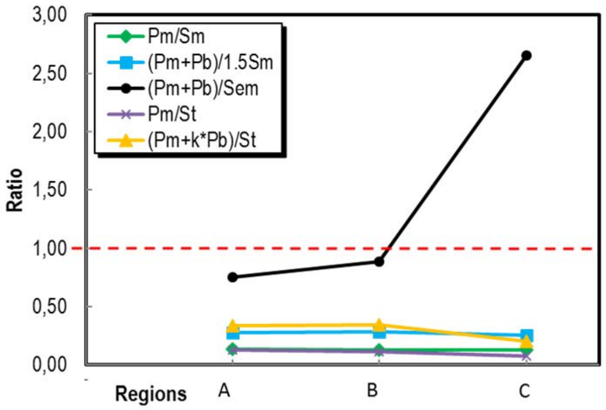


Display of paths for stress linearization









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5. Primary Heat Transfer System Integration

- DEMO HCPB BoP = PHTS(He) + IHTS(MS) + PCS(Rankine)
- Goal: maximize TRL for He-cooled DEMO PHTS
  - PHTS TRL mostly driven by strict limit on He circulator power: currently, technology proven up to 6 MW/circ.
  - Design drivers HCPB PHTS: Δp_{PHTS} (Δp_{BB} & Δp_{IHX}) and $\dot{m}_{plant}$
  - $\Delta p_{BB} = \Delta p_{FW} + \Delta p_{BZ} + \Delta p_{BSS} \approx 1.6$ bar(IB) / 1.1 bar(OB)

***Base** PHTS BL2015*		
Reference HCPB *$P_{BB,th} \approx 2100$ MW*		
T_{in}/T_{out} He [°C]	**500**/292.5	
T_{in}/T_{out} MS [°C]	270/465	
Δp [bar]		
	IB	**OB**
In-VV	2.14**	1.74**
Piping	0.62	0.57
IHX *S&T U-tube* *ΔT_{log} = 28°C*	0.88	0.85
Total	3.64	3.16
$P_{tot,circ}$ & $P_{tot,el}$ [MW]		
IB	**OB**	
36.5	80.9	
117.4	(η_{is}=0.85)	
130.4	(η_{el}=0.90)	

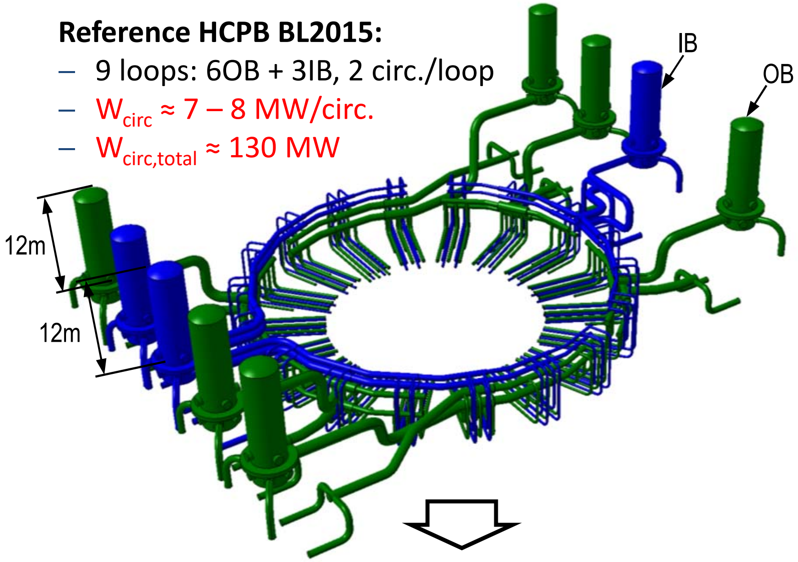
***Base** PHTS BL2015*			***Advanced** PHTS BL2017*		
Enhanced HCPB *$P_{BB,th} \approx 2100$ MW*			**Enhanced HCPB** *$P_{BB,th} \approx 2100$ MW*		
T_{in}/T_{out} He [°C]	**520**/291.1		T_{in}/T_{out} He [°C]	**520**/292.3	
T_{in}/T_{out} MS [°C]	270/465		T_{in}/T_{out} MS [°C]	270/465	
Δp [bar]			**Δp [bar]**		
	IB	**OB**		**IB**	**OB**
In-VV	1.56	1.07	**In-VV**	1.56	1.07
Piping	0.45	0.94	**Piping**	0.45	0.94
IHX *S&T 1-through* *ΔT_{log} = 35°C*	0.63		**IHX** *CWHE* *ΔT_{log} = 36°C*	0.34	
Total	2.68		**Total**	2.35	
$P_{tot,circ}$ & $P_{tot,el}$ [MW]			**$P_{tot,circ}$ & $P_{tot,el}$ [MW]**		
IB + OB			**IB**	**OB**	
86.1			75.3		
86.1	(η_{is}=0.85)		75.3	(η_{is}=0.85)	
94.2	(η_{el}=0.90)		**83.6**	(η_{el}=0.90)	

***not conservative for BL2017: it does not take into account BB thickness reduction*

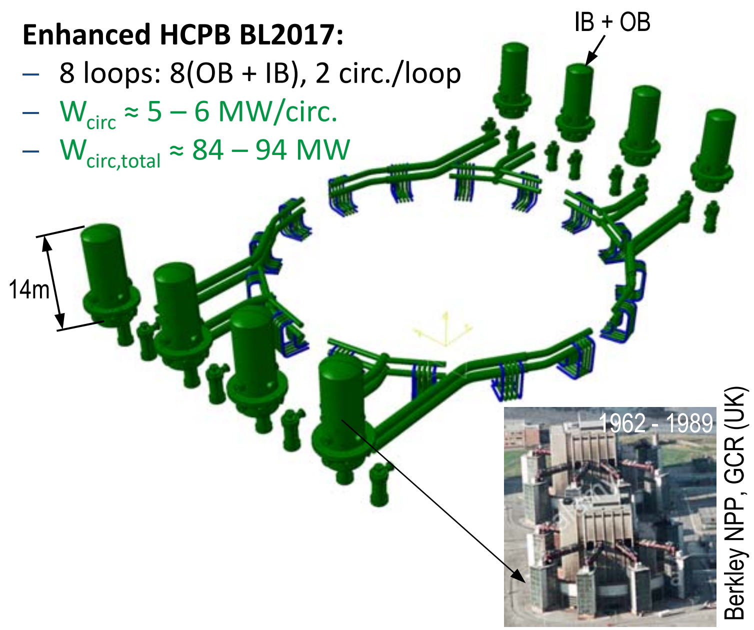
E. Bubelis et al., O3C.5

I. Moscato et al., P2.218

A. Tarallo et al., P4.168



Reference HCPB BL2015:
- 9 loops: 6OB + 3IB, 2 circ./loop
- $W_{circ} \approx 7 - 8$ MW/circ.
- $W_{circ,total} \approx 130$ MW



Enhanced HCPB BL2017:
- 8 loops: 8(OB + IB), 2 circ./loop
- $W_{circ} \approx 5 - 6$ MW/circ.
- $W_{circ,total} \approx 84 - 94$ MW

Berkley NPP, GCR (UK)

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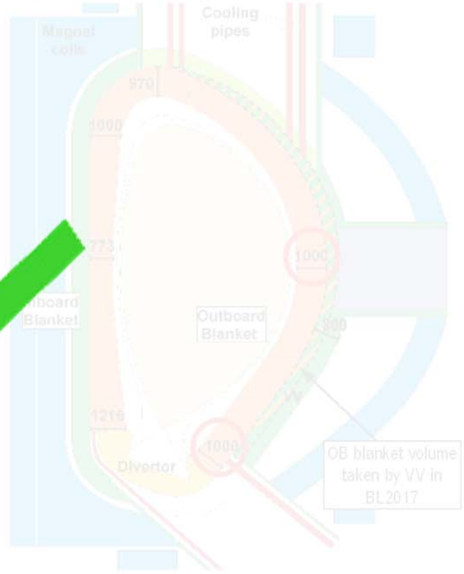
2. …Key Issues

- …key issues mitigated by the enhanced HCPB “fuel-breeder pin” design:

- FW heat flux issue
  - Local FW and BZ cooling needs are opposite!
  - Revised understanding of FW heat flux loads: ITER-like FW rooftop shaping essential to shadow leading edges => TBR compromised

✓

- New DEMO 1 tokamak baseline 2017
  - R_0 = 9.0m, a = 2.9m, A=3.1
  - Burn time = 2hr
  - Dwell time 10 min
  - P_{fusion} ≈ 2000 MW
  - 16 sectors
  - 3 OB + 2 IB segments / sector
  - OB thickness ≈1000mm (to mitigat[illegible] plasma stability problem with BL2015)
  - Current MMS arrangement seems not feasible: BSS judged to be too thin to withstand EM-loads after disruption
  - Significantly thiner blanket => TBR compromised



✓

- Flow complexity (high DP)
  - Coolant redundancy too complex for PHTS
  - Δp in BB still large, re[illegible]ing in large $W_{circ,total}$
  - Strict limit [illegible]ulator technology (<6MW), TRL o[illegible]CPB PHTS compromised

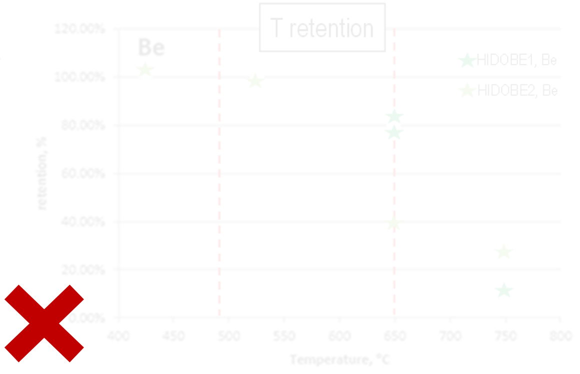
✓

- CP with multi mm-sized channels
  - Complex manufacturi[illegible] & high costs
  - Compromis[illegible]d RAM[illegible]
  - Risk of ther[illegible]ing of CPs

✓

- The Be issue
  - Be retention at 650°C still 40%! => several kg of T inventory in Be expected => key safety issue for DEMO (less for ITER)
  - High water & air reactivity
  - Toxicity
  - Recyclability (U impurities => Pu)
  - Limited resources
  - Mass production and costs

✗

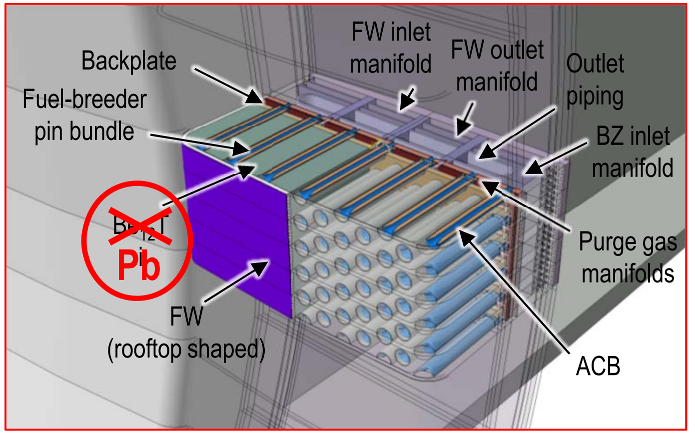


6. Be-free blanket? An alternative Molten Lead Ceramic Breeder Blanket

- Long search for alternatives to Be NMM: only practical element is Pb and Pb compounds
  - Solid form: $LaPb_3$, Zr_4Pb_5… with fair TBR (up to 1.20, BZ-„long“, ^6Li: 90%)
  - Liquid form: molten Pb as NMM… (up to 1.22, BZ-„long“, ^6Li: 90%), found to be easiest solution! => MLCB
    - Liquid form => Pb inmune to neutron irradiation
    - no tritium in NMM => no recirculation needed, no MHD issue
    - Production of gases and ^{210}Po found to be negligible
    - NMM-empty (lighter!) segments during installation, then Pb filling
    - Non-reactive BB funtional materials =>
      - *Water cooling possible: at the moment focus on He-cooled version*
      - *H_2O as purge gas additive possible: permeation potentially improved orders of magnitude*

F. A. Hernández et al, „First Principles Review of Options for Tritium Breeder and Neutron Multiplier Materials for Breeding Blankets in Fusion Reactors“, Fus. Eng. Des., under 2nd (minor) revision

- Development log and current status:
  - Decision: common architecture with enhanced HCPB (perfect draining)
    - Allows a fast development path together with the enhanced HCPB design
  - Neutronics: only with minor adjustments, performance close to HCPB (^6Li: 90%, CB=20mm, BZ-OB: +60mm, BZ-IB: +30mm):
    - TBR≈1.13… with fully heterogeneity (FW & BZ + rooftop FW)
    - Shielding similar to enhanced HCPB
    - Energy multiplication: enhanced HCPB => 1.35, MLCB => 1.20
  - Thermohydraulics and thermomechanics as for enhanced HCPB
    - Temperature peaks slightly better than for HCPB (less power density)
    - Structural behaviour analogous to enhanced HCPB under N.O and in-BB LOCA



P. Pereslavtsev et al., P1.175

G. Zhou et al., P1.186

Overview

7. Conclusions & Outlook

- Enhanced HCPB design developed to address standing issues with the reference concept
- Key achievements with the enhanced HCPB design:
  - Δp_{BB} strongly reduced => current circulator tech. is relevant => goal of mature BoP is now realistic
  - Use of $Be_{12}Ti$ (seems a must for DEMO) with high TBR in compact BZ => better safety
  - Simpler blanket internals => simpler manufacturing, reduced costs and improved RAMI
- Standing concern: use of Be
  - Alternative blanket based on a (helium cooled) „Molten Lead Ceramic Breeder“ concept developed on the basis of the enhanced HCPB „fuel-breeder pin“ concept
- Future work and R&D needs
  - Finish HCPB „fuel-breeder pin“ concept maturity:
    - Complete design: design of chimneys and full segment thermomechanical analyses against VDE loads
    - System analyses: safety, tritium transport and global thermohydraulics
  - MLCB „fuel-breeder pin“ concept:
    - Helium-cooled variant: reach design maturity as for HCPB
    - Scoping analyses of tritium breeding performance for a water-cooled variant

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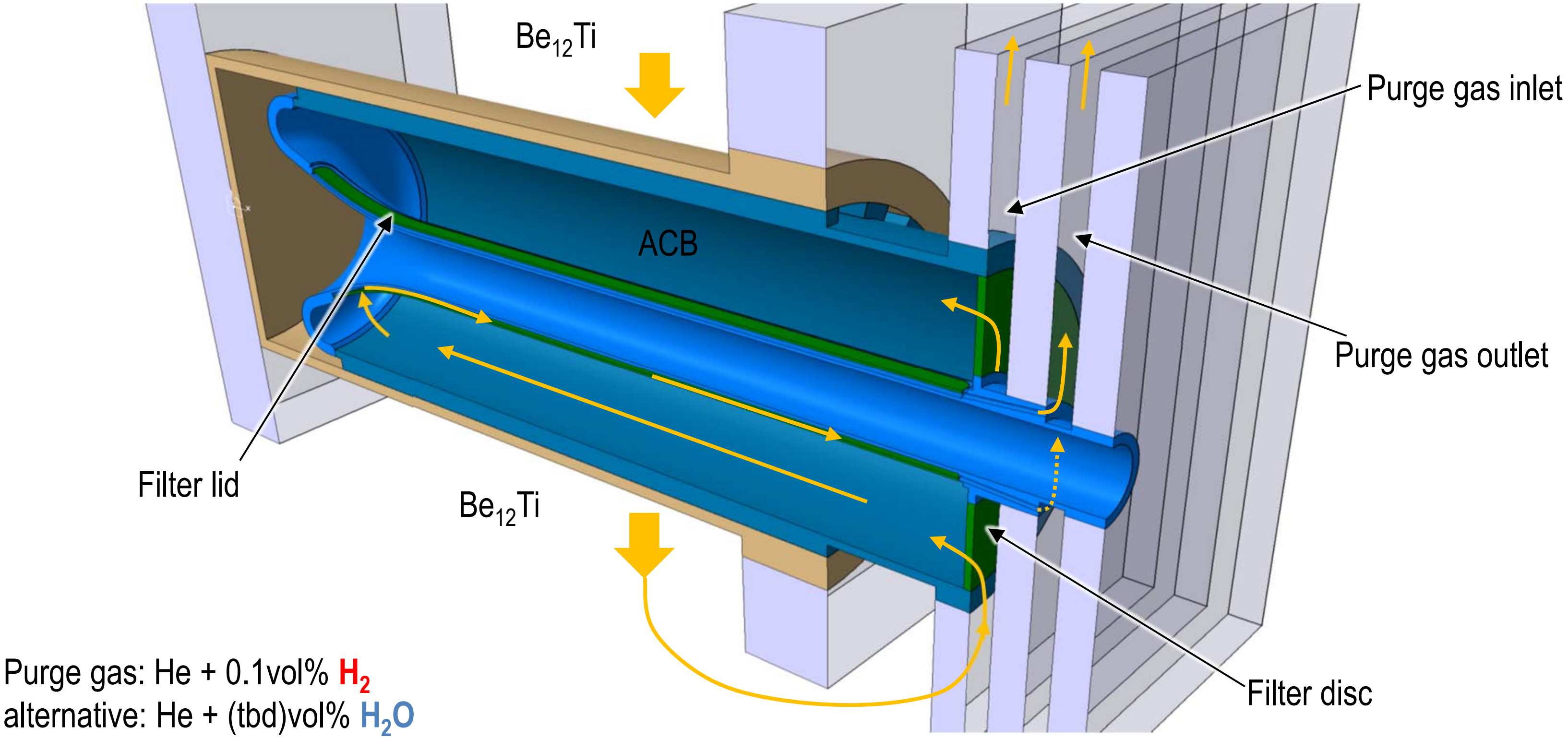
Back-up slides

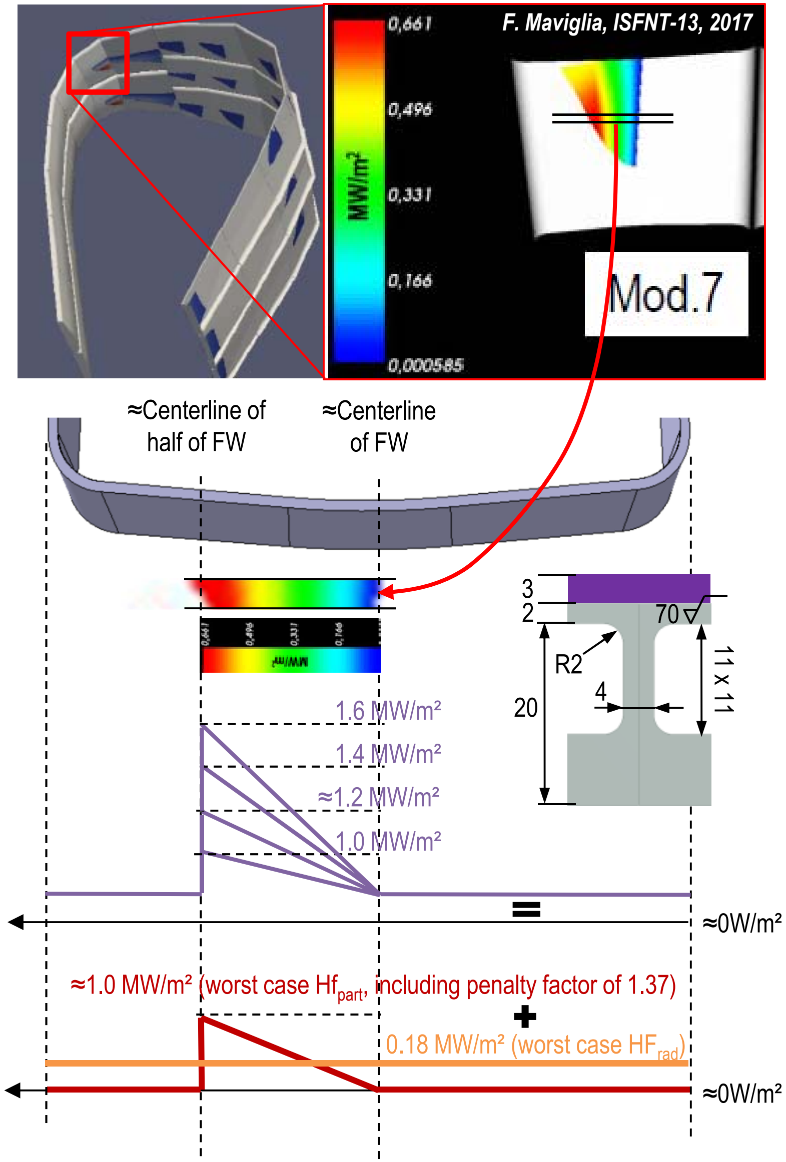
Purge gas loop in BZ

- Purge gas loop:
  - Sequential: first $Be_{12}Ti$ (top-bottom poloidal flow), then in-pin flow through KALOS CBs

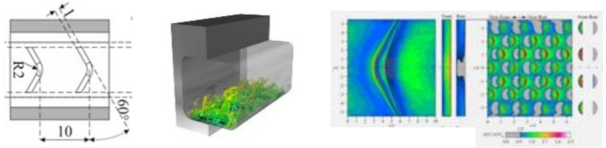


Purge gas: He + 0.1vol% H_2
alternative: He + (tbd)vol% H_2O

Performance Figures: Thermohydraulics

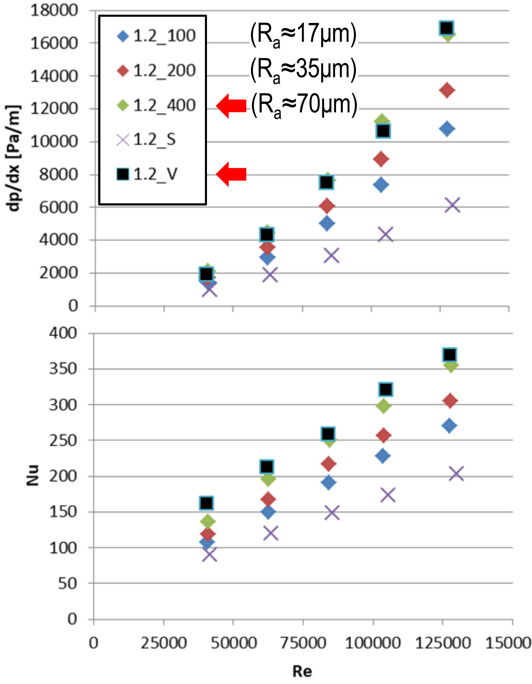

F. Maviglia, ISFNT-13, 2017

- Knowledge of FW DEMO HHF vastly improved since 2015
  - HF_{tot} = HF_{rad} + HF_{part} , non-homogeneous HF loads
- Rib-roughened channels (e.g. V-ribs): best HTC vs dp/dx



S. Ruck et al., P2.129

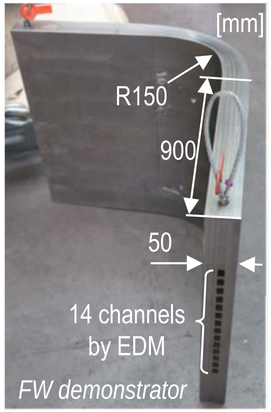
- Rib-roughened channels use complex, resource-intensive CFD procedures for full-scale FW and BB CFD analyses
  - V-ribs vs. augmented surface roughness

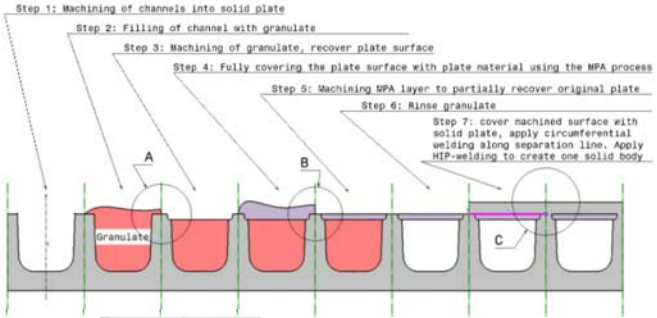


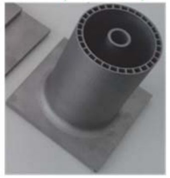
	m [kg/s]	FW T_{peak} [°C]	Δp [bar]	
Peak q" 1 MW/m²	**0.03**	**553.3**	**0.37**	OB
	0.04	508.8	0.64	
	0.05	481.7	0.98	
	0.06	463.8	1.39	
Peak q" 1.2 MW/m²	**0.03**	**593.284**	**0.38**	
	0.04	**542.150**	**0.64**	IB
	0.05	511.107	0.98	
	0.06	490.605	1.39	
Peak q" 1.4 MW/m²	**0.03**	**633.9**	**0.38**	
	0.04	**576.0**	**0.64**	
	0.05	**540.8**	**0.98**	
	0.06	517.6	1.39	
Peak q" 1.6 MW/m²	**0.03**	**675.340**	**0.38**	
	0.04	**610.247**	**0.65**	
	0.05	**570.883**	**0.98**	
	0.06	**544.921**	**1.39**	

Manufacturing, Costs & RAMI

- Manufacturing and costs:
  - EDM + forming: key technology for full scale FW
    - However, costs scale up fast with length for EDM
    - Technological limit ≈2m with channels ≈15x15mm
  - New approach: Metal Powder Application (MPA)
    - Less limitations, cost reduction ≈50% w.r.t EDM
  - Alternative routine for FW and BZ: SLS, but not in nuclear code (e.g. RCC-MRx)
  - Fuel-breeder pin matrix: conventional fabrication
    - Straightforward scalability to mass production
    - Cost reduction of at least 50% w.r.t CPs







H. Neuberger et al., P4.162

C. Köhly et al., P4.161

- RAMI:
  - *„Main Challenge of Fusion " (D. Maisonnier, ISFNT, 2017); „Achilles Heel for Fusion" (M. Abdou):*
    - Imperative to include RAMI relevant aspects into design from beginning
  - Conclusions on initial scoping RAMI studies of enhanced HCPB w.r.t. reference HCPB:
    - Design seems more robust against degraded operation due to higher modularization in pins
    - General improvement on failure modes related to welds scaling with length
    - Large improvement on failure mode related to channels (clogging)

	(1) Reference HCPB	(2) Enhanced HCPB	Type of weld (1) vs (2)	Ratio (2)/(1)	Failure mode	Predicted Yearly Failure Rate Ratio (2)/(1)
Cooling channels/small pipes in BB modules	1 461 400 m	300 500 m	-	**-79.4%**	Clogging	**-70%**
Welds in BB acting as seals against in-BB coolant leak	167 000 m	94 200 m	Mostly rectangular vs. Mostly orbital	**-43.6%**	In-BB coolant leak	**-51%*** / **+159%****
Welds in BB acting as seals against in-VV leak (coolant and purge gas)	22 700 m	10 400 m	Mostly linear / Mostly linear	**-54.2%**	In-VV coolant leak	**-57%**

*Estimation considering unit length of welds
**Conservative estimation considering only no. of welds, irrespective of their length
HIP welds not included / Possible reliability differences between linear vs. orbital welds not included

Toroidal blanket dimension variation: how are the pins at the boundaries?

- The case of the VVER reactor (Russian version of PWR):
  - VVER has also core with hexagonal assemblies
  - Core has a hexagonal matrix, but reactor core is circular, i.e. „toroidal dimension“ also variable
  - => core baffle acts as transition between matrix and core boundary
- => **side walls of the FW** (analog to core baffle in VVER –also for PWR-) can adjust the geometry toroidaly

VVER-1000
Source: gidropress.podolsk.ru