EUROfusion

The Technology of Fusion Energy (TOFE 2018)
Hilton Orlando Bonnet Creek, 15th November 2018

Advancements in the Helium Cooled Pebble Bed Breeding Blanket for the EU DEMO: Holistic Design Approach and Lessons Learned

Francisco A. Hernández, **Pavel Pereslavtsev, Guangming Zhou, Qinlan Kang, Heiko Neuberger, Lorenzo V. Boccaccini, Galdolfo A. Spagnuolo, Salvatore D'Amico (*KIT*)**

Béla Kiss (*BME NTI*)

Ivo Moscato (*Università di Palermo*)

Karlsruher Institut für Technologie

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

Breeding Blanket Project

Overview

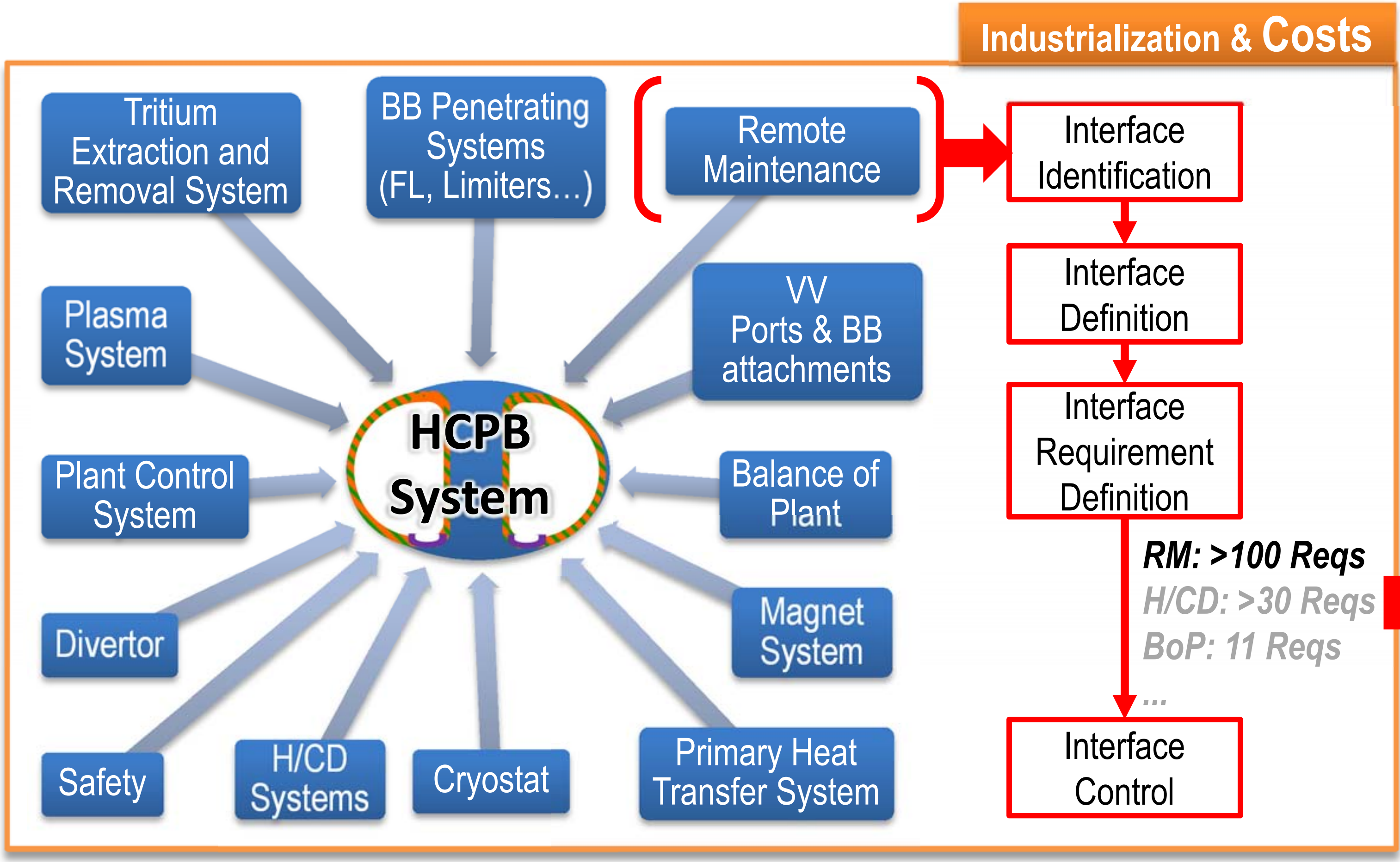
1. Introduction: Holistic design approach
2. Lessons learned
3. Enhanced HCPB with “fuel-breeder” pins
4. Performances
5. PHTS integration
6. Summary and Outlook

Overview

1. Introduction: Holistic design approach
2. Lessons learned
3. Enhanced HCPB with “fuel-breeder” pins
4. Performances
5. PHTS integration
6. Summary and Outlook

1. Introduction: Holistic design approach

- Current EU DEMO pre-Conceptual Design: focus on Systems Engineering
  - DEMO: >40 systems identified @level 1 PBS => huge number of interfaces
  - Case of BB System:



Some interface requirements are design drivers for BB!
=> Many lessons learned!

G. A. Spagnuolo, Proceedings SOFT 2018

Overview

2. Lessons learned

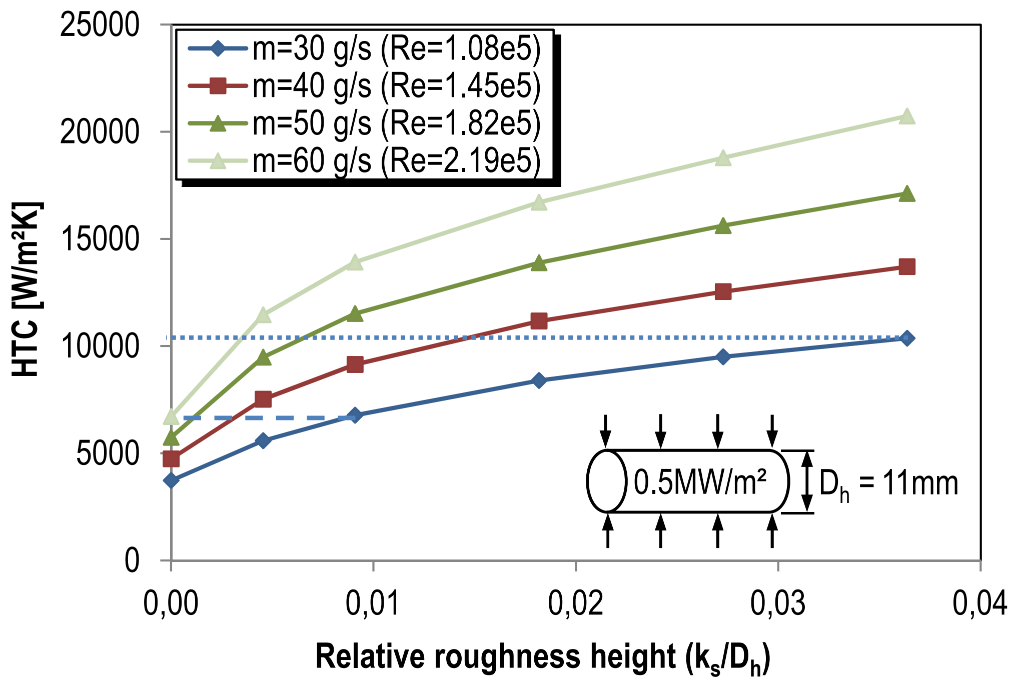
INT On **plant integration**

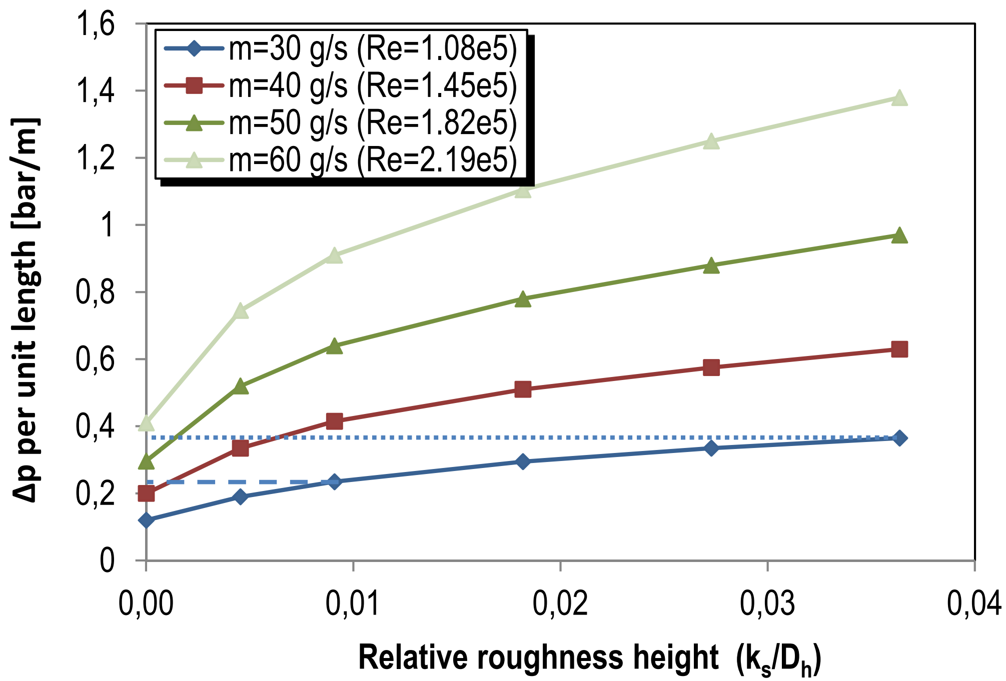
- EU DEMO BoP requirement: maximization of resulting BoP System TRL
- Redundant cooling scheme in BB too complex for BoP
- Systems penetrating BB is unavoidable: modularization of BZ
- DEMO/BB large: minimize piping and weight of segments to ease RM (plant availability)

TH On **efficient thermo-hydraulics**

- He circulating power quickly escalates with Δp: minimization of Δp at each level
- DEMO/BB large: maximize „core" ΔT to reduce plant circulating mass flow
- If HTC need: max. turbulence (friction), min. flow speed / If no HTC need: min. both

Common problems in GCR program! What did we learn?





2. Lessons learned

INT On **plant integration**

- EU DEMO BoP requirement: maximization of resulting BoP System TRL
- Redundant cooling scheme in BB too complex for BoP
- Systems penetrating BB is unavoidable: modularization of BZ
- DEMO/BB large: minimize piping and weight of segments to ease RM (plant availability)

TH On **efficient thermo-hydraulics**

- He circulating power quickly escalates with Δp: minimization of Δp at each level
- DEMO/BB large: maximize „core“ ΔT to reduce plant circulating mass flow
- If HTC need: max. turbulence (friction), min. flow speed / If no HTC need: min. both

Common problems in GCR program! What did we learn?

SIMP On **design simplification, industrialization and costs**

- DEMO/BB large => need to simplify manufacturing for mass production and good RAMI
- DEMO/BB large => mass production and costs of functional materials, especially Be NMM

SAFE On **safety**

- DEMO/BB large and „core“ ΔT not large: He inventory quickly escalates => impact on VVPSS
- Be: 40% T retention @ 600°C => *few* kg of T inventory after 20dpa
- Be: reactivity with steam and air and high swelling

Reducing size of DEMO (e.g. using HTS or less ambitious P_{fus}) would mitigate many key problems
If „HTS“ path: more challenging T breeding (and power exhaust), but HCPB may offer enough margin

Overview

1 Introduction: Holistic design approach

2 Lessons learned

3 Enhanced HCPB with “fuel-breeder” pins

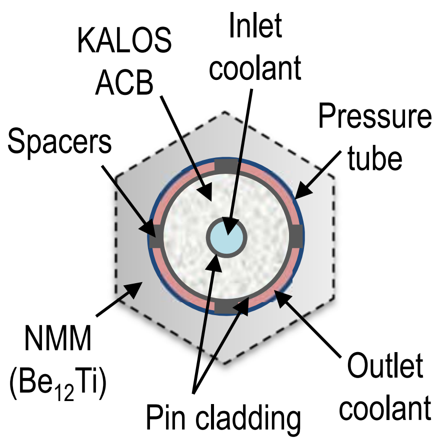
4 Performances

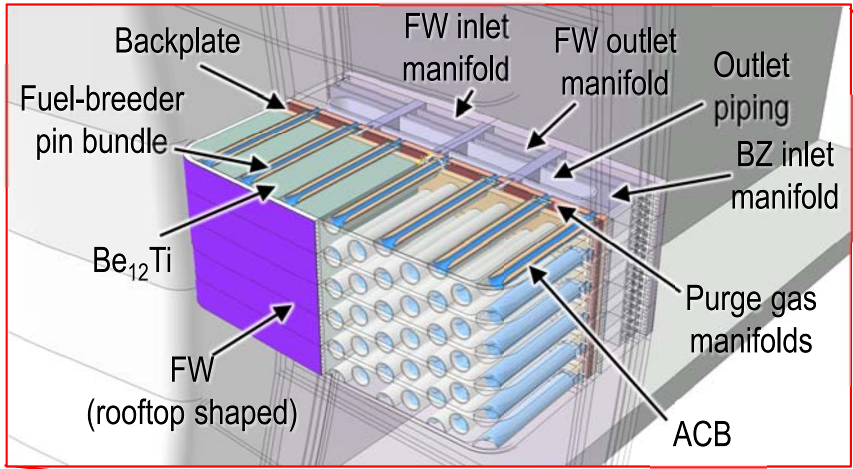
5 PHTS integration

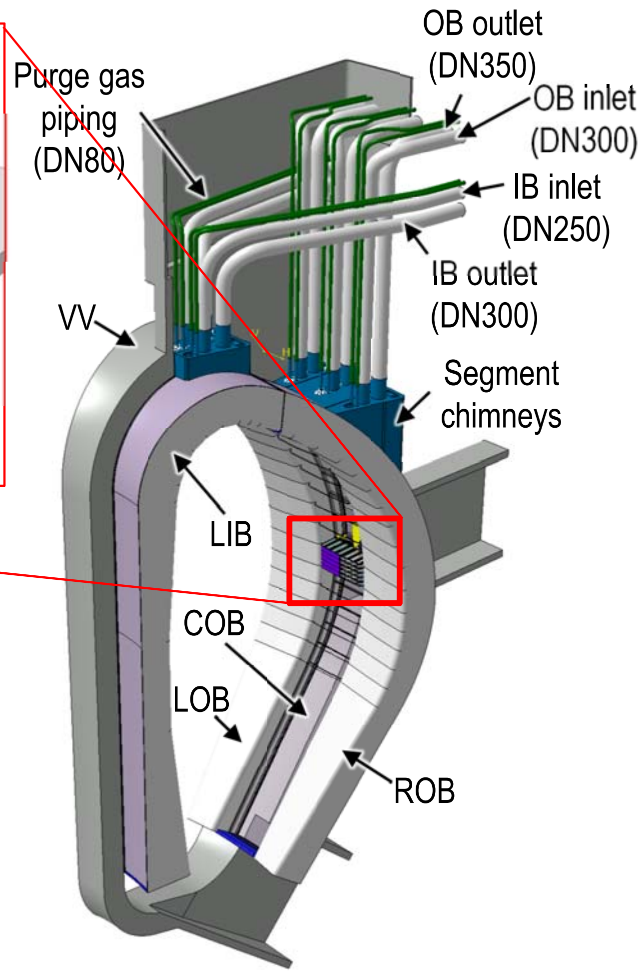
6 Summary and Outlook

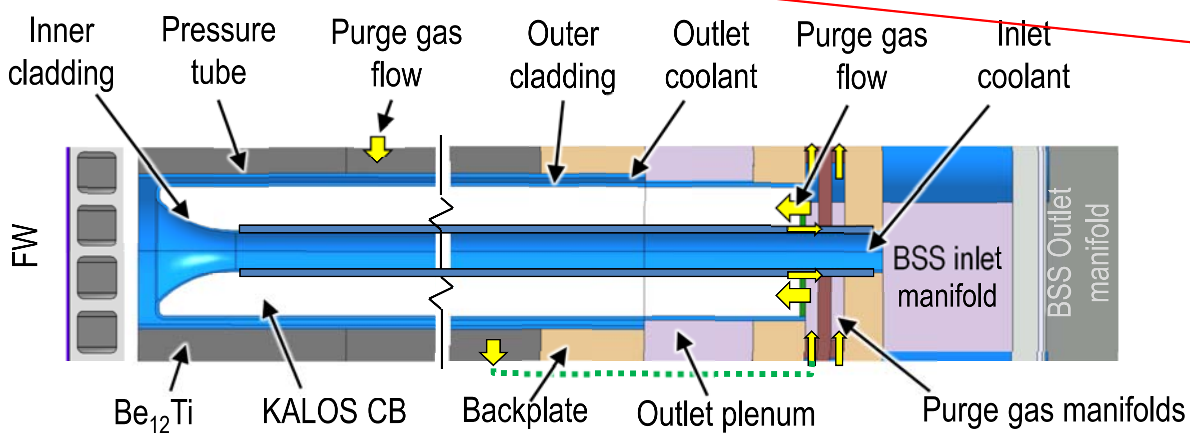
3. Enhanced HCPB with „fuel-breeder" pins

- Design features:
  - Coolant redundancy eliminated: BZ flexibility! INT
  - Fission-like fuel-breeder pins: simple TH & manufacturing, larger area, low v => low Δp TH SIMP INT
  - Rooftop shaped FW and Single Module Segment architecture INT
  - Structural steel: EUROFER97
  - BZ: KALOS (Li_4SiO_4 + Li_2TiO_3) + beryllides



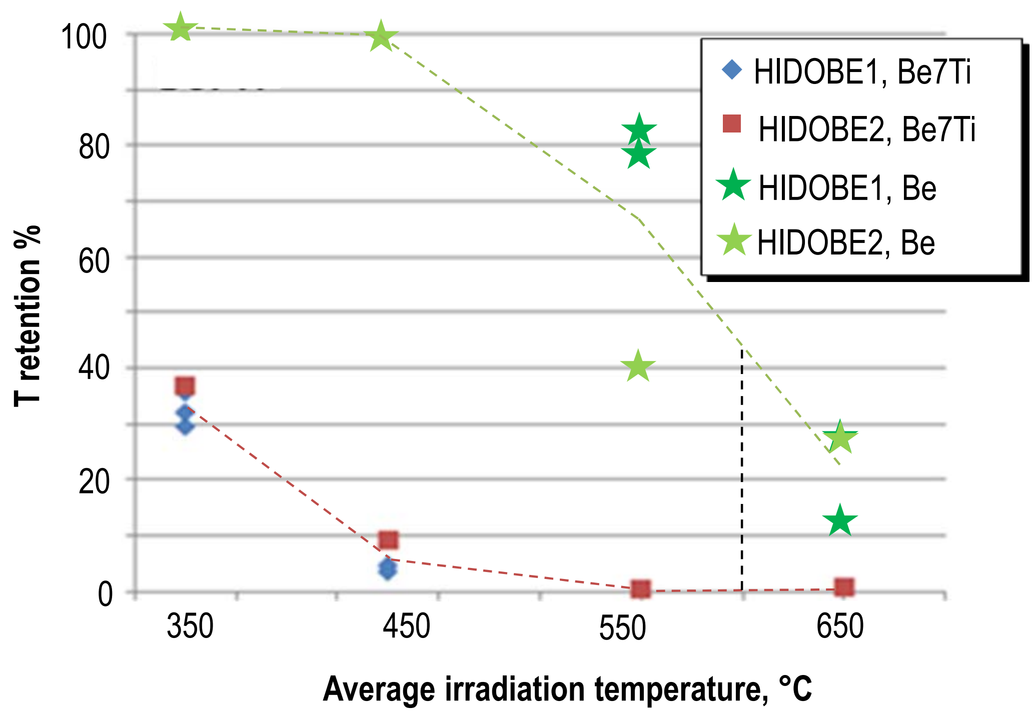


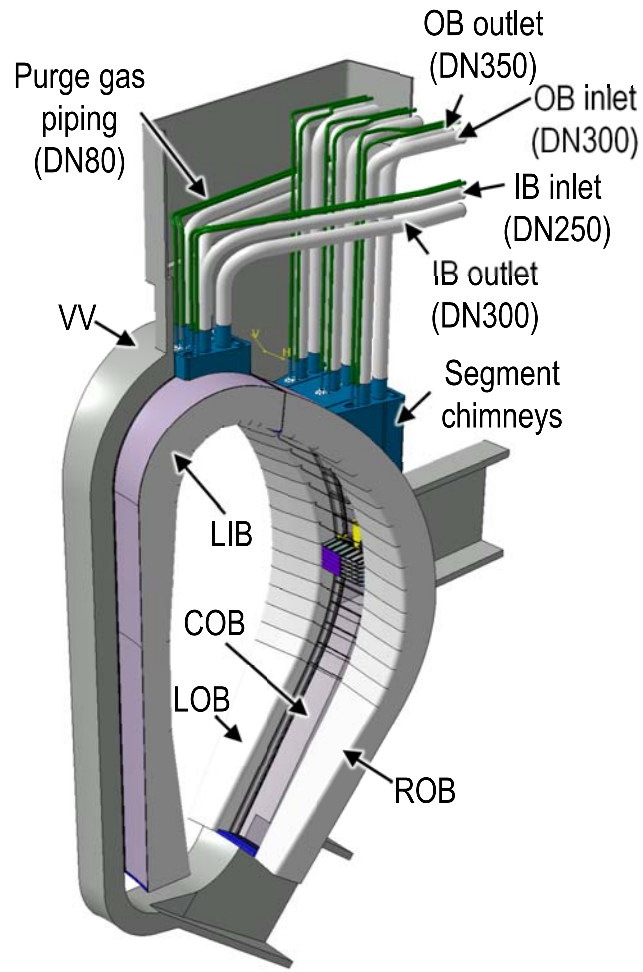




3. Enhanced HCPB with „fuel-breeder“ pins

- Design features:
  - Coolant redundancy eliminated: BZ flexibility! INT
  - Fission-like fuel-breeder pins: simple TH & manufacturing, larger area, low v => low Δp TH SIMP INT
  - Rooftop shaped FW and Single Module Segment architecture INT
  - Structural steel: EUROFER97
  - BZ: KALOS (Li_4SiO_4 + Li_2TiO_3) + beryllides
- Rationale for switching to beryllides
  - T retention ≈0% @600°C (≈40% for Be) SAFE

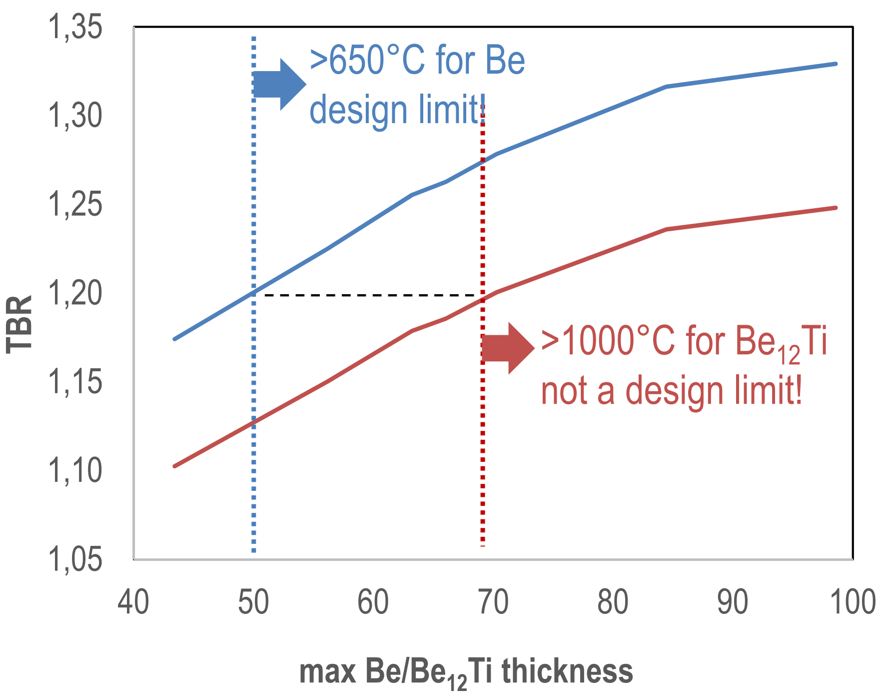


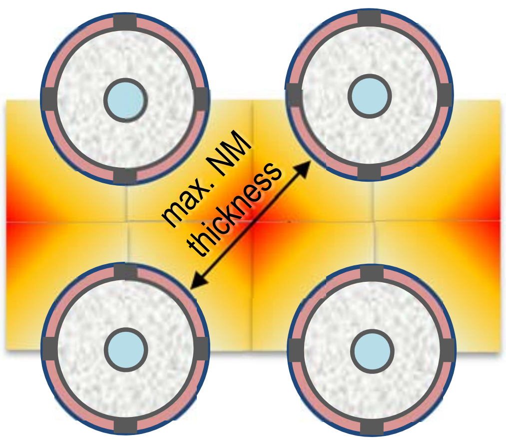


3. Enhanced HCPB with „fuel-breeder" pins

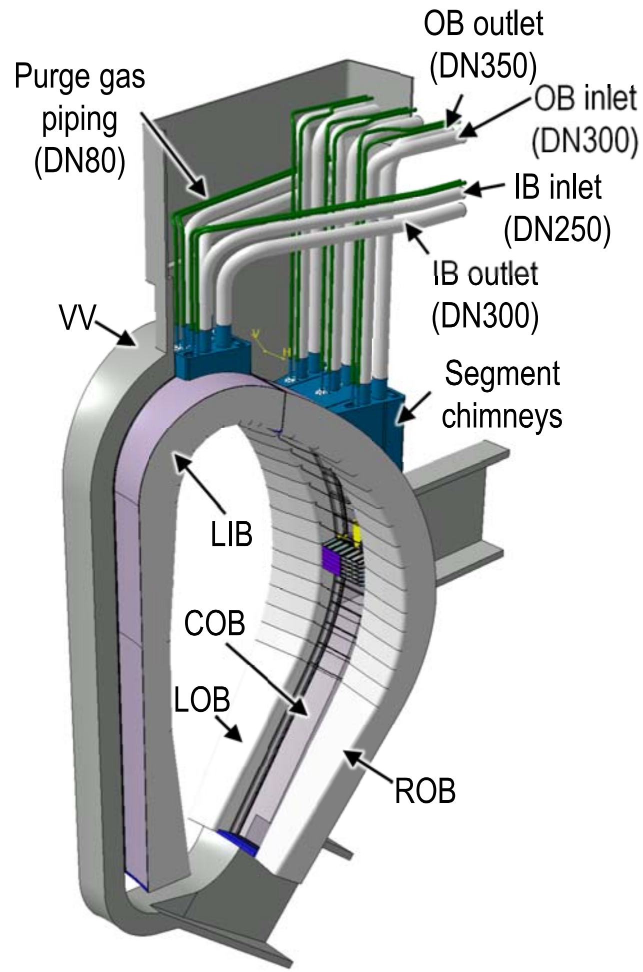
- Design features:
  - Coolant redundancy eliminated: BZ flexibility! INT
  - Fission-like fuel-breeder pins: simple TH & manufacturing, larger area, low v => low Δp TH SIMP INT
  - Rooftop shaped FW and Single Module Segment architecture INT
  - Structural steel: EUROFER97
  - BZ: KALOS (Li_4SiO_4 + Li_2TiO_3) + beryllides

- Rationale for switching to beryllides
  - T retention ≈0% @600°C (≈40% for Be) SAFE
  - Higher temp. limit => no clear TBR advantage of Be over $Be_{12}Ti$





Results obtained with a former, squared pin arrangement

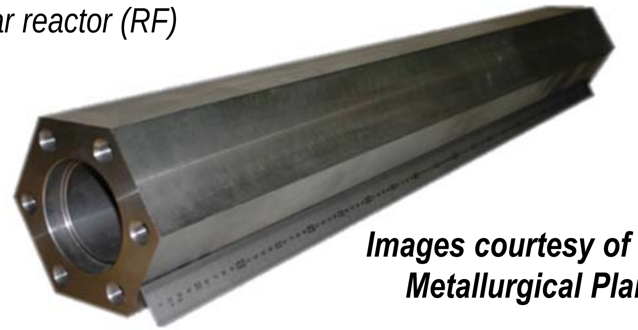


3. Enhanced HCPB with „fuel-breeder“ pins

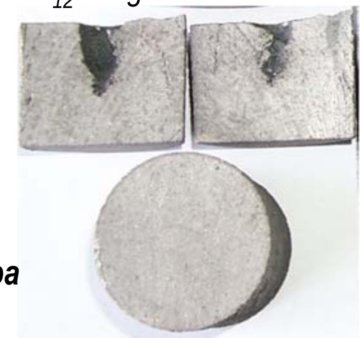
- Design features:
  - Coolant redundancy eliminated: BZ flexibility! INT
  - Fission-like fuel-breeder pins: simple TH & manufacturing, larger area, low v => low Δp TH SIMP INT
  - Rooftop shaped FW and Single Module Segment architecture INT
  - Structural steel: EUROFER97
  - BZ: KALOS (Li_4SiO_4 + Li_2TiO_3) + beryllides

- Rationale for switching to beryllides
  - T retention ≈0% @600°C (≈40% for Be) SAFE
  - Higher temp. limit => no clear TBR advantage of Be over $Be_{12}Ti$
  - Better T release and lower swelling => no need for pebbles! => use fission-like $Be_{12}Ti$ as prismatic blocks SIMP

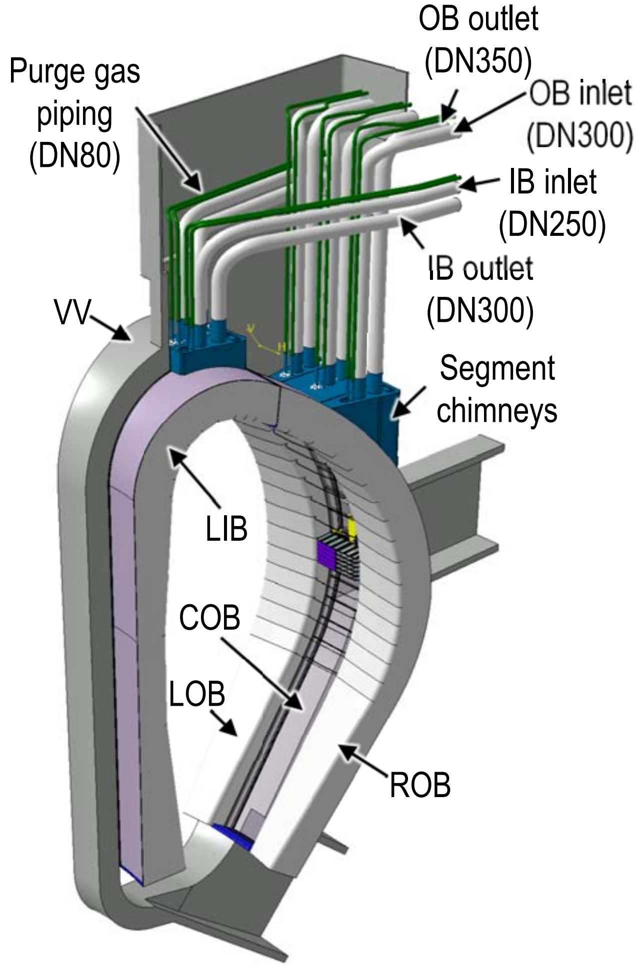
Moderator Be prismatic block for MIR nuclear reactor (RF)



$Be_{12}Ti$ ingots



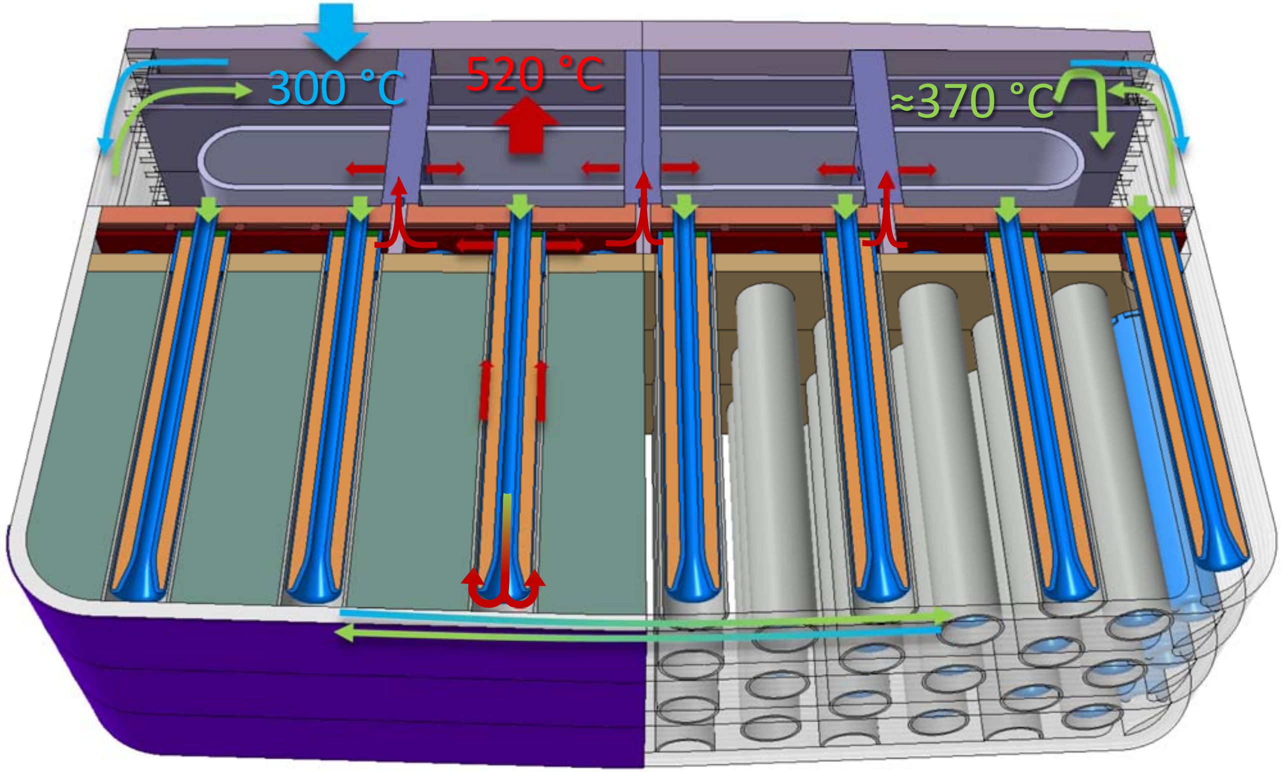
Images courtesy of Ulba Metallurgical Plant

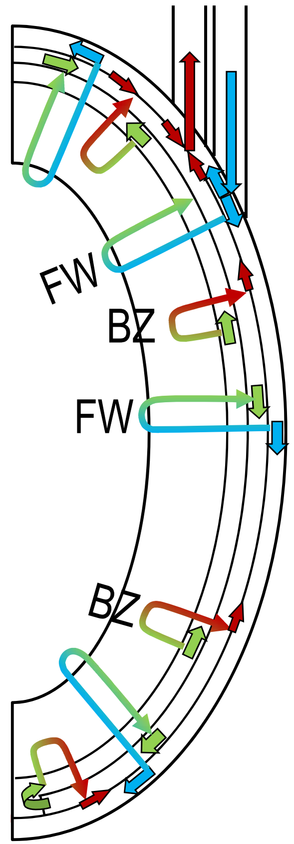


  - R&D 2019-2020: quick demonstration industrial production of $Be_{12}Ti$ prismatic blocks and consolidate material properties

3. Enhanced HCPB with „fuel-breeder“ pins

- HCPB internals: thermohydraulic scheme
  - FW and BZ in series
  - Better temperature control in BZ





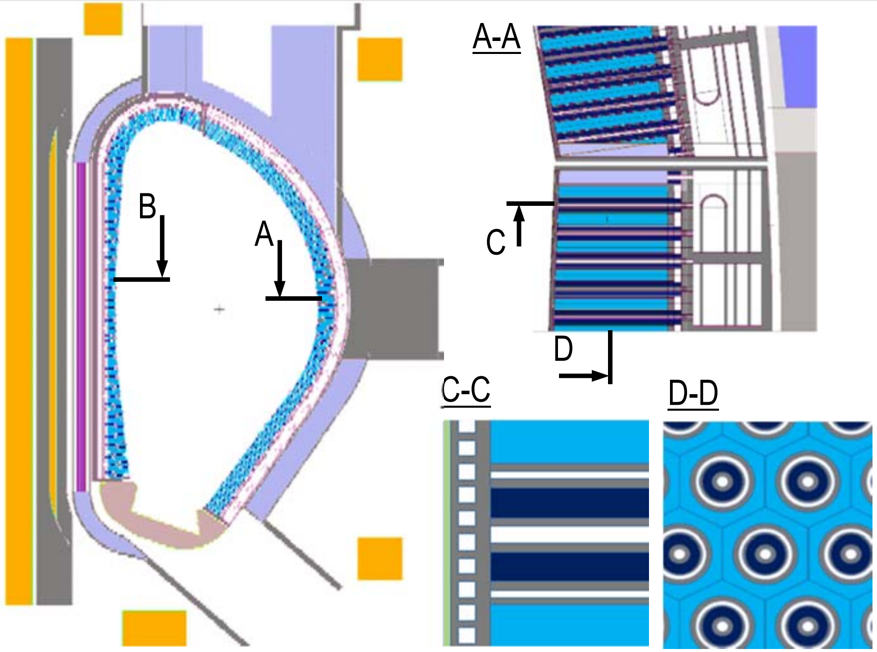
- Manifold design: result of a design iteration

- Coolant: He, 8 MPa, T_{in} = 300°C, **T_{out} = 520°C** => +20°C (due to better thermal management of BZ with pins) => -10% plant mass flow (w.r.t. former designs) => **key advantage for PHTS and BoP**

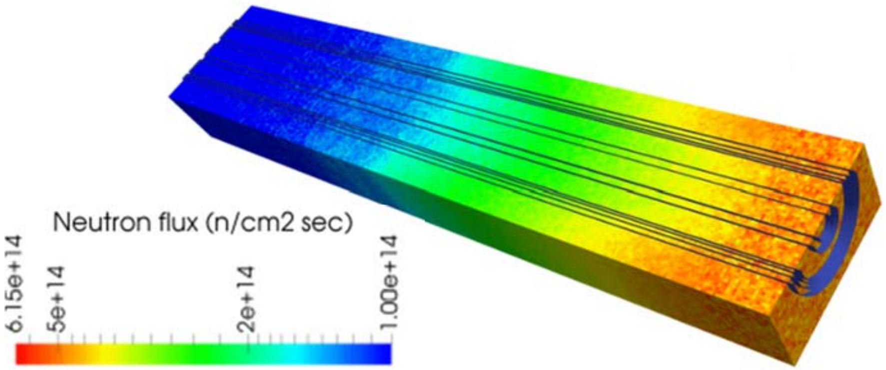
Overview

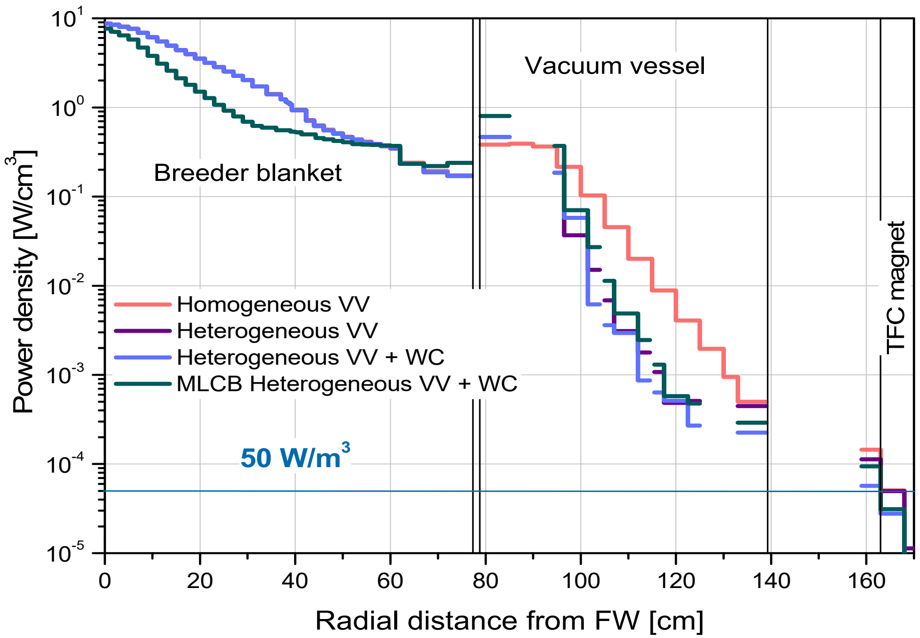
4. Performances: Neutronics

- Tritium breeding performance
  - Fully heterogeneous MCNP model (key for reliability)
  - $Be_{12}Ti$ pebble bed (^6Li 60%): **TBR ≈ 1.16**
  - $Be_{12}Ti$ prismatic blocks (^6Li 60%): **TBR ≈ 1.20**
  - **High TBR in very compact configuration: OB = 1m!**
    - Allows very compact BB for small tokamak configurations
    - Allows large coverage reduction for e.g. DN, penetrations…

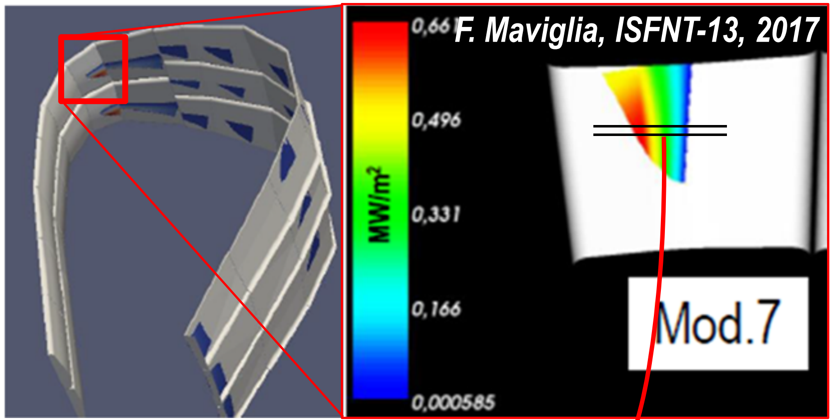


- Shielding
  - Streaming in BZ ok despite radial channels
  - Limit 50 W/m³ in TFC ok, yet low margin
  - WC inserts in VV can reduce PD ≈50%
  - Future focus on shielding improvement keeping compact configuration

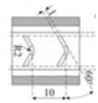




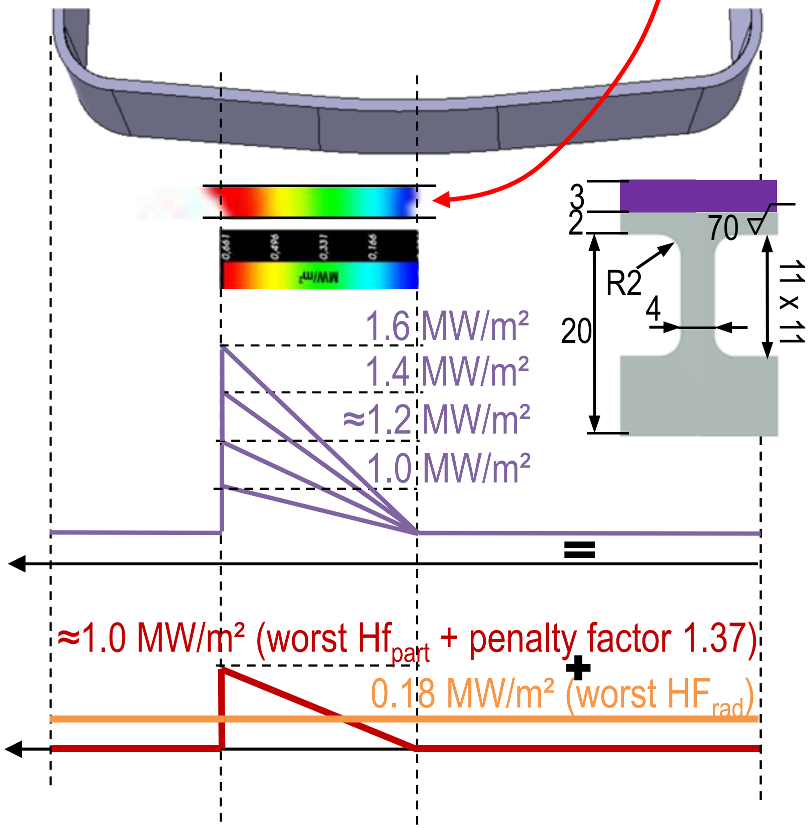
4. Performances: FW thermo-hydraulics

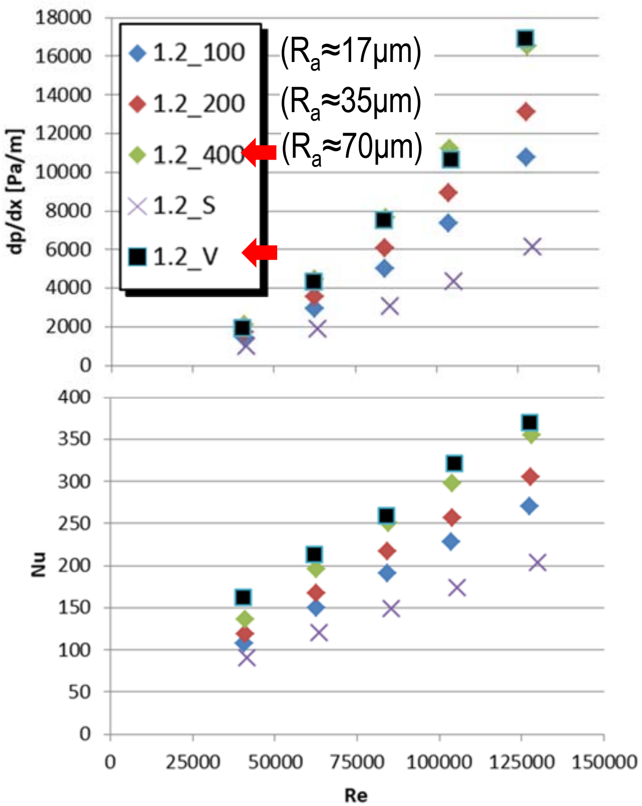


- FW DEMO HHF knowledge vastly improved
  - $HF_{tot} = HF_{rad} + HF_{part}$, non-homogeneous HF loads
- Channels with V-ribs: best HTC vs dp/dx



- Resource-intensive CFD procedures for full-scale FW and BB CFD analyses of V-ribs (LES):
  - V-ribs vs. augmented surface roughness

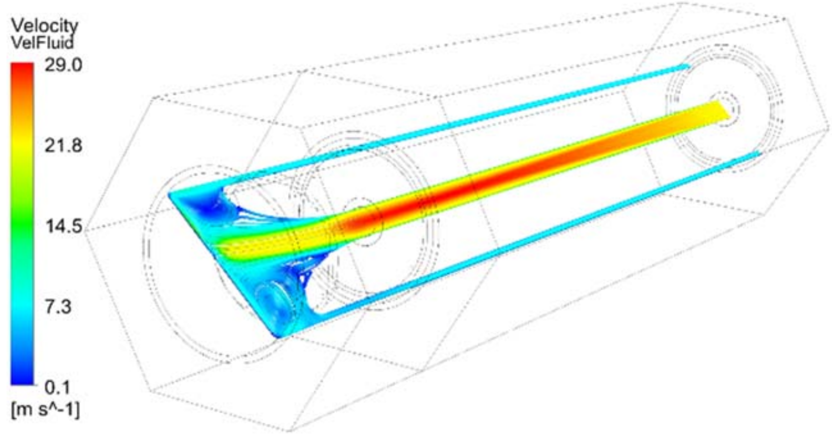


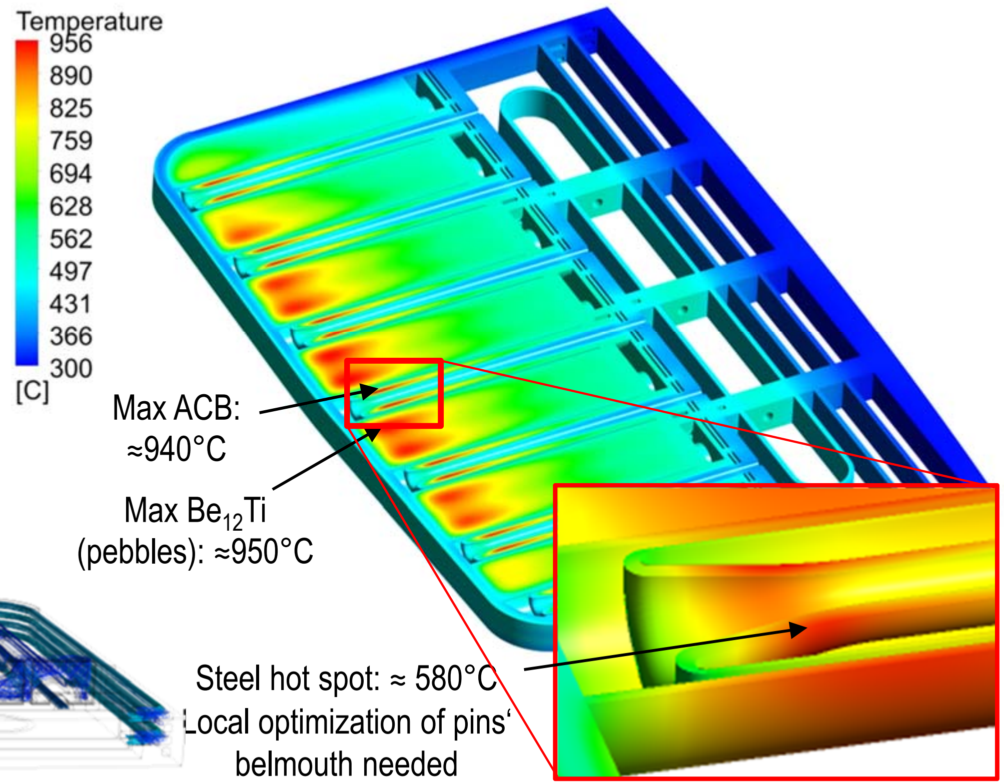


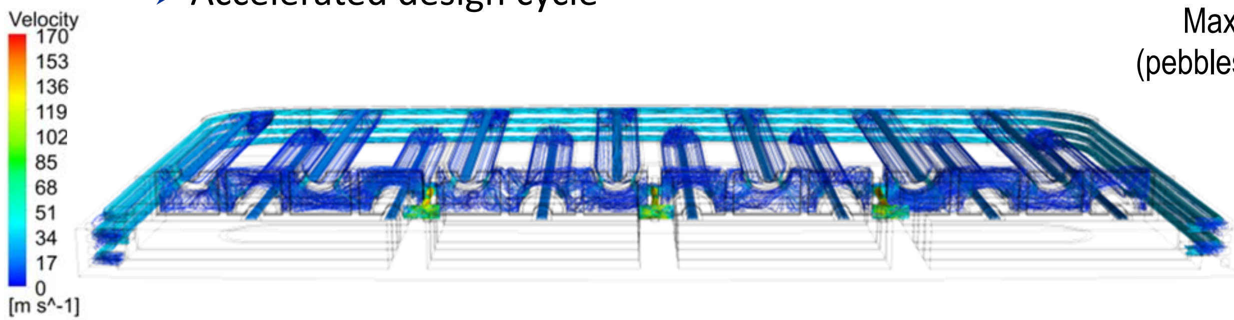
	m [kg/s]	T_{peak} [ºC]	Δp [bar]	
Peak q" 1 MW/m²	0.03	553	0.37	OB
	0.04	509	0.64	
	0.05	482	0.98	
	0.06	464	1.39	
Peak q" 1.2 MW/m²	0.03	593	0.38	
	0.04	542	0.64	IB
	0.05	511	0.98	
	0.06	491	1.39	
Peak q" 1.4 MW/m²	0.03	634	0.38	
	0.04	576	0.64	
	0.05	541	0.98	
	0.06	518	1.39	
Peak q" 1.6 MW/m²	0.03	675	0.38	
	0.04	610	0.65	
	0.05	571	0.98	
	0.06	545	1.39	

4. Performances: BZ thermo-hydraulics

- Fuel-breeder pins design rationale:
  - Maximize size: reduce number pins
  - Large area A (low speed) + rough walls (ε_s/D_h<0.05)
- BZ temperatures and colant Δp:
  - $\Delta p_{\text{fuel-pin (i.e. BZ)}}$ <0.1 bar ($\Delta p_{\text{CP, former designs}}$ ≈1 bar)
  - Unit slice CFD: temperature globaly under limits
  - T_{out} increased to 520°C
- BBS colant pressure drops:
  - to be updated and optimized
    - $\Delta p_{\text{BBS,IB}}$ ≈ 0.91 bar
    - $\Delta p_{\text{BBS,OB}}$ ≈ 0.66 bar
  - Future approach: design optimization with TH system codes (RELAP5)
    - First benchmarks CFD – RELAP5
    - Accelerated design cycle



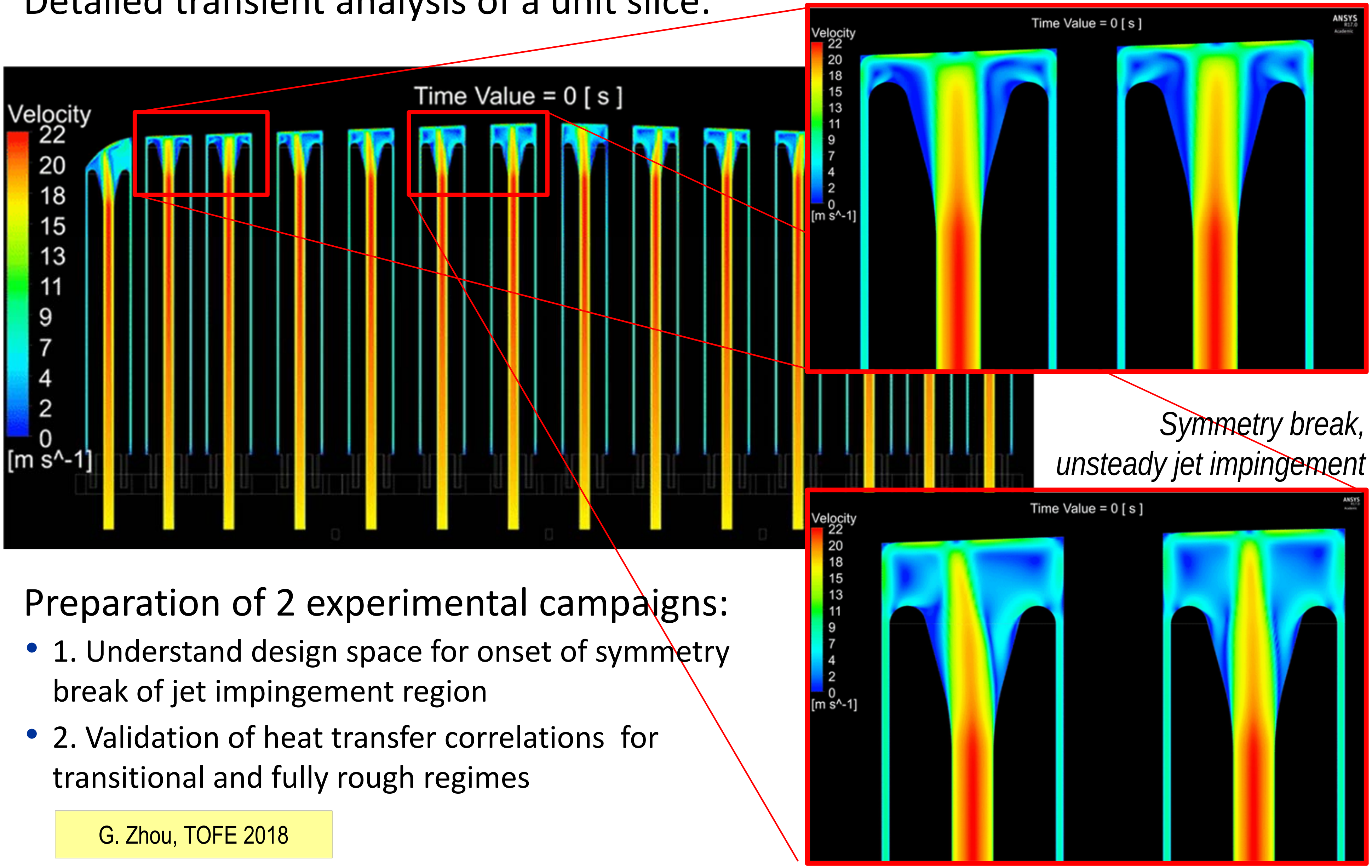




4. Performances: BZ thermo-hydraulics

- Detailed transient analysis of a unit slice:

Symmetry, ≈steady jet impingement



Symmetry break, unsteady jet impingement

- Preparation of 2 experimental campaigns:
  - 1. Understand design space for onset of symmetry break of jet impingement region
  - 2. Validation of heat transfer correlations for transitional and fully rough regimes

G. Zhou, TOFE 2018

Overview

6. Primary Heat Transfer System integration

- HCPB BoP = PHTS (He) + IHTS (MS) + PCS
- Goal BoP: maximize TRL for PHTS
  - PHTS TRL in HCPB mainly limited by He circulator technology currently proven for <6MW/unit

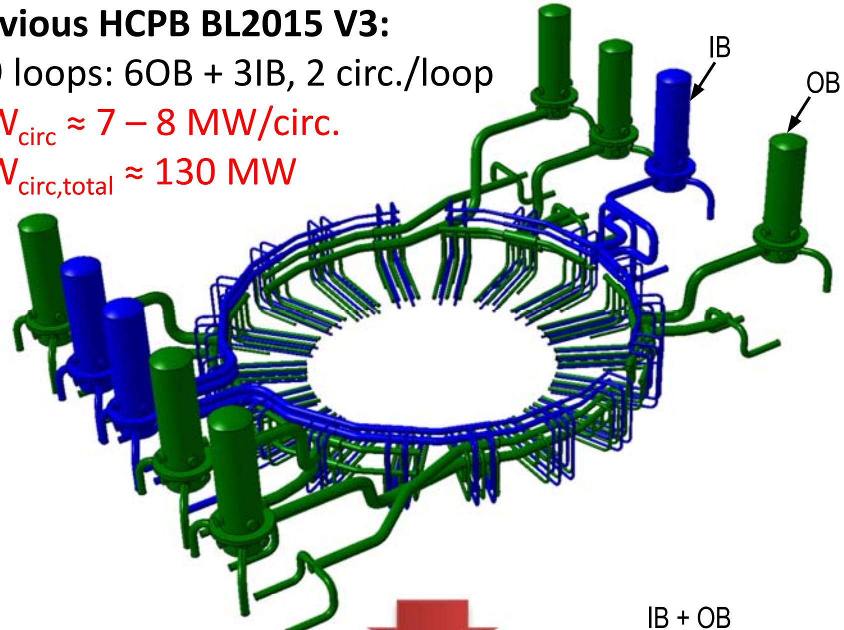
Former *PHTS BL2015*		
Former HCPB design $P_{BB,th} \approx 2100$ MW		
T_{in}/T_{out} He [°C]	**500**/292.5	
Δp [bar]		
	IB	**OB**
In-VV	2.14	1.74
Piping	0.62	0.57
IHX *S&T U-tube* $\Delta T_{log} = 28°C$	0.88	0.85
Total	3.64	3.16
$P_{tot,el}$ [MW]		
130.4	(η_{el}=0.90)	

Proposed *PHTS BL2017*		
HCPB pin design $P_{BB,th} \approx 2100$ MW		
T_{in}/T_{out} He [°C]	**520**/292.3	
Δp [bar]		
	IB	**OB**
In-VV	1.56	1.07
Piping	0.45	0.94
IHX *CWHE* $\Delta T_{log} = 36°C$	0.34	
Total	2.35	
$P_{tot,el}$ [MW]		
83.6	(η_{el}=0.90)	

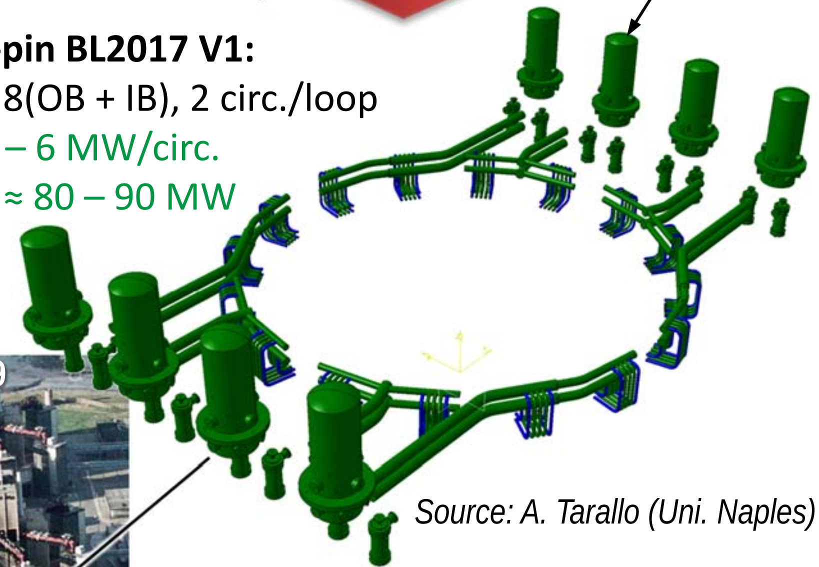
Source: I. Moscato (Uni. Palermo)

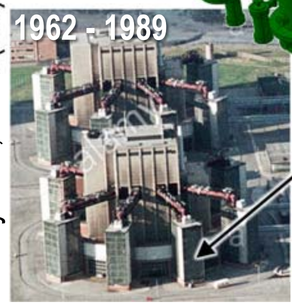
- Target: 60 – 70 MW
  - Key component to optimize now: manifold

Previous HCPB BL2015 V3:
- 9 loops: 6OB + 3IB, 2 circ./loop
- $W_{circ} \approx 7 – 8$ MW/circ.
- $W_{circ,total} \approx 130$ MW



HCPB fuel-pin BL2017 V1:
- 8 loops: 8(OB + IB), 2 circ./loop
- $W_{circ} \approx 5 – 6$ MW/circ.
- $W_{circ,total} \approx 80 – 90$ MW





Berkley NPP, GCR (UK)

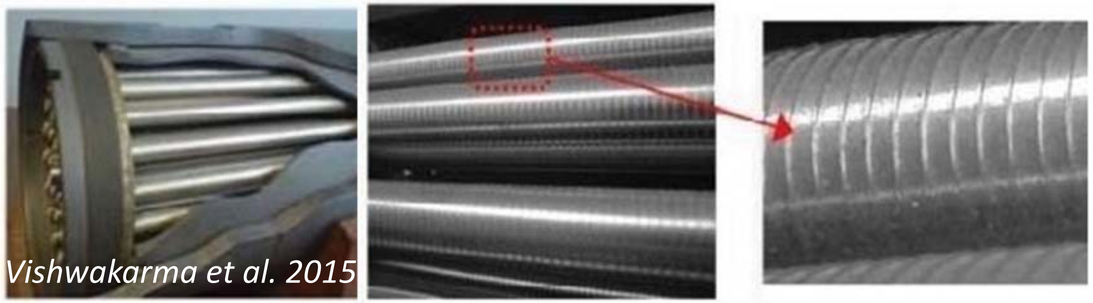
Source: A. Tarallo (Uni. Naples)

Overview

7. Summary and outlook

- EU DEMO development strategy: holistic (systems engineering) design
  - Many interfaces, requirements, some drive design => lessons learned => enhanced HCPB, fuel-pins
- Maximize/exploit commonalities of solid BB (fusion) with solid core (fission)
  - Lesson learned for heat transfer enhancement with low Δp with common approach to GCR program

AGR fuel element

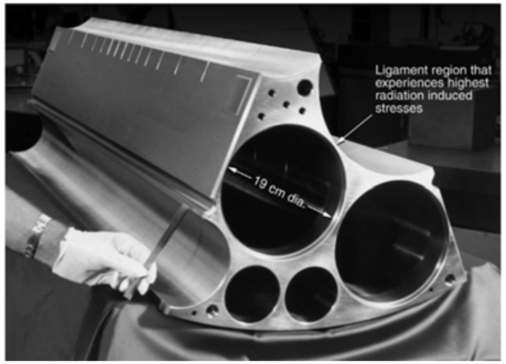


  - Multiplier ($Be_{12}Ti$) prismatic blocks: common configuration to other Be-moderated reactors

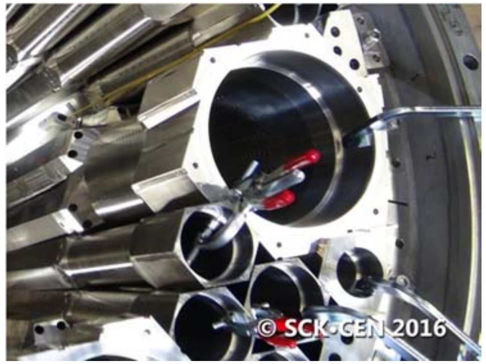
MIR (RF, 1967-today)

ARE (US, 1940s)

ATR (US, 1967-today)



BR2 (BE, 1962-today)



7. Summary and outlook

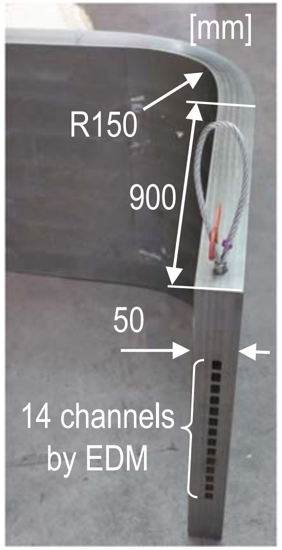
- EU DEMO development strategy: holistic (systems engineering) design
  - Many interfaces, requirements, some drive design => lessons learned => enhanced HCPB, fuel-pins
- Maximize/exploit commonalities of solid BB (fusion) with solid core (fission)
  - Lesson learned for heat transfer enhancement with low Δp with common approach to GCR program
  - Multiplier/moderator ($Be_{12}Ti$) prismatic blocks : inspiration from Be-moderated reactors
- Design research led to the HCPB fuel-breeder pin design
  - Milestone: record low reactor circulating power (80-90MW)! Aim at 60-70MW
  - AGR-like PHTS, state-of-the-art He-turbomachinery can be used => milestone of high BoP-TRL!
  - Simpler internals, manufacturing, functional materials => cost reduction and RAMI improvement
- Main R&D needs for near future
  - Near term: validation of fuel-breeder pins thermohydraulics with 2 tests in HELOKA
    - 1. Determination of design space range for onset on symmetry break of jet-impingment region
    - 2. Validation of heat transfer correlations for transitional and fully rough regime in FW and BZ (pins)
  - Mid term: multiple-effects experiment with fuel-pin bundle in HELOKA
  - Functional materials: proof of industrial scale and irradiation campaign

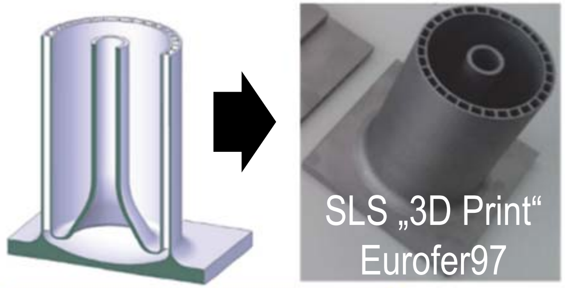
✉ *francisco.hernandez@kit.edu*

Back-up slides

5. Manufacturing and costs

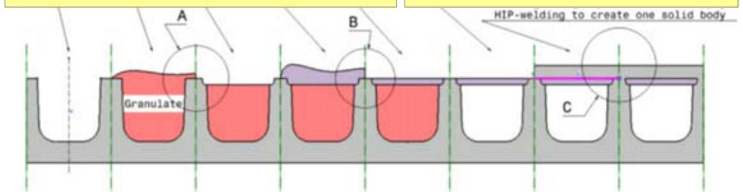
- Manufacturing and costs:
  - Fuel-pins: conventional fabrication
  - FW former enabler technology: EDM + forming, but costs increase rapidly with length of EDM
  - New approaches: „Metal Powder Application“ (MPA) or „fail-safe“ (Commin, 2013),
    - ➢ Less limitations, cost reduction ≈50% w.r.t EDM
  - Alternative: SLS, but not in code (e.g. RCC-MRx)





H. Neuberger, SOFT 2018

C. Köhly, SOFT 2018



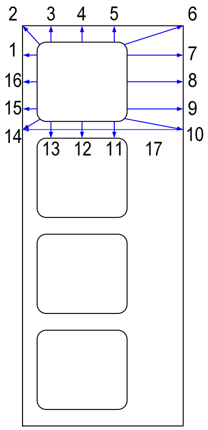
- RAMI:
  - *„Main Challenge of Fusion “ (D. Maisonnier, 2017); „Achilles Heel for Fusion“ (M. Abdou):*
    - ➢ Imperative to include RAMI relevant aspects into design from beginning
  - Initial scoping RAMI studies:
    - ➢ Design seems more robust against degraded operation due to higher modularization
    - ➢ 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 Fail Rate Ratio (2)/(1)
Cooling channels/ small pipes	1461 km	300 km	-	-79.4%	Clogging	-70%
Welds as seals for in-BB leak	167 km	94 km	rectang. vs. orbital	-43.6%	In-BB coolant leak	-51%* / +159%**
Welds as seals for in-VV leak	23 km	10 km	linear vs. linear	-54.2%	In-VV coolant leak	-57%

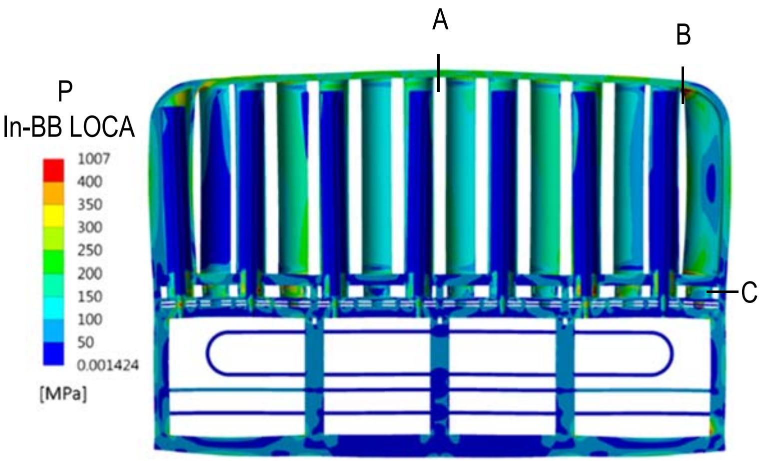
*Estimation considering number AND unit length of welds
**Conservative estimation considering ONLY no. of welds
HIP welds not included / Reliability differences linear vs. orbital welds not included

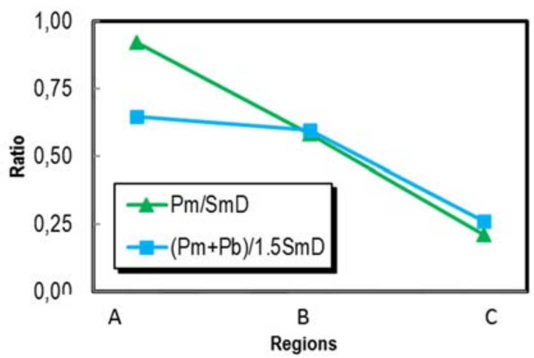
3. HCPB performance highlights: Thermo-mechanics

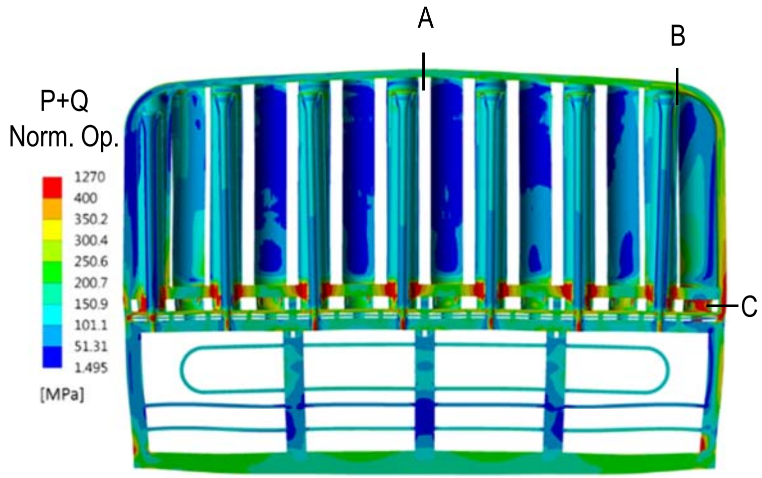
- Accidental scenario
  - In-box LOCA: level D, globaly ok
- Normal operation
  - Monotonic modes: level A, globaly ok
    - ➢ Design optimization needed for local peak stresses
    - ➢ Revision of the IPFL mode: overly-conservative for EUROFER97

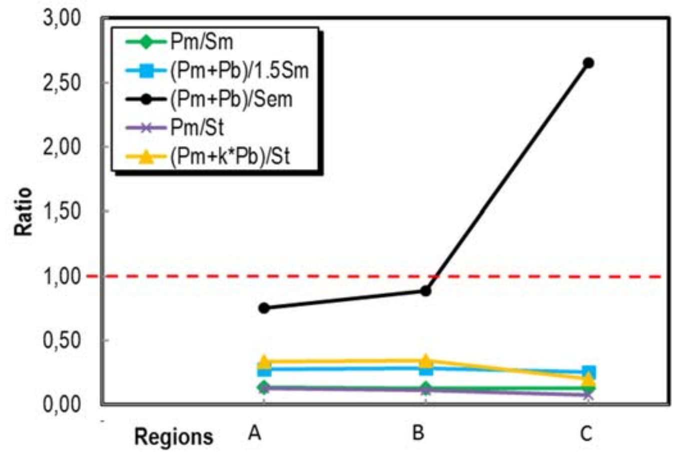


Display of paths for stress linearization



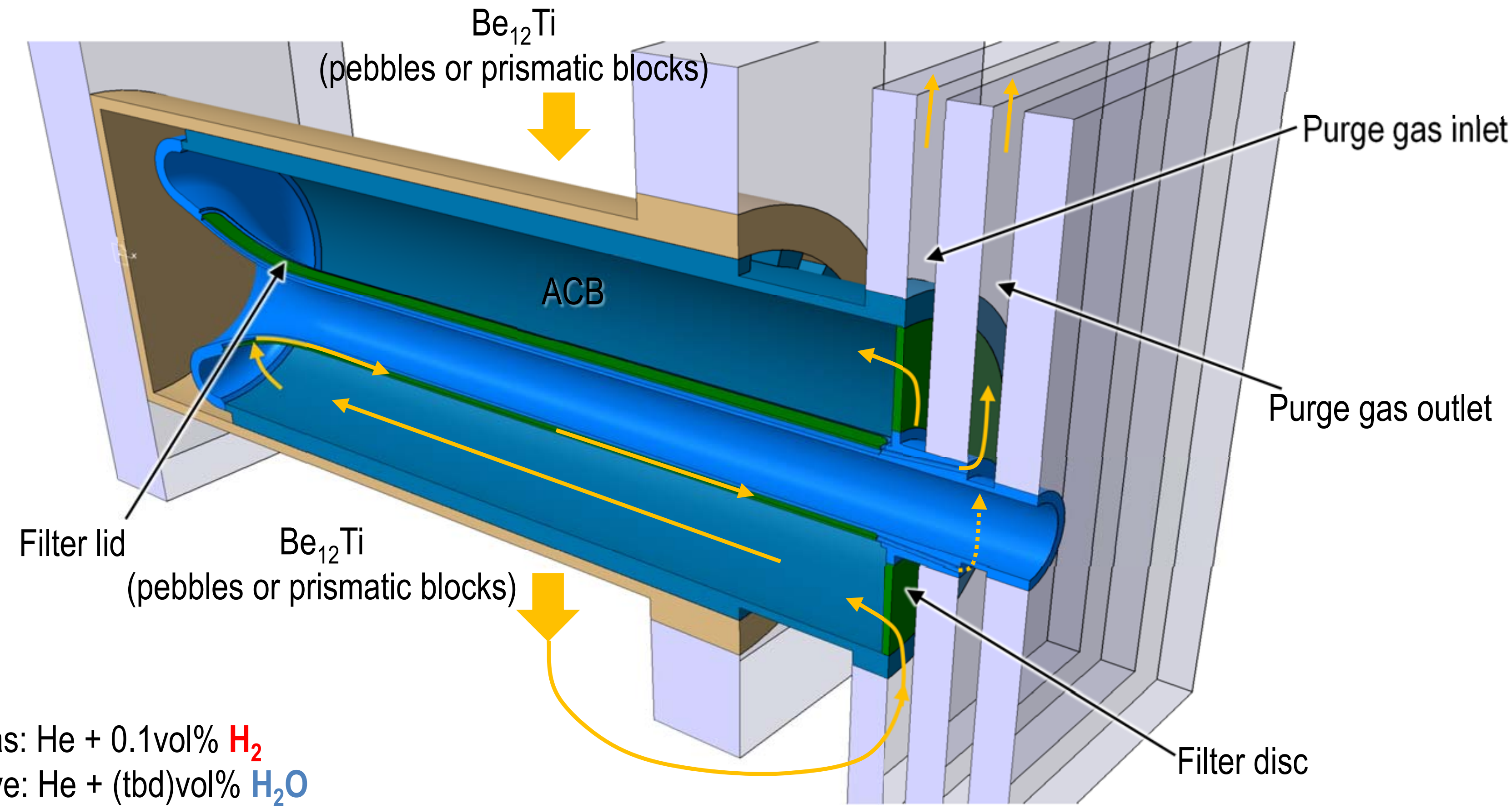






Purge gas loop in BZ

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

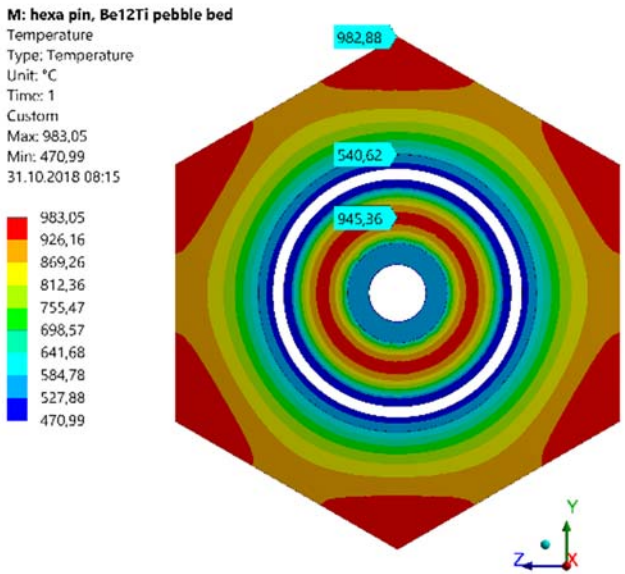


Purge gas: He + 0.1vol% H_2
alternative: He + (tbd)vol% H_2O

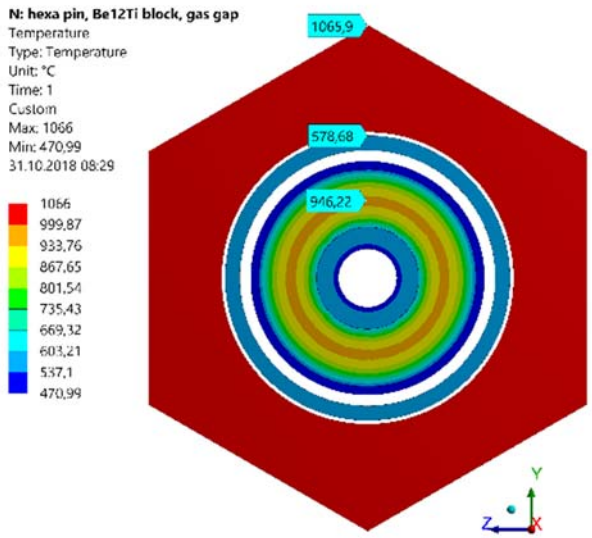
3. HCPB design: rationale and performances

- Sensitivity analysis on thermal conductivity degradation

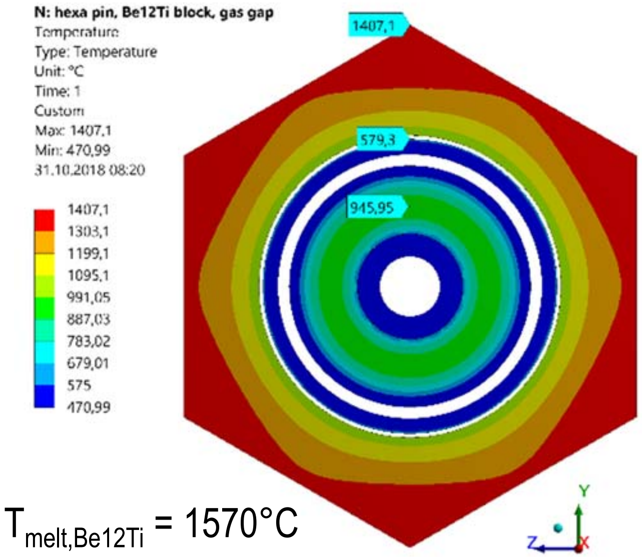
Cross section ≈50mm behind FW
$Be_{12}Ti$ pebble bed



Cross section ≈50mm behind FW
$Be_{12}Ti$ prismatic block, 1mm gas gap
Conductivity as in Be-Ti HIDOBE2
650°C@37.1 dpa



Cross section ≈50mm behind FW
$Be_{12}Ti$ prismatic block, 1mm gas gap
Hypothetical EoL, conductivity as a pebble bed

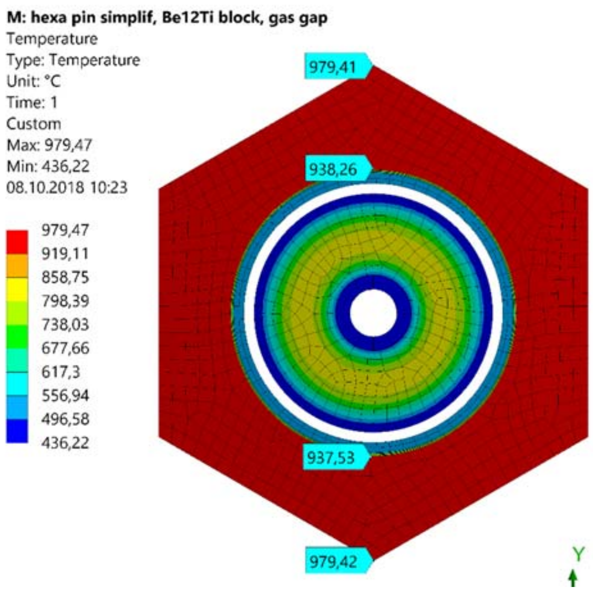


$T_{melt,Be12Ti}$ = 1570°C

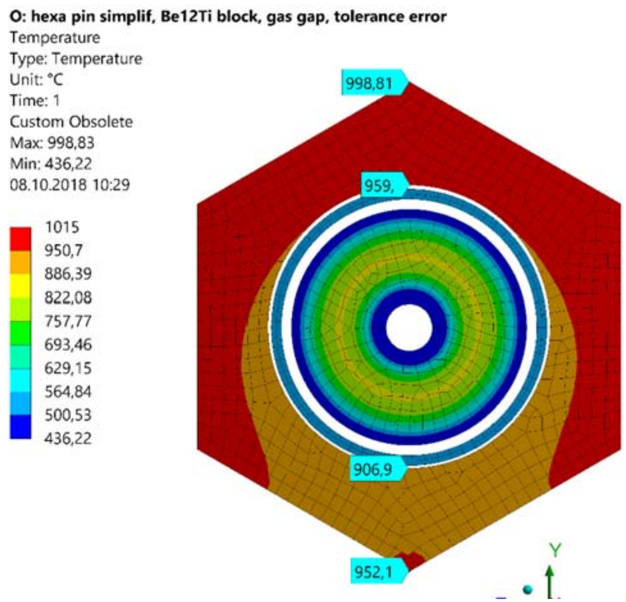
- Conclusions:
  - No melting of beryllide even under hypothetical case of block reduced to a pebble bed

Outcomes from CMSB simulation

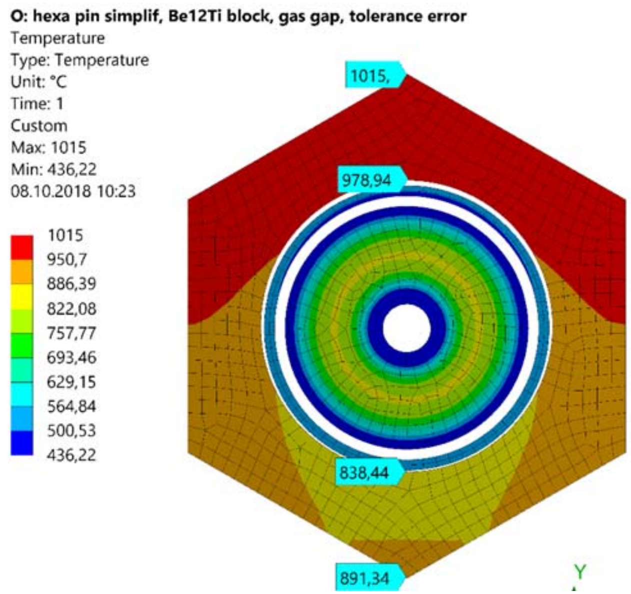
- Sensitivity analysis on concentricity mismatch tolerance error of prismatic $Be_{12}Ti$ blocks with He gas gap



1mm He gas gap



1mm He gas gap, 0.2mm concentricity error



1mm He gas gap, 0.5mm concentricity error

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