Karlsruhe Institute of Technology

TBM Consortium of Associates

Solid and Liquid Breeder Blankets

Forschungszentrum Karlsruhe in der Helmholtz-Gemeinschaft

Universität Karlsruhe (TH) Research University • founded 1825

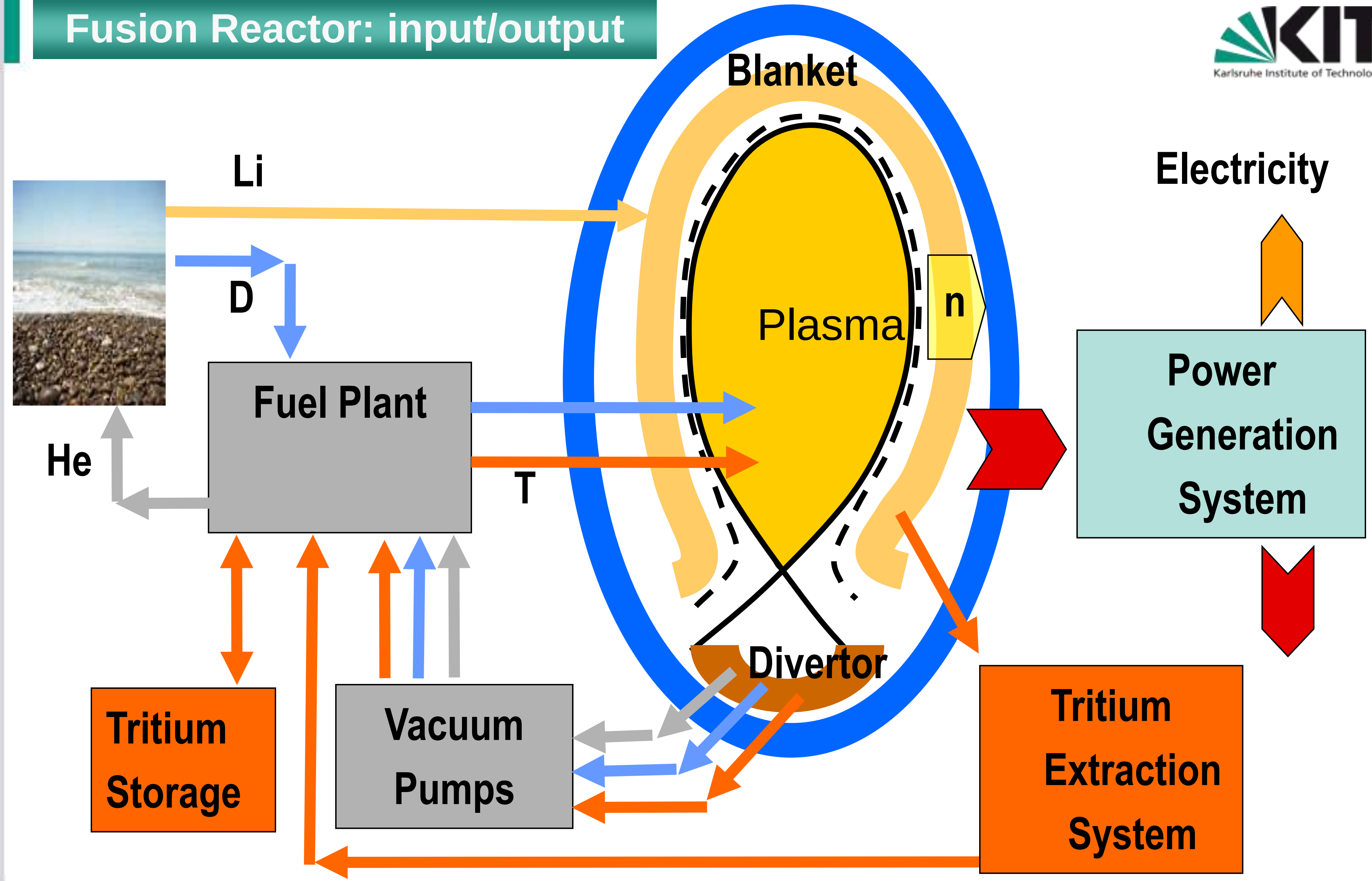
Dr Fabio CISMONDI

Karlsruher Institut für Technologie (KIT)

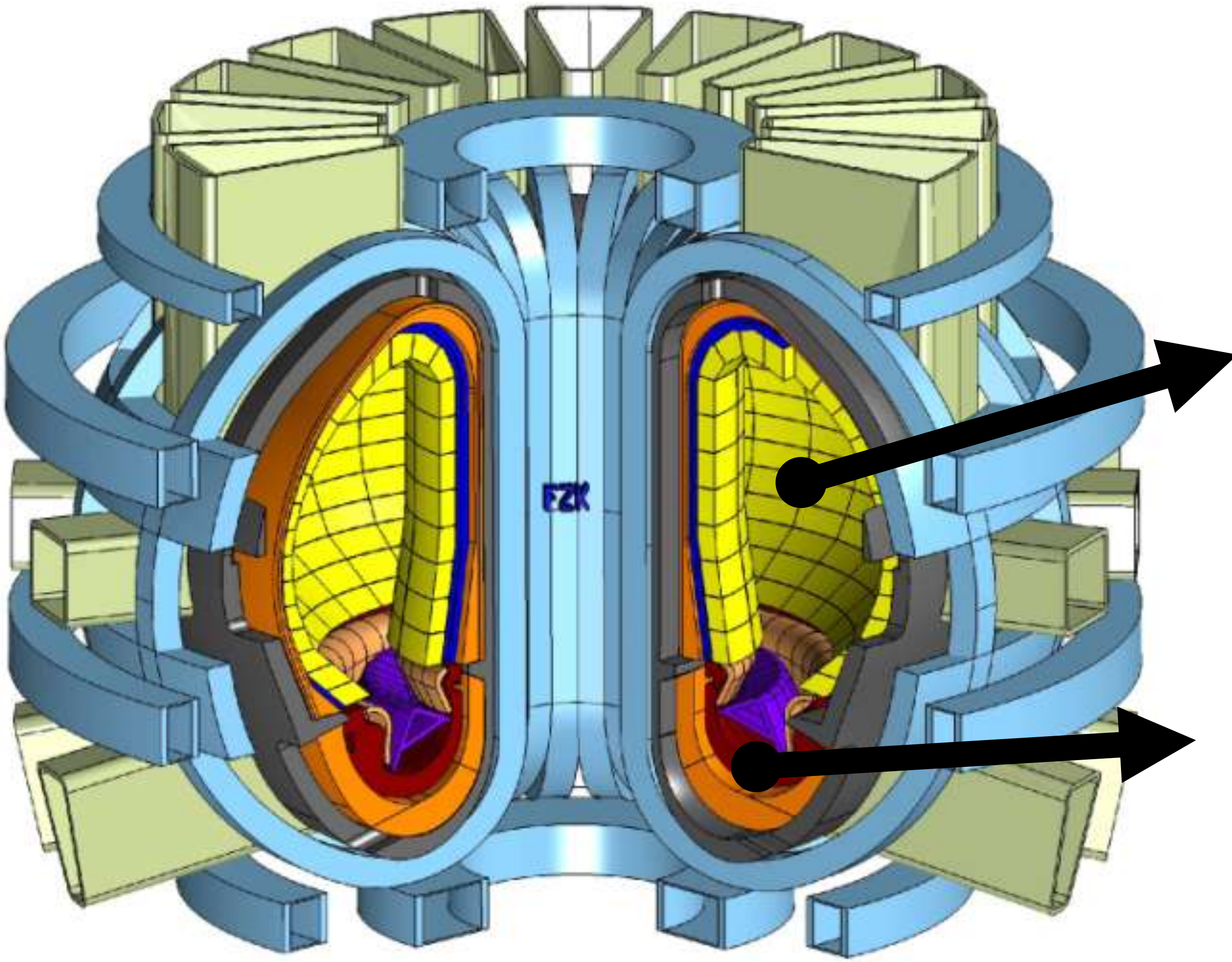
Institut für Neutronenphysik und Reaktortechnik

e-mail: fabio.cismondi@kit.edu

Fusion Reactor: input/output



Fusion Reactor Core



Blanket

-T production

- high temperature coolant for electricity production

- Remote replacement 3 - 5 years (80...150 dpa)

Divertor

- Exhaust alfa and impurities from plasma
-Contribute to electricy production
- Remote replacement 1.5 - 2.5 years

Breeding blankets functions and requirements

Main functions of the blanket:

1. Tritium production (breeding) and extraction
2. Transforming surface and neutron power into heat and collection of the heat for electricity production
3. Contribute to the shielding of the Vacuum Vessel and Toroidal Field Coils

The design has to be featured in order to achieve:

1. Low maintenance time
2. Sufficiently long lifetime
3. High safety level (e.g. accidents, operations, etc.) and low environmental impact (including waste)
4. Reasonable direct cost including operation (e.g. small dimensions, high efficiency, etc.)

Blanket concepts

Karlsruhe Institute of Technology

In general there are three types of blanket concepts

1.) Ceramic Breeder Blanket (solid breeder)
- a) Helium-cooled HCPB
- b) Water-cooled in Japanese concept

2.) Self Cooled Liquid Metal Blanket

The liquid breeder cools the structure

3.) Liquid Metal Blanket with Helium cooling

The structure is cooled by Helium
and the Breeder in the Blanket is
- a) also cooled by Helium and moved slowly (HCLL)
- b) Breeder is not cooled but moved fast (DCLL)

Structural material

- **Reduced activities characteristics:** e.g EUROFER can be recycled after ~100 years storage.

- **Withstand vs. radiation damages:** e.g. EUROFER target 80 up to 150 dpa.

- **Compatibility with breeder/multiplier and coolant** (e.g. corrosion): EUROFER is compatible (up to 550°C with Solid Breeder and Be); corrosion with PbLi is an issue starting from 450°C.

- **Temperature window**: EUROFER >300-550°C, SiC_f/SiC ~600-1100°C, V-4Cr-4Ti ~400-650°C

- **Thermal properties:** conductivity, thermal expansion, allowable stress, etc.: good for EUROFER and V-alloy. Worst for SiC_f/SiC due to low conductivity.

- **Code and Standards:** e.g. EUROFER is under an EU programme with the aim to qualify it for ITER up to 3 dpa (in 2018) and up to 80 dpa for DEMO (~2030).

- **EUROFER is a ferritic martensitic steel:** C12%, Cr9%. Very low content of Ni, Mo, Nb. Substituted by V, W and Ta.

- **SiC_f/SiC: Silicon carbide composites** are attractive as structural materials in fusion environments because of their **low activation, high operating temperature and strength.**

- **V-alloy:** it exhibits **favorable neutronic properties** which include lower parasitic neutron absorption leading to better tritium breeding performance (e.g Li-V blankets).

Coolant

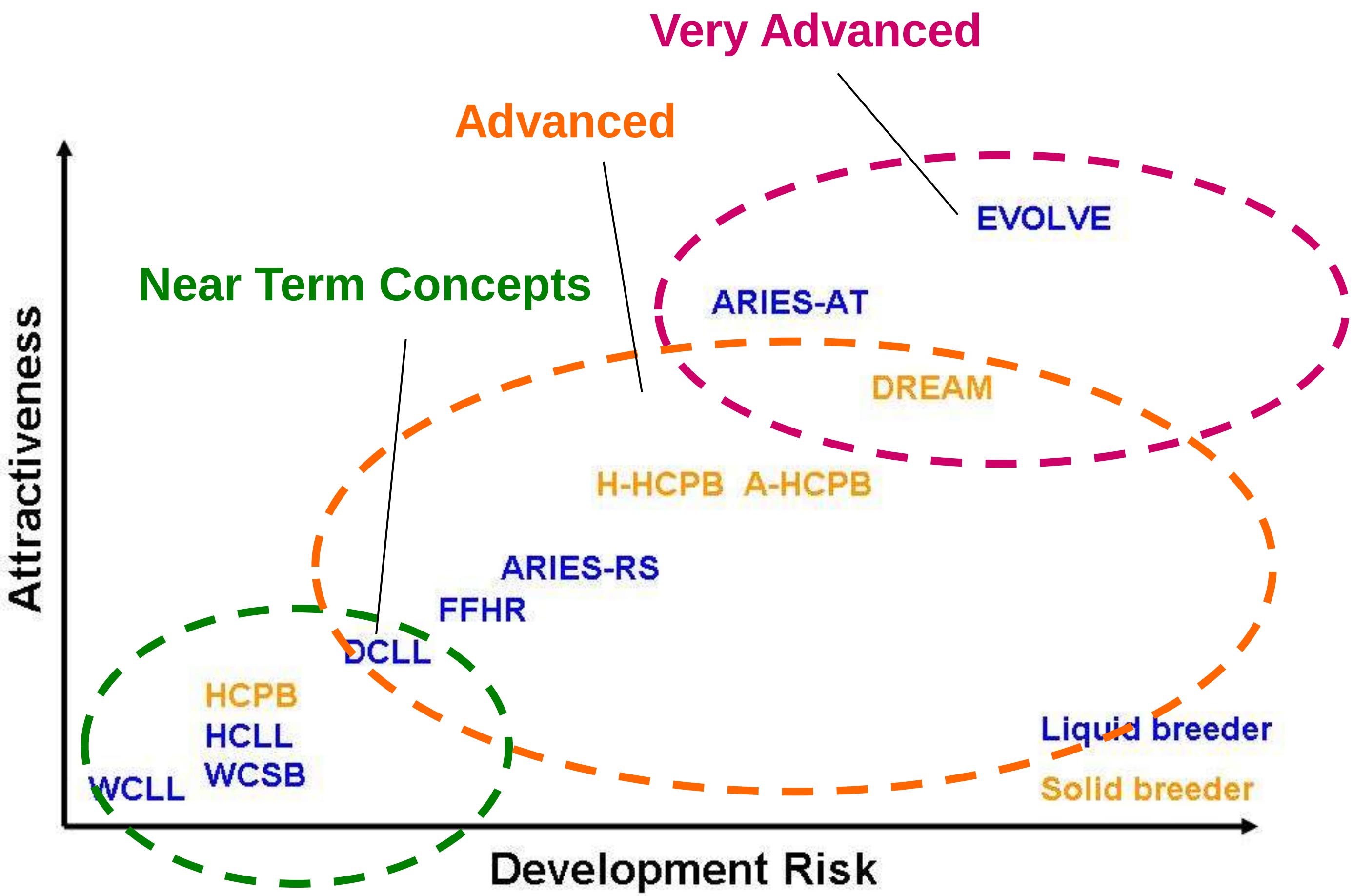
Water:
exceptional cooling capability. High density that allow small flow section. Low ΔT in Blanket. PWR range (275-315°C @15.5 MPa): lower temperature range for use with F/FM steels. Corrosion. Issue with T contamination.

Helium:
exceptional compatibility with the material used in blanket and other part of the reactor. Possibility to cope with all the temperature windows of the materials. Lower heat removal features and higher pumping power. Large tubes with low shielding features (issue for the reactor integration of pipes and manifolds).

Liquid Metal (PbLi and Li):
high heat removal capability but strongly conditioned by MHD effects (suitable only if insulation barriers with conducting structures are available). Low pressure. Must accomplish the double functions of heat removal and T transport. Corrosion.

Molten salt (FLiBe):
Low pressure. Must accomplish the double functions of heat removal and T transport. High corrosion issues. Low thermal conductivity. Difficult chemistry.

Blanket concepts



Not exhaustive

Classification according to:

- Maturity level (near term -> Very Advanced)
- Structural material (e,g. steel, SiC_f/SiC or V-alloy)
- Breeder / multiplier (solid and liquid breeder)
- Coolant (water, gas, liquid metal, molten salt)
- Heat and T extraction (e.g. Self Cooled, Dual Coolant)

Near term Blanket concepts

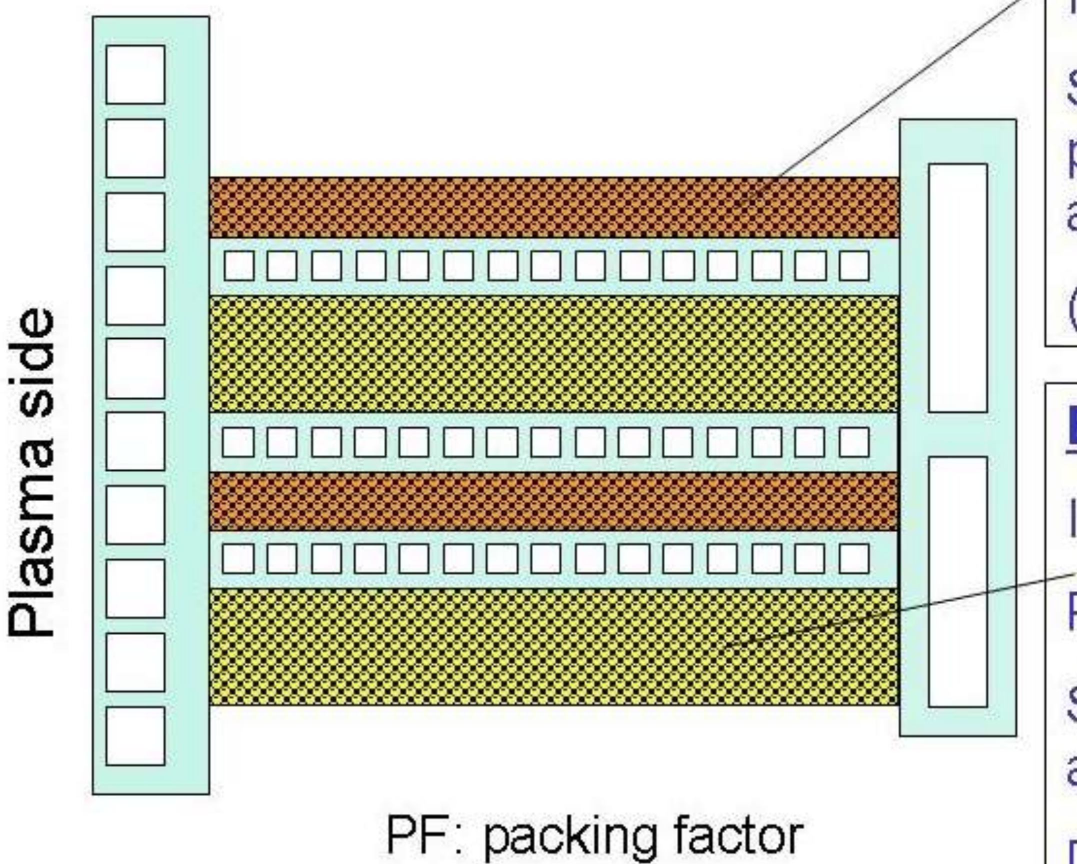
Concept	Structural Material	Breeder/Multiplier	Coolant	T-Extraction	Known Blanket Concepts
HCSB (*)	RAFM (**)	Ceramic Breeder /Beryllium	Helium	He low pressure purging	**EU, Japan, China, Korea, RF, (US)**
WCSB	RAFM (**)	Ceramic Breeder /Beryllium	Water	He low pressure purging	**Japan**
HCLL	RAFM (**)	PbLi	Helium	PbLi slow recirculation	**EU**
DCLL	RAFM (**)	PbLi	Helium PbLi	PbLi fast recirculation	**US, EU, China**

(*) in EU the HCPB (Helium Cooled Pebble Bed) is the solid breeder concept
(**) in EU EUROFER is the RAFM steel under development

Legenda: HC = Helium Cooled; WC = Water Cooled; SB= Solid Breeder;
LL = Lithium-Lead; DC = Dual Coolant; SC = Self Coolant

Note: in this category only concepts that use RAFM (reduced activation ferritic martensitic) steels are present.

HCPB: Breeder and neutron multiplier



Ceramic breeder in form of a pebble bed.

Materials: Li_4SiO_4 (or Li_2TiO_3)

Single bed at 64% PF with pebbles of D=0.2-0.6 mm and about 10 mm thickness

(or D=~1mm for Li_2TiO_3)

Be Multiplier:

In form of a Pebble beds

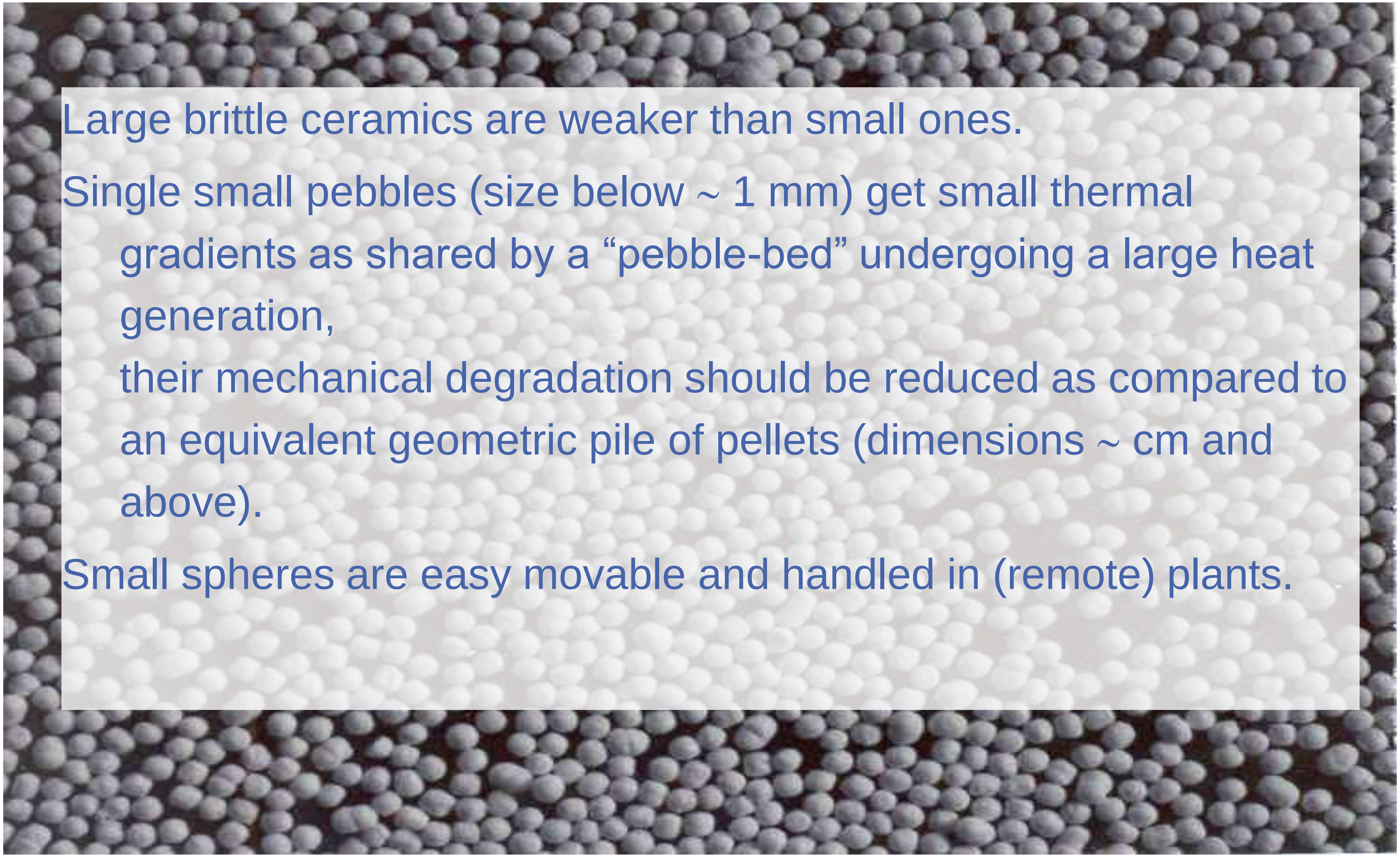
Pebble D=~1mm

Single bed at 64% PF with about 40 mm thickness

[or Binary (82% PF)]

Solid breeder shape pebbles vs. pellets

KIT – Karlsruhe Institute of Technology



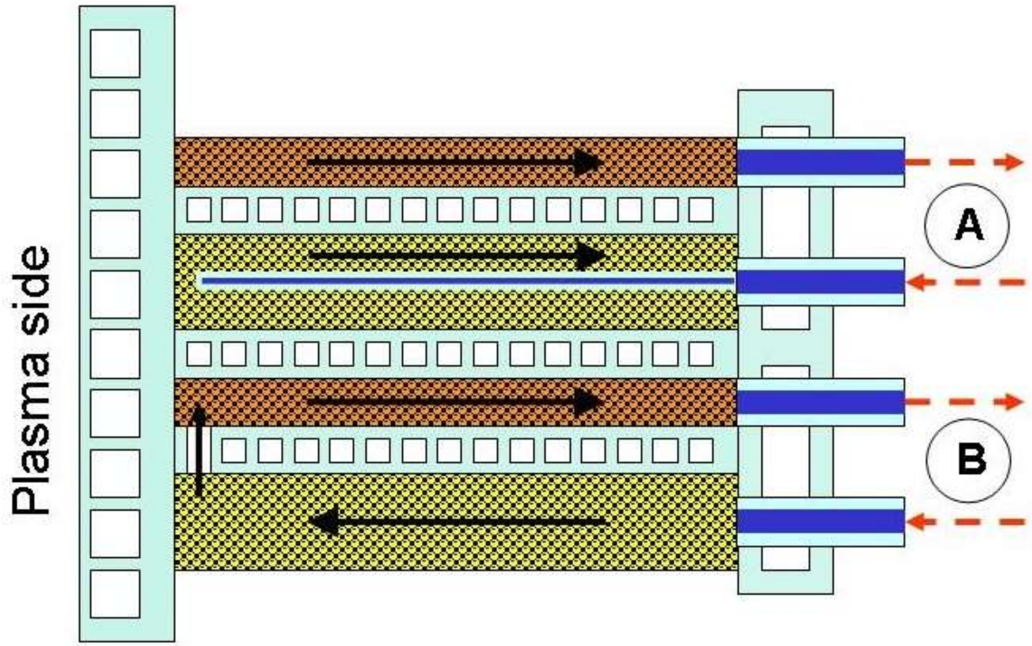
Large brittle ceramics are weaker than small ones.

Single small pebbles (size below ~ 1 mm) get small thermal gradients as shared by a “pebble-bed” undergoing a large heat generation,

their mechanical degradation should be reduced as compared to an equivalent geometric pile of pellets (dimensions ~ cm and above).

Small spheres are easy movable and handled in (remote) plants.

HCPB: Tritium extraction



To possible variants: in B the radial direction in the Be beds is reversed. The direction in CB is important for T control.

Purge flow:

Tritium extraction in CB and Be.

Independent loop.

Pressure ~0.4 MPa

Chemical composition (H_2 addition, ref 0.1% to enhance T extraction from CB)

Mass flow: to optimise in order to reduce H circulation and minimise T partial pressure (~10 cm/sec).

CB=Ceramic Breeder

A Li-ceramic breeder list with main properties

Items \ Materials	Li_2O	Li_2TiO_3	Li_2ZrO_3	Li_4SiO_4	γ-$LiAlO_2$
Li Density (g/cm³)	0.94	0.43	0.38	0.51	0.27
Thermal Conductivity (500°C)•(W/m°C)	4.7	2.4	0.75	2.4	2.4
Thermal Expansion (500°C)•(DL/L₀%)	1.25	0.8	0.50	1.15	0.54
Reaction of Water	very	less	less	little	little
Residence Time (440°C)•(h)	0.03	(-)	0.01	3.0	50
Swelling* (DV/V₀%)	7.0	(-)	<0.7	1.7	<0.5
Transmutation Nuclides	^{16}O(n,p):7s	^{46}Ti(n,p):84d ^{47}Ti(n,p):3.4d ^{48}Ti(n,p):1.8d	^{90}Zr(n,p):64h ^{91}Zr(n,p):57d ^{94}Zr(n,2n):10^6y ^{96}Zr(n,2n):64d	^{28}Si(n,2n):4s ^{29}Si(n,p):6m ^{30}Si(n,α):9m	^{27}Al(n,2n):6s ^{27}Al(n,p):9.5m ^{27}Al(n,α):15h
Melting Point (°C)	1430	1550	1615	1250	1610

Important for Tritium breeding rate

Operation T < 0.6..0.8 x T_m sintering closes pores

Solid breeder comparison

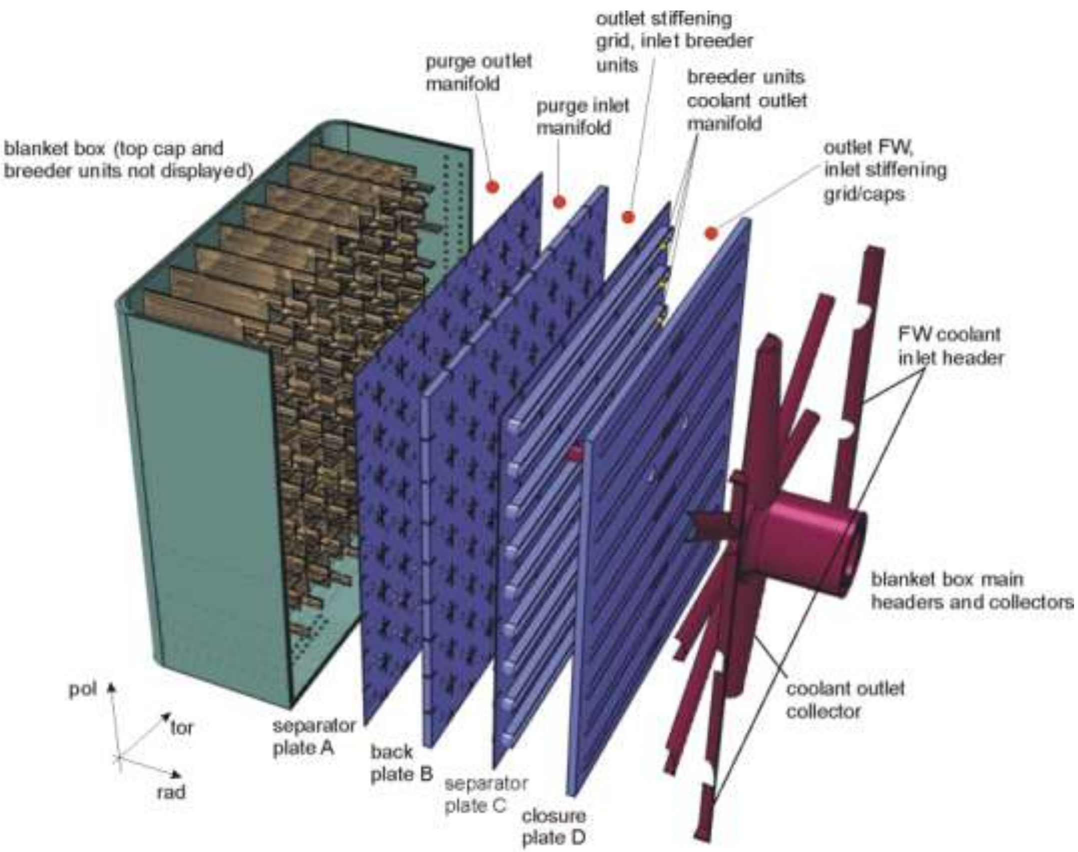
- **Li_4SiO_4** **medium lithium content;**
  fair mechanical properties, hygroscopic, fair tritium residence time, higher thermal expansion

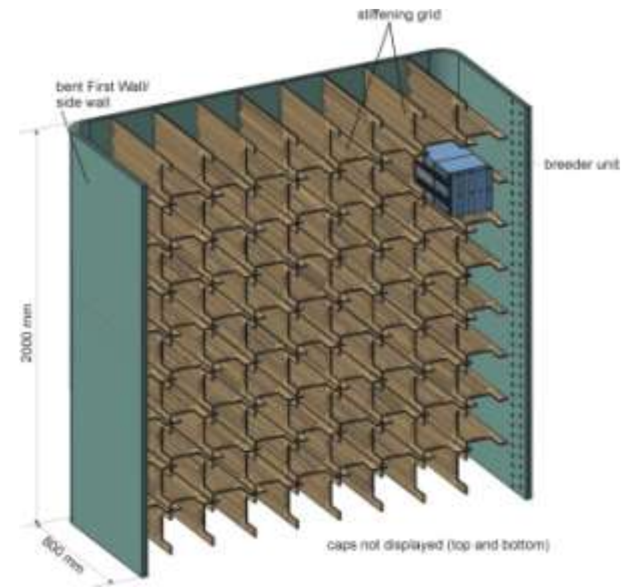
- **Li_2TiO_3** **low lithium content;**
  good mechanical properties, not hygroscopic, fair tritium residence time, lower thermal expansion

- **LiO_2** **highest lithium content;**
  Good conductivity; large thermal expansion
  Poor mechanical behavior;
  precipitate formation (LiOH) → loss of Li

HCPB: Hermsmeyer-Malang (FZK, 2003)

Karlsruhe Institute of Technology

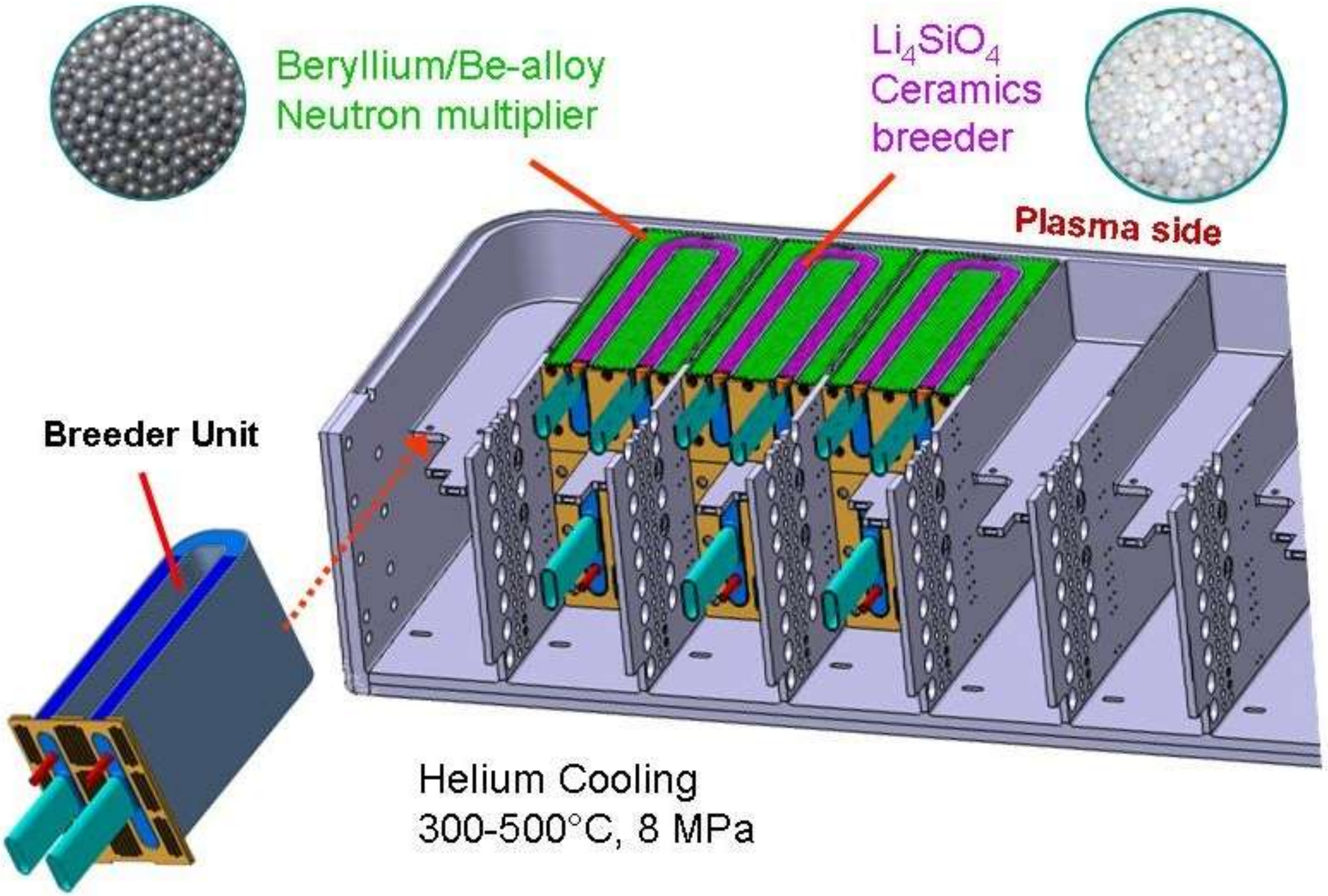




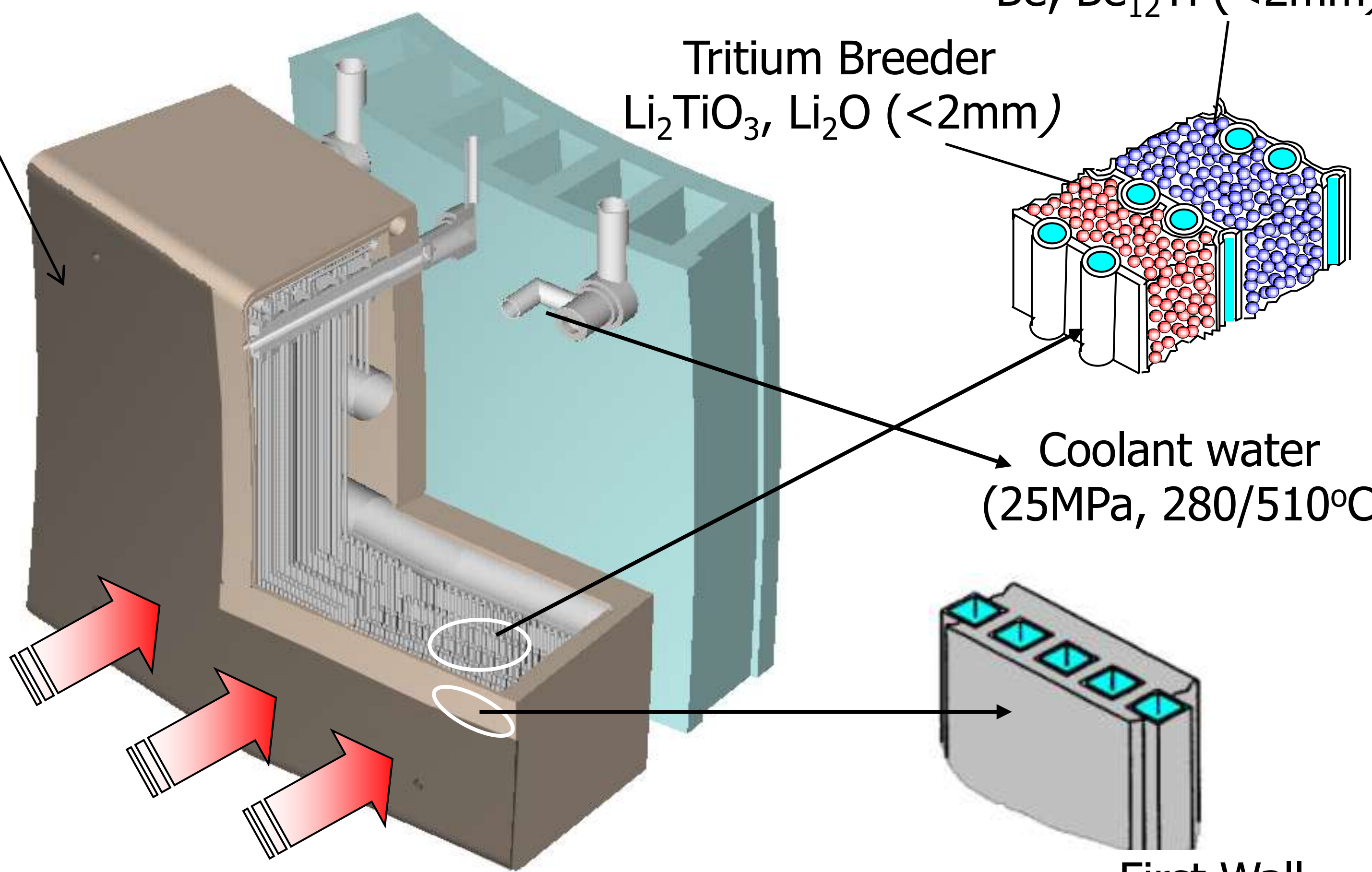
Operational parameters	HCPB/HCLL
FW heat flux (peak)	**0.5 MW/m²**
Neutron wall load (peak)	**2.4 MW/m²**
Power Generation System	**Rankine**
Pressure Coolant	**He: 8 MPa**
Temperature Coolant	**He: 300 – 500°C**

Box Dimensions: 2m (pol) x 2 m (tor)

HCPB for ITER

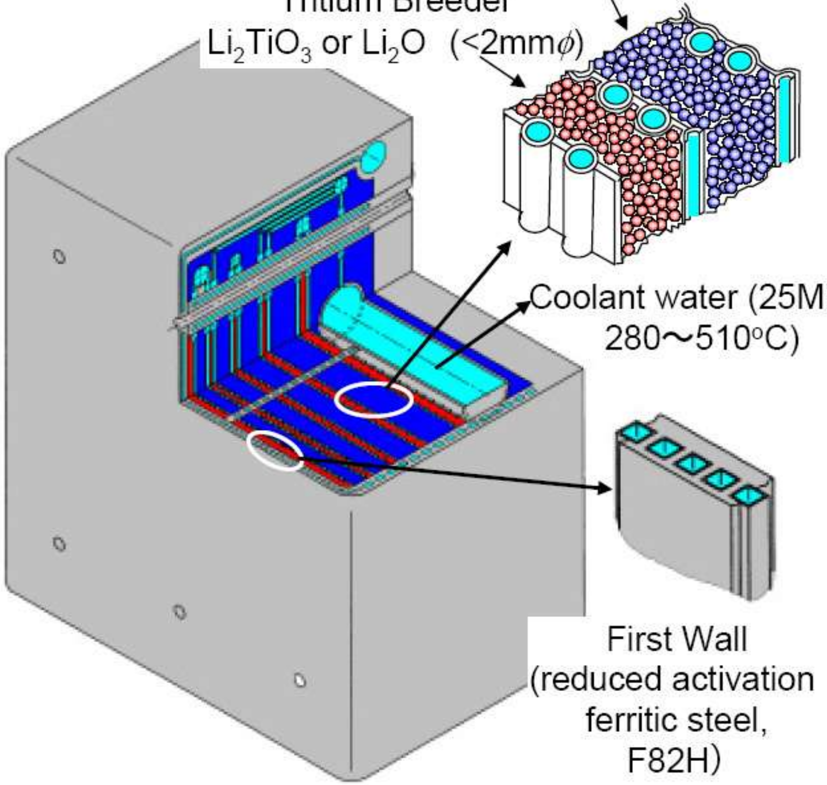


Japanese solid breeder concept

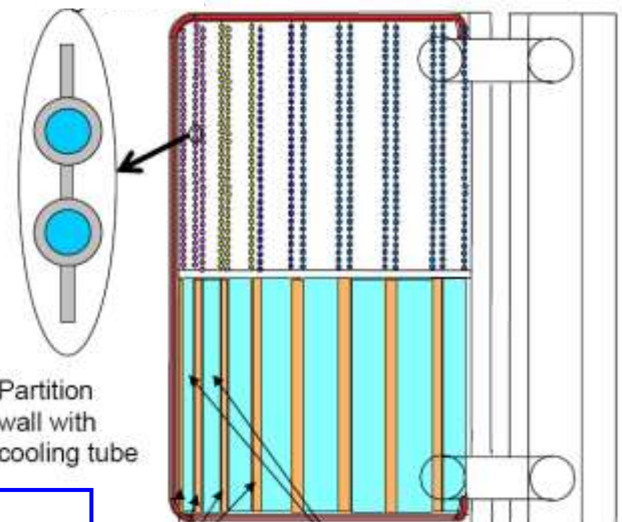


Surface Heat Flux: 1 MW/m^2
Neutron Wall Load: 5 MW/m^2(1.5×10^{15}n/cm^{2}s)

Japanese solid breeder concept



Tritium breeder	:Li_2O or Li_2TiO_3
Neutron multiplier	:Be or $Be_{12}Ti$
6-Li enrichment	:Natural to 90 %
Structural material	:Reduced activation ferritic steel
Coolant	:Supercritical water (25 MPa, 280 – 510 °C)
Blanket structure	:Modular structure, front access by remote handling
Dimension	:1 m x 2m, < 4 ton



Radial-toroidal view

Liquid Breeders

Several liquid breeder concepts have been proposed, all have key feasibility issues.

Selection needs additional R&D and fusion testing.

Type of Liquid Breeder:

a) Liquid Metal: Li, $PbLi_{eu}$(15.7 at%).

High conductivity, low Pr number, melting point: ~235°C for $PbLi_{eu}$

Dominant issues: MHD, chemical reactivity for Li (corrosion and water reaction), tritium permeation for LiPb

b) Molten Salt: Flibe $(LiF)_n \cdot (BeF_2)$, Flinabe (LiF-BeF_2-NaF)

Low conductivity, high Pr number, melting point Li_2BeF_4 : ~459°C, not flammable and does not react with air or water

Dominant Issues: Melting point, chemistry, tritium control, corrosion.

European concepts and TBMs

- **Helium Cooled Pebble Beds (HCPB)** and **Helium Cooled Lithium Lead (HCLL) Test Blanket Modules (TBMs)** are the two DEMO blankets concepts selected by EU to be tested in ITER.

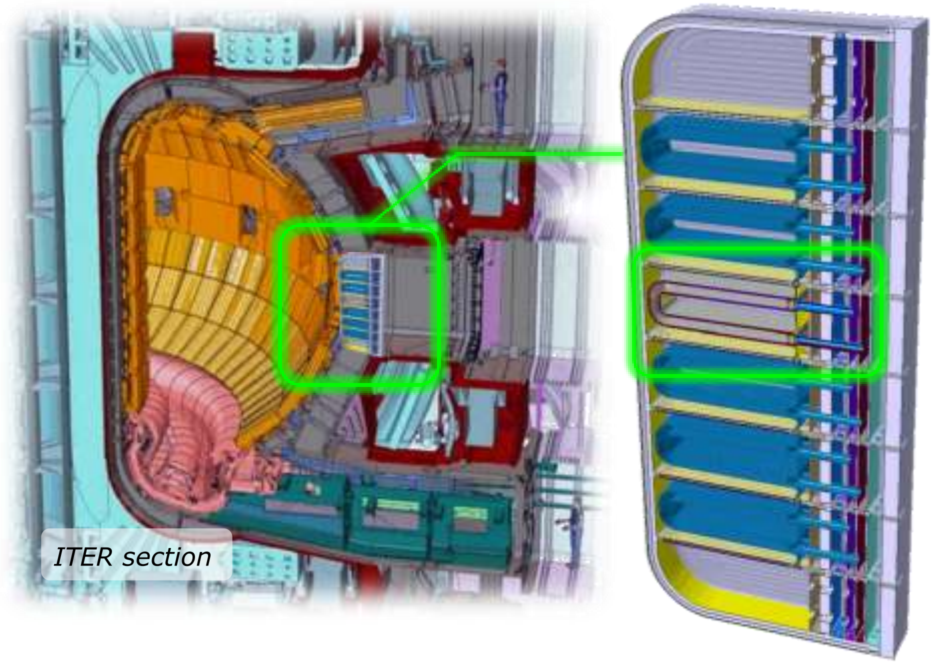
- The Test Blanket Systems (TBS) are developed by different Associations throughout EU.

- The European Joint Undertaking "Fusion for Energy" is in charge of delivering the Test Blanket Modules System (TBS) to ITER.

- The European partners developing the TBS are joint together into a **Consortium Agreement (TBM-CA).**

- The TBM CA works under contracts with F4E

- KIT and CEA develop within TBM CA the design of the HCLL and HCPB TBMs.



TBM-CA is a strategic and organisational cooperation among Associates **(CEA, CIEMAT, ENEA, FZK, NRI and RMKI)** to implement contracts with the domestic agency to **develop, produce, qualify, install and operate the EU TBM Systems in ITER.**

TBM Consortium of Associates

European TBMs

TBM test programme main objectives in ITER

- Demonstrate tritium breeding capability and verify on-line tritium recovery and control systems;
- Ensure high grade heat production and removal;
- Demonstrate the integral performance of the blanket systems in a fusion relevant environment;
- Validate and calibrate design tools and database used in the blanket design process.

DEMO relevancy:
HCPB and HCLL TBMs insure maximum resemblance to the corresponding DEMO blanket

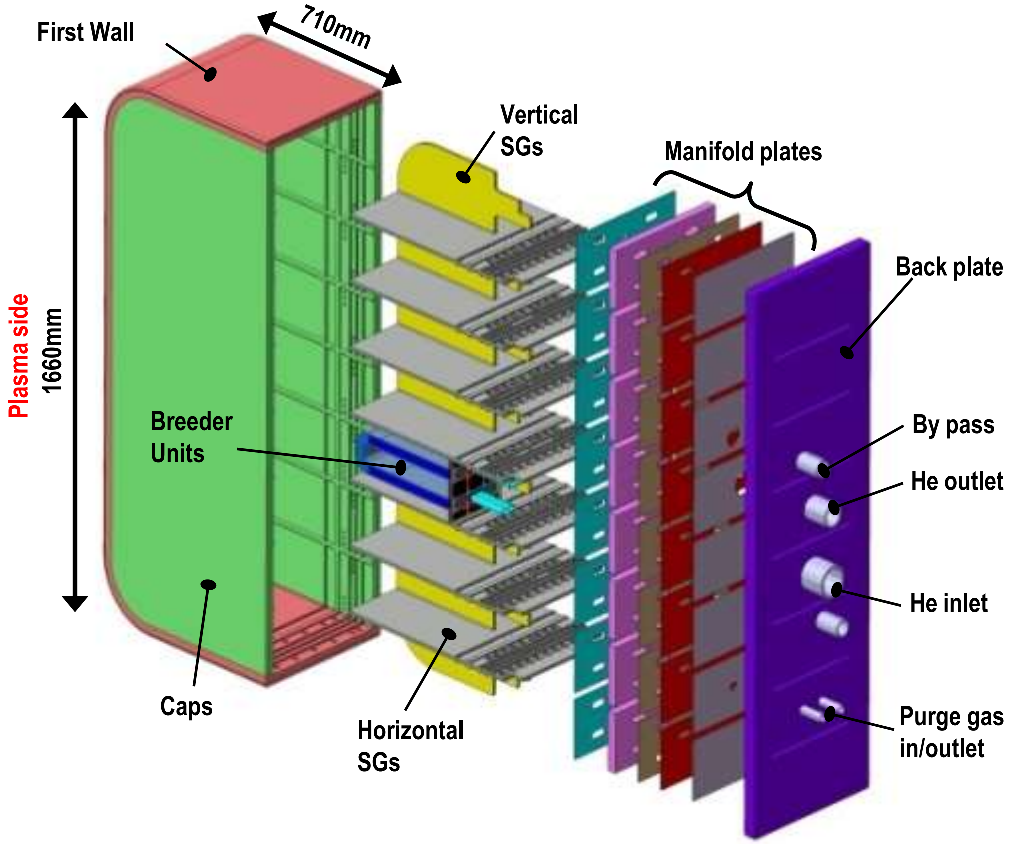
DEMO relevancy for the TBMs:

- Maximum geometrical similarity between the design of the TBM and the corresponding DEMO blanket modules;
- Active cooling of the structure by Helium at 8 MPa with 300°C/500°C inlet/outlet temperatures,
- Same structural materials;
- Maximum structural temperature limited to 550°C;
- Same manufacturing and assembly techniques.

Structural material

HCPB and HCLL TBMs structural material is the **Reduced Activation Ferritic-Martensitic (RAFM) steel EUROFER97**.
RAFM steels derive from the conventional modified 9Cr-1Mo steel eliminating the high activation elements (Mo, Nb, Ni, Cu and N).
Main advantages: **excellent dimensional stability (low creep and swelling) under neutron irradiation.**
Drawback: **ductility characteristics considerably lower than austenitic steels and severely reduced following irradiation**.

HCPB TBM design description



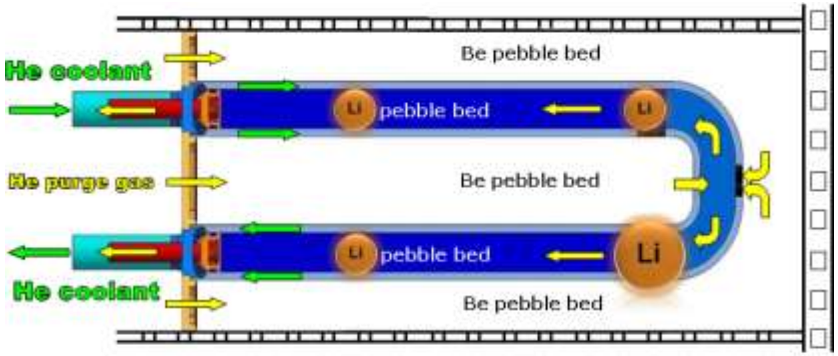
1660 mm (poloidal) × 484 mm (toroidal) × 710 mm (radial)

- Robust box (**First Wall and Caps**)
- Internal structure of **Stiffening Grids** (SGs)
- 5 backplates (BP) constitute the coolant manifolds
- **Horizontal SGs crossing the TBM box to ensure the box stiffness**

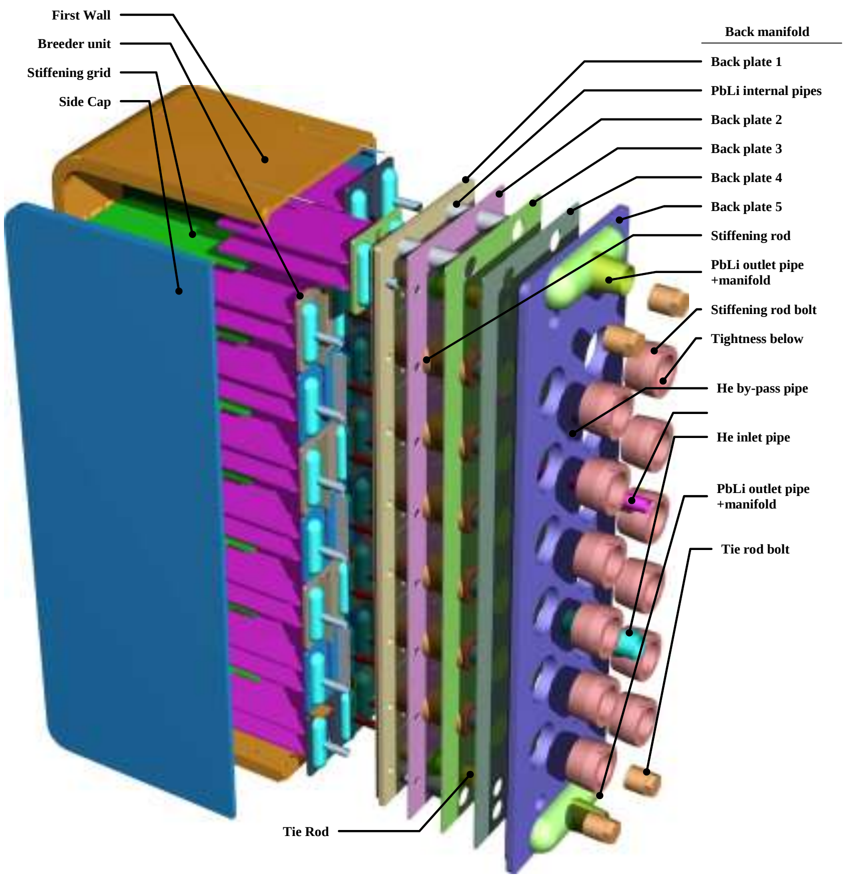
Breeder Units (BUs):

- **Arranged in the space defined by the SGs.**
- **Filled by ceramic breeder pebbles (Li_4SiO_4) and Beryllium neutron multiplier pebbles**
- **Based on U-shaped Cooling Plates (CPs) extracting the heat**

Helium at 80bar cools the TBM box components and the BUs CPs.
Helium at 4bar purges the Breeder Zone for tritium removal



HCLL TBM design description



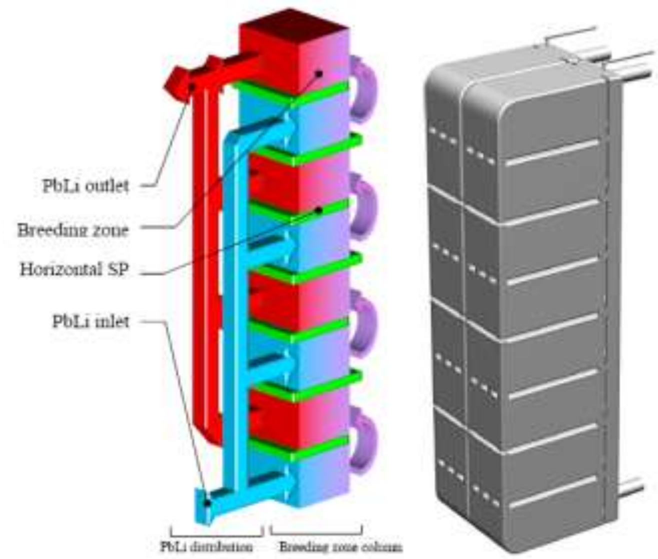
1660 mm (poloidal) × 484 mm (toroidal) × 626 mm (radial)

- U-shaped **First Wall** closed by lateral **CAPs**
- Internal radial–poloidal and radial–toroidal stiffening grids (SG).
- 5 backplates (BP) constitute the coolant manifolds
- **Additional Rods to ensure the box stiffness**

Breeder Units:

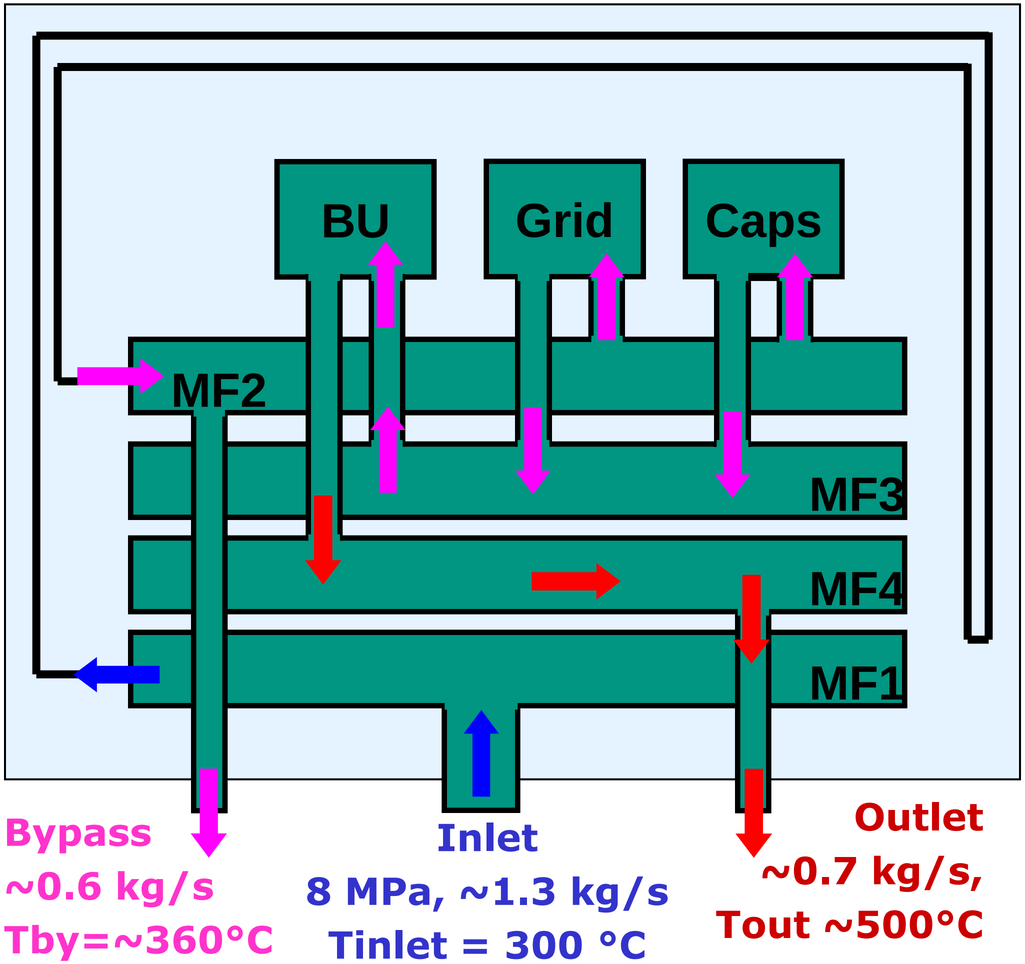
- Arranged in the space defined by the SGs
- Horizontal cooling plates (CPs) in the BU ensure the insert rigidity
- **Breeder and neutron multiplier: the eutectic PbLi**

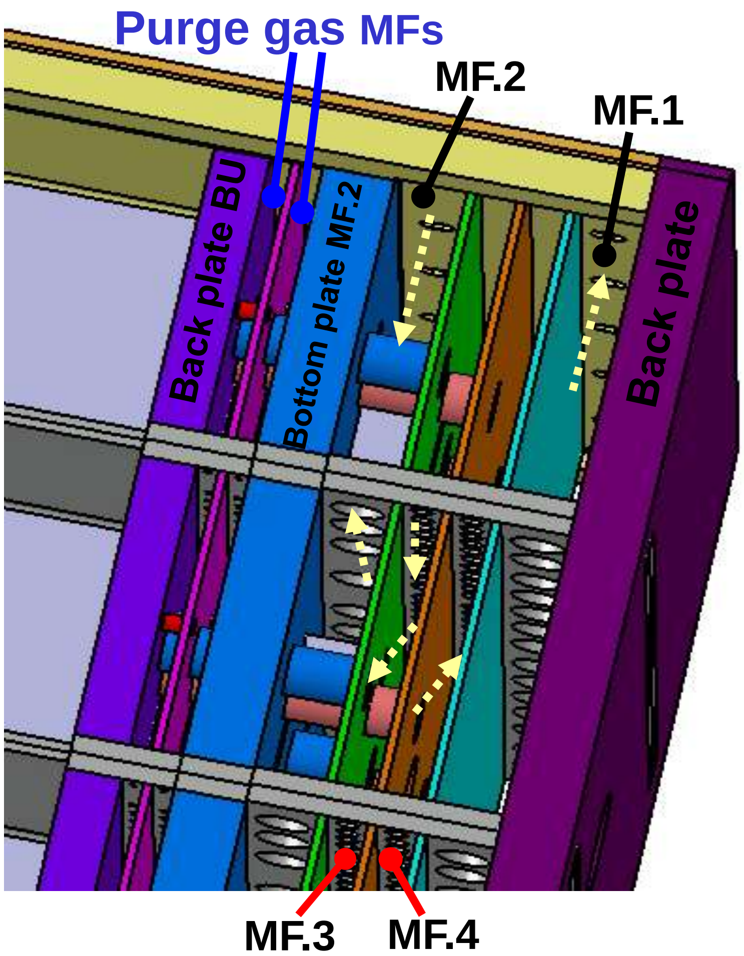
Helium at 80bar cools the TBM box components and the BUs CPs.
PbLi at 3bar purges the Breeder Zone for tritium removal



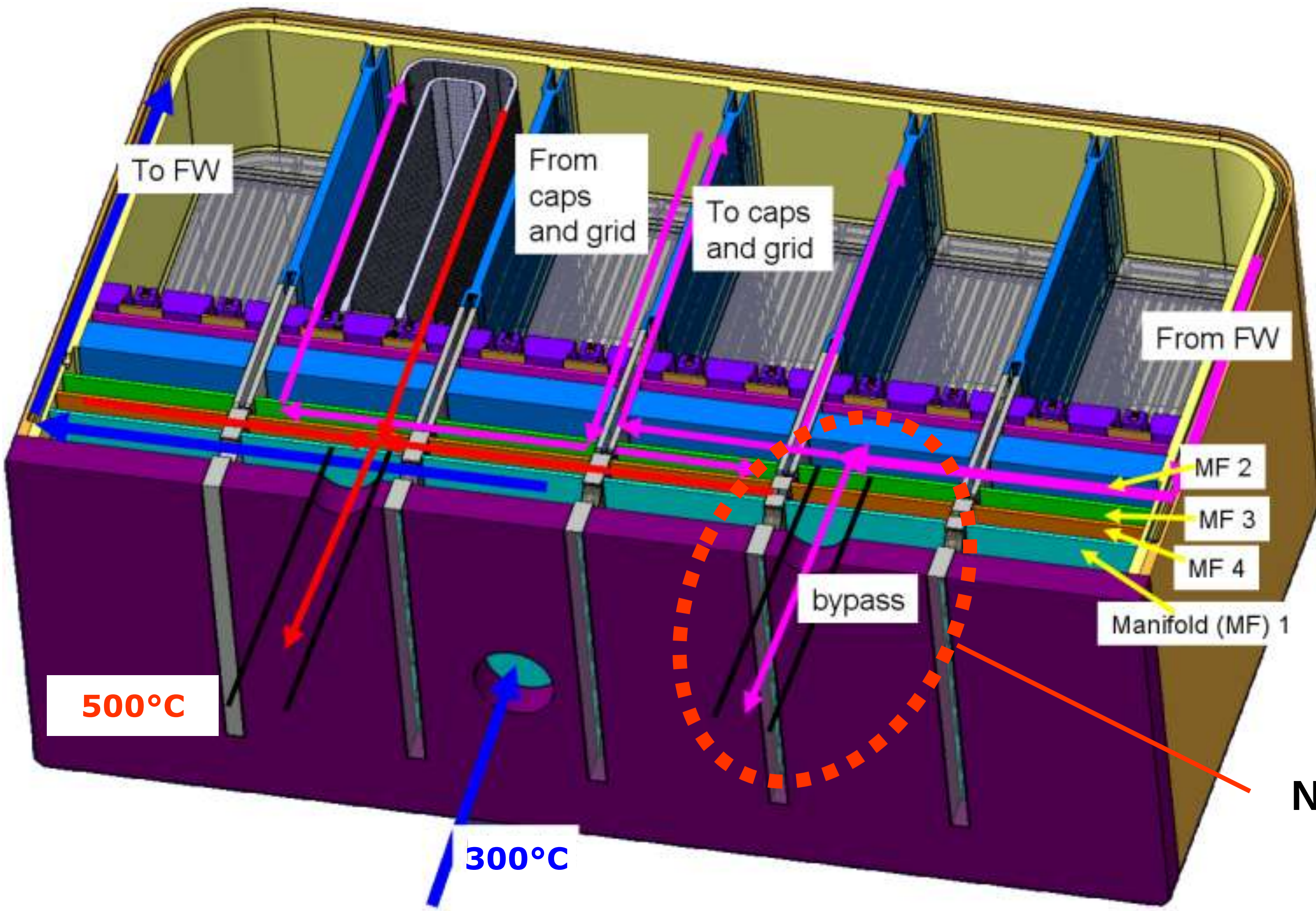
HCPB: Helium cooling

Helium flow scheme overview



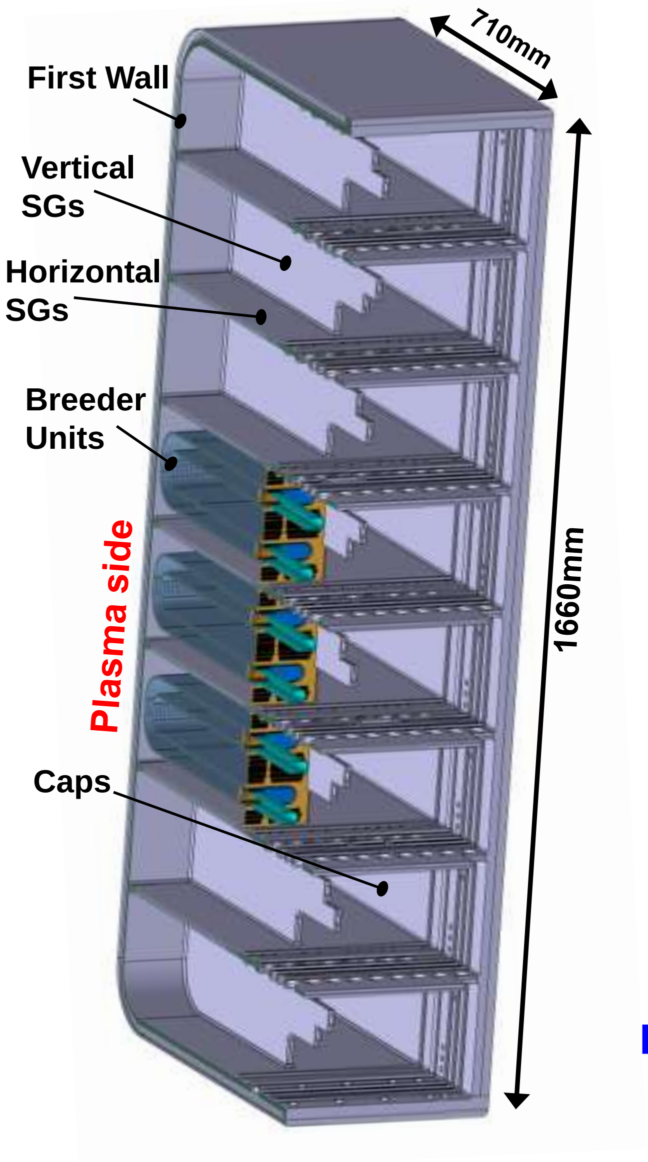


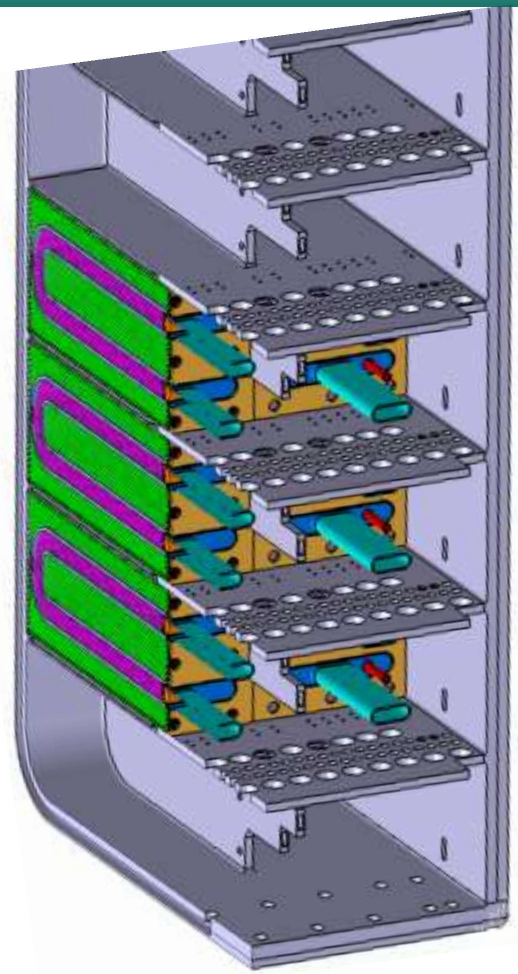
HCPB: Manifold system



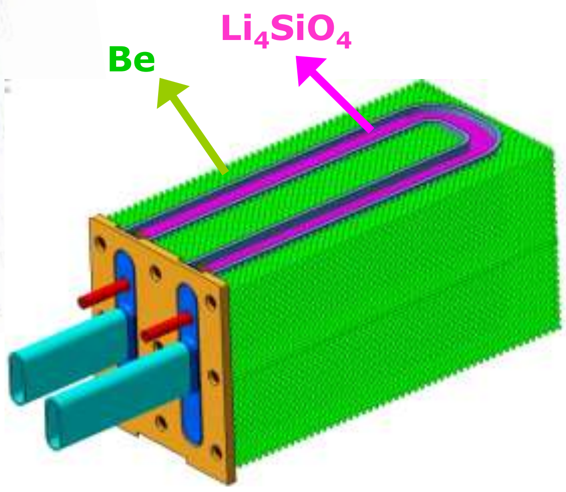
Not reactor relevant

Development of the HCPB TBM for ITER





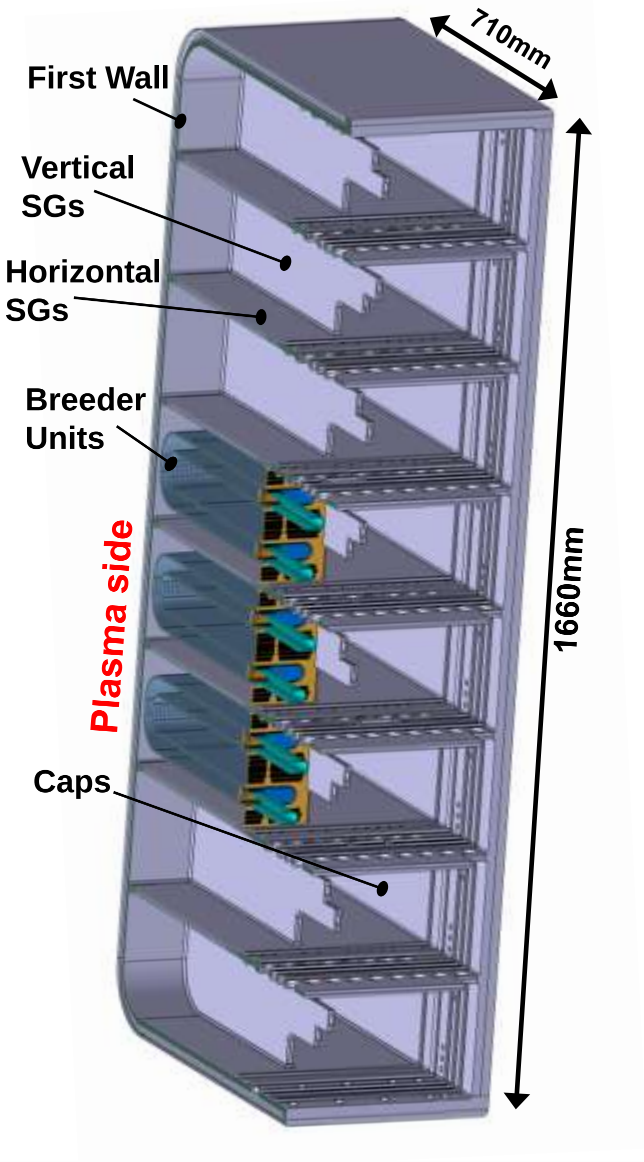
Radial-poloidal cut and BU zoom



He at 8 MPa, T 300 to 500 °C

Development of the HCPB TBM for ITER

Karlsruhe Institute of Technology



Design based on DEMO relevancy criteria:

I) Maintain the same architecture used for the DEMO Blanket,

Geometrical similitude:

Maintain the same architecture used for the DEMO Box

Maintain about the same dimensions of the Breeder Units

II) Consider the parameters values with respect to a specific class of experiments,

III) Design a TBM for each ITER phase

Geometrical similarity = look-alike design,
Internal design of the BU = act-alike design

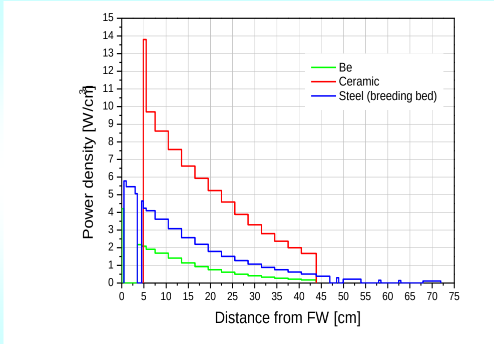
Basic relevant design parameters identified for the HCPB TBM considered in the D-T high duty phase are:

- **EUROFER temperature limit (550°C),**
- **Helium coolant outlet temperature (500°C).**
- **Ceramic breeder temperature (920°C),**
- **Beryllium multiplier temperature (650°C),**

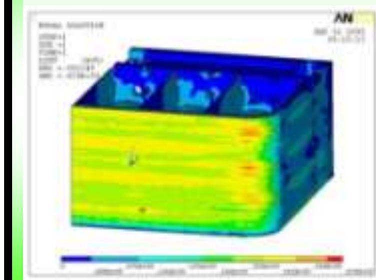
Development of the HCPB TBM for ITER

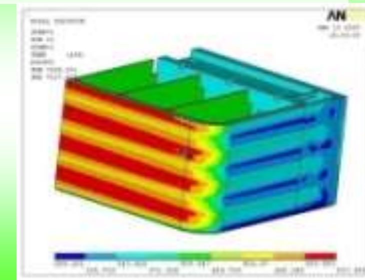
Karlsruhe Institute of Technology

Neutronic Calculation

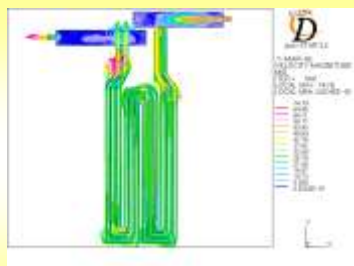


Stress- and Temperature Fields

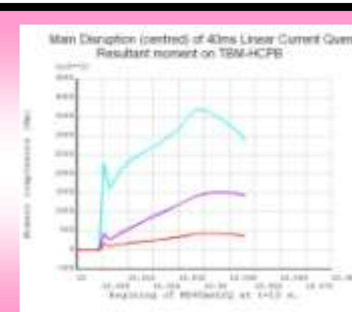




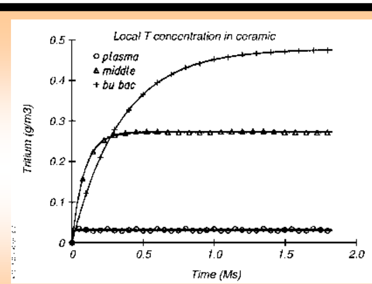
Computational Fluid Dynamics of Heliumsystems



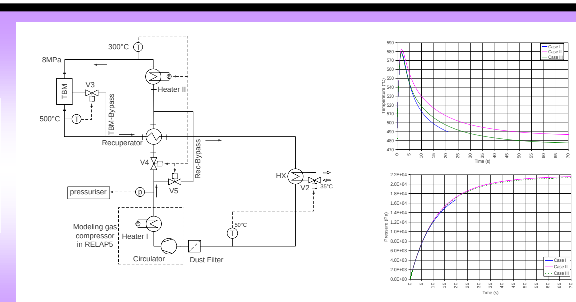
Electromagnetic Forces (Disruptions)



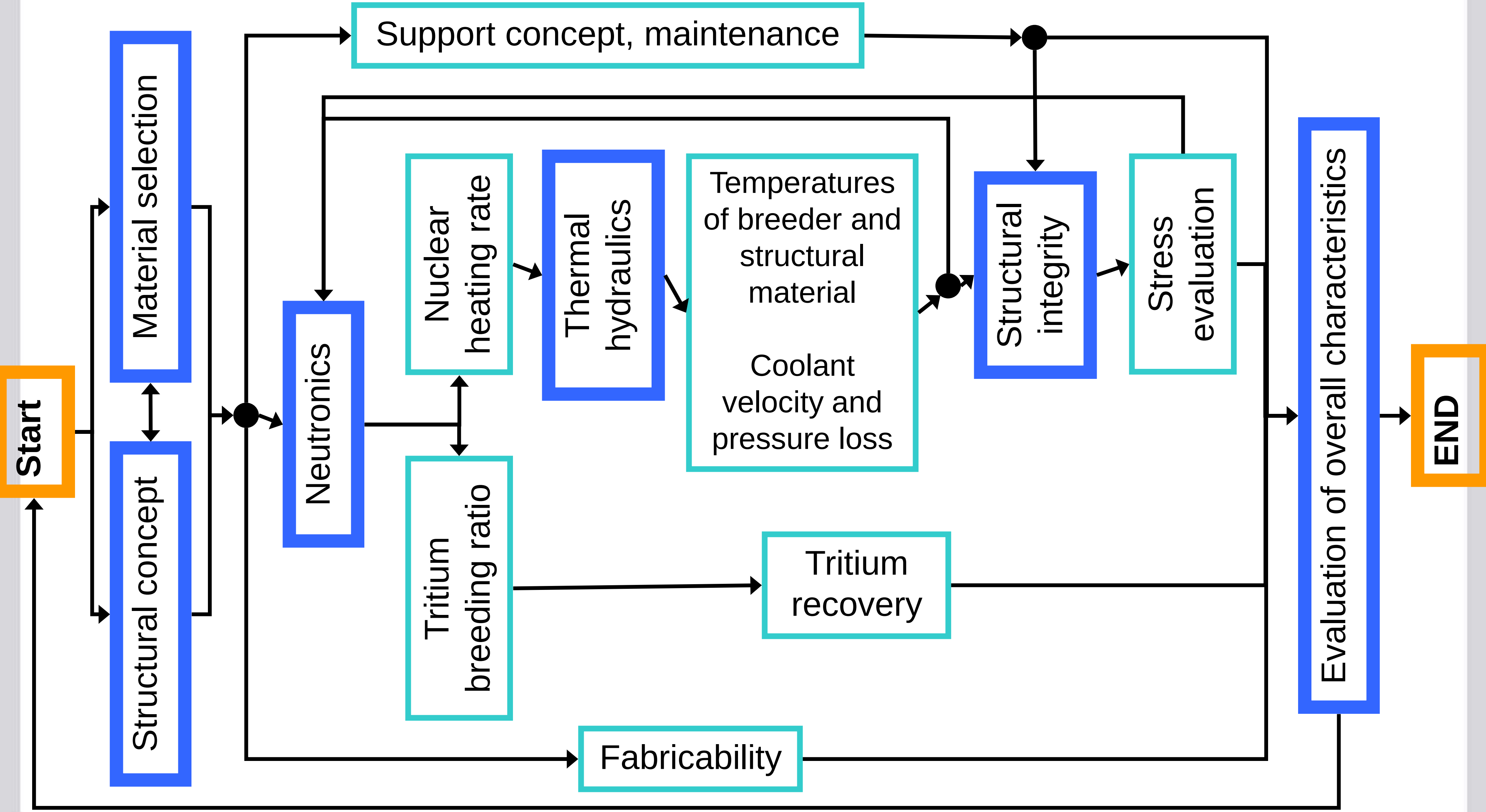
Tritium-Inventary Analyses



Safety-studies



Blanket development



Development of the HCPB TBM for ITER

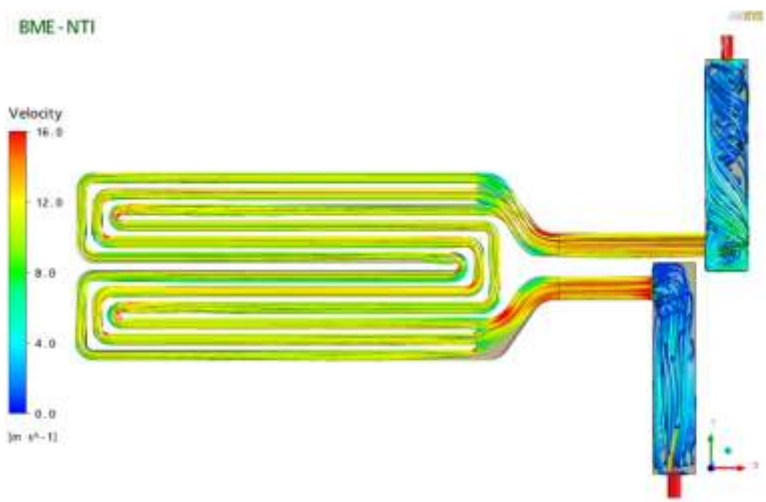
Design analyses aims at:

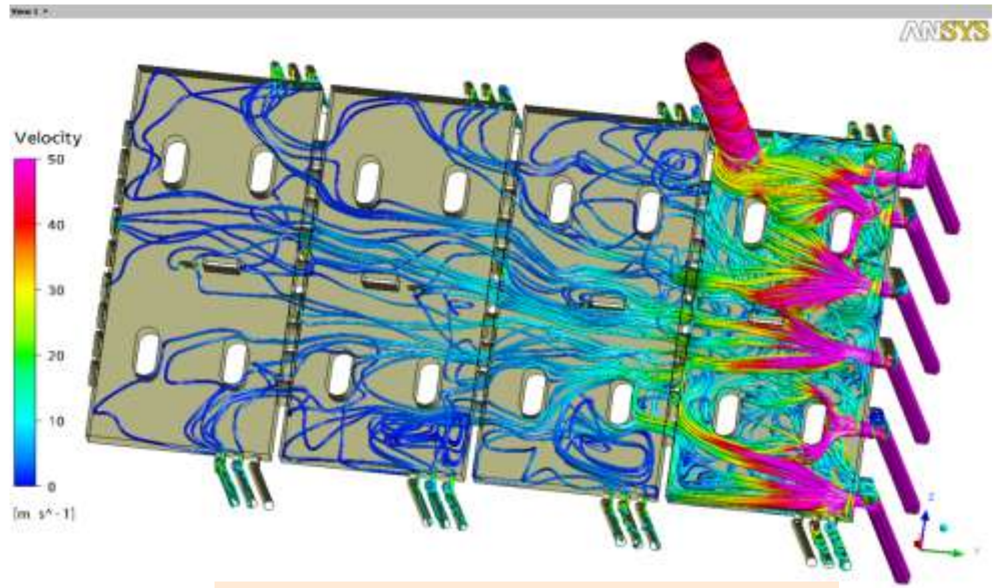
- Qualify the **thermal-hydraulic** performances of the box: reach a set of operating cooling parameters to ensure the respect of the imposed temperature limits. Limits fixed by DEMO relevancy criteria and by specificities of the ITER/TBS environment.
- Qualify the **thermo-mechanical** behaviour of the box: verify the accordance of the mechanical analyses with respect the C&S design limits.
- Assess the reachable **DEMO-relevancy** level;

Fluid dynamic analyses:

Helium coolant mass flow and pressure drop in the TBM components

Velocity profile and mass flow in the Stiffening Grids





Helium coolant fluid lines (velocity profile) in the Manifold system

Loading conditions

- Definition of **ITER/TBM operational domain** (plasma operation, stand-by, test and conditioning…)
- Definition of **loads** and assign loads to each operational condition
- Definition of the **loading conditions** to be considered:

Id.	Loading Condition description	
LC1	**Nominal operation in D-T phase / Design of the Box** • VV pressure: 10^{-6} Pa • Pressure in cooling circuit: PS • Pressure in PbLi volume: 3bar, in purge gas 4bar • Heat flux on FW: max, value 0,5 MW/m², 30s ramp-up, 400s plateau, 60s ramp down, total pulse duration 1800 s • He inlet temperature: 300°C • He mass flow: to be determined in the frame of design assumptions • 3000 cycles/year	*Normal operation during a typical DT phase plasma pulse*
LC2	**Nominal operation in D-T phase / Conservative global design** • VV pressure: 10^{-6} Pa • Pressure in cooling circuit: PS • Pressure in PbLi volume: 3bar, in purge gas 4bar • Heat flux on FW: 0,5 MW/m² max, with 10s 0,64 MW/m² transient • He inlet temperature: 300°C • He mass flow: nominal, to be determined in the frame of design assumptions • 100 cycles/year	*Power excursion associated to a MARFE event*
LC3	**Internal LOCA in D-T phase / Conservative global design13)** • VV pressure: 10^{-6} Pa • Pressure in cooling circuit: PS • Pressure in PbLi or in purge gas volume = Pressure in cooling circuit • Heat flux on FW: 0,5 MW/m² as maximum • He inlet temperature: 300°C • He mass flow: nominal, as determined in previous loading conditions	*Accidental pressurization of the box in case of internal LOCA*

Codes & Standard

KIT Karlsruhe Institute of Technology

Codes and Standards for TBM design

- TBMs must fulfill French regulations on pressure vessel equipments (**ESPN order**)
- **RCC-MR 2007** is proposed as main reference design code for the TBM box design.
- RCC-MR is completed by **ITER SDC-IC** for some specific aspects (irradiation effects, etc.).
- RCC-MR provides:
  - consistent design, manufacturing and materials rules implementing regulation requirements related to ESPN order.
  - specific rules for “box structures” (RB 3800).

-RCC-MR assigns **Criteria Level** to the loading conditions defined.
-Criteria Level protect the components against a
specific type of damage.

Id.	Loading Condition description	Criteria Level
LC1	**Nominal operation in D-T phase / Design of the Box** • Heat flux on FW: max, value 0,5 MW/m^2, 30s ramp-up, 400s plateau, 60s ramp down, total pulse duration 1800 s	A
LC2	**Nominal operation in D-T phase / Conservative global design** • Heat flux on FW: 0,5 MW/m^2 max, with 10s 0,64 MW/m^2 transient	A
LC3	**Internal LOCA in D-T phase / Conservative global design)** • Pressure in cooling circuit: PS • Pressure in PbLi or in purge gas volume = Pressure in cooling circuit	D

-**Rules to be considered:**

- Design rules in RCC-MR are meant to protect the component against **Monotonic and Cyclic type damage modes (M-type and C-type damage modes).**
- Design rules are applied in order to insure protection of the components against:
  - ***Immediate plastic collapse and instability (M-type);***
  - ***Immediate plastic flow localization (M-type);***
  - ***Local fracture due to exhaustion of ductility (M-type);***
  - ***Thermal creep (M-type);***
  - ***Ratcheting (C-type);***
  - ***Fatigue (C-type).***

Design and analyses studies

LC1: steady state thermo-mechanical analyses

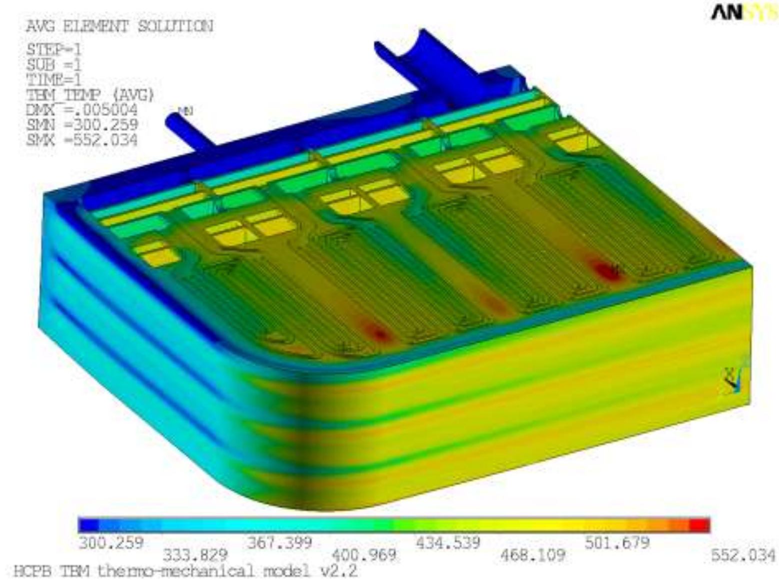
FE model built in ANSYS (KIT) and CAST3M (CEA).

Geometry: ¼ scaled TBM assembly.

Boundary conditions:

- Heat flux deposed on the plasma side of the FW, 0,5MW/m2.
- Heat generation in the TBM components, input from neutronic.
- 3D CFX model (HCPB TBM) of the BUs calculating:
    - Heat flux produced in the BU and deposed on the TBM box
    - Helium coolant mass flow distribution.
- 3D CFX models calculate the HTC in the FW cooling channels.
- Gnielinski correlation to determine the HTC in the other actively cooled components.

The temperature field resulting from the steady state thermal analysis is applied to the structure for the structural analysis



LC1: transient thermo-mechanical analyses

Same FE model and boundary conditions

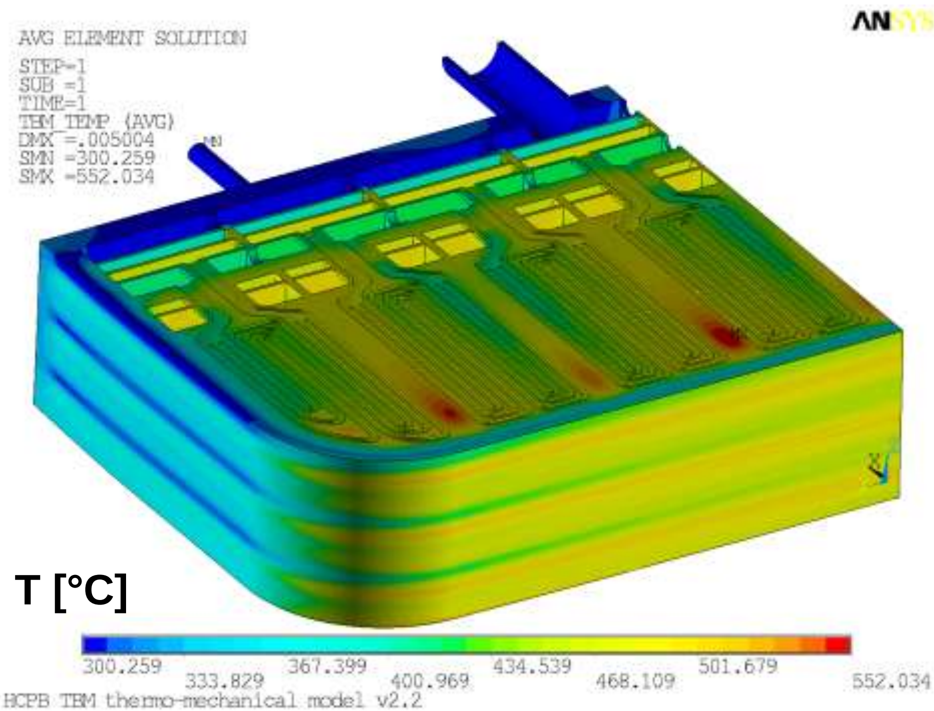
Typical plasma pulse, D-T phase: 30s ramp-up, 400s plateau, 60s ramp-down

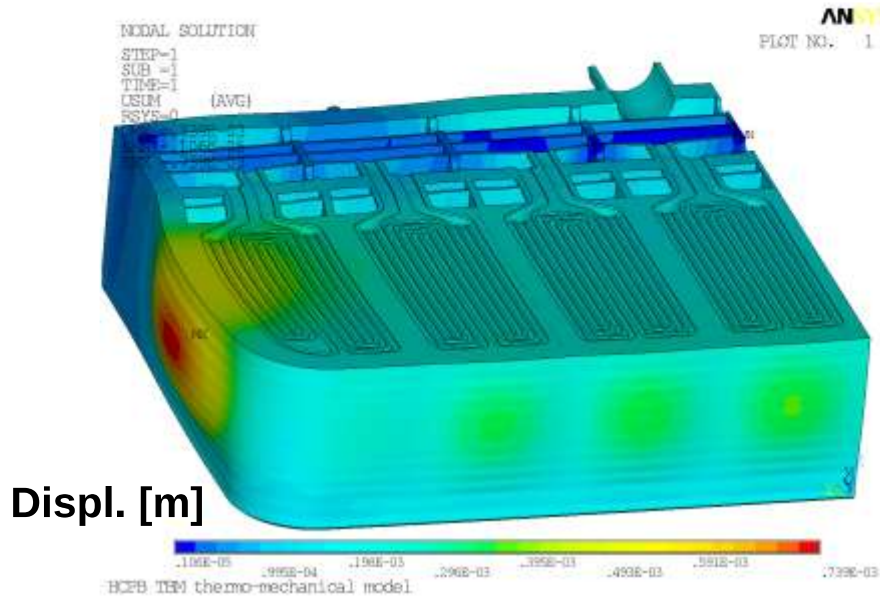
- Are plasma pulses sufficiently long to attain stationary temperature conditions?
- Transient thermo mechanical conditions are the most demanding for the mechanical withstanding of the box structure.

Design and analyses studies

Finite Element analyses with ANSYS

LC1: Steady state thermal analyses (ITER high duty DT phase), temperature field on the HCPB TBM





Accidental case analyses: internal LOCA at 100bar, displacement field

Transient thermo-mechanical analyses

HCLL simulation of the thermal transient :

- Apart from the FW, stationary conditions are never reached.
- Helium outlet temperature at the end of the plasma pulse ~435°C.
- Inversion of the thermal gradient between FW and BZ

Time instants significant for the mechanical analysis:

-t_1=60s: FW reaches nearly stationary conditions.
t_3=600s: cooling phase, inversion of the temperature difference between FW and BZ is maximal

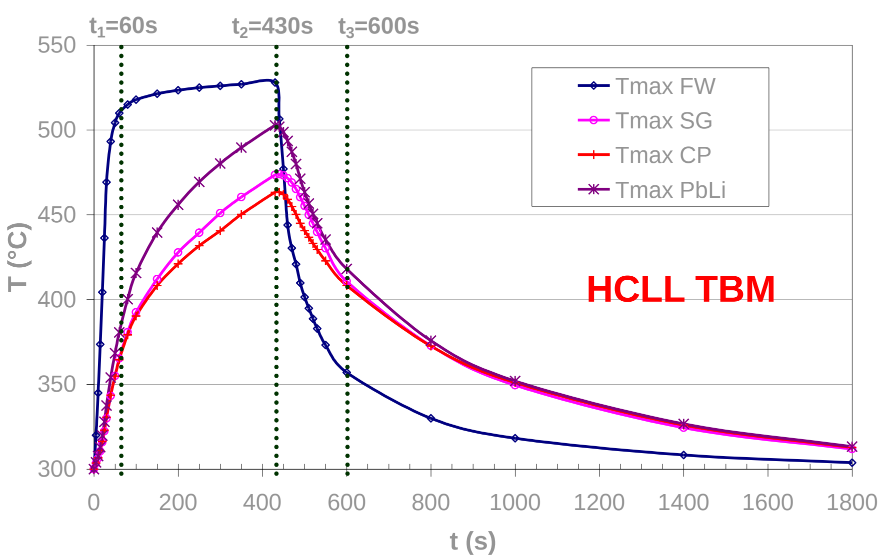
HCPB simulation of the thermal transient:

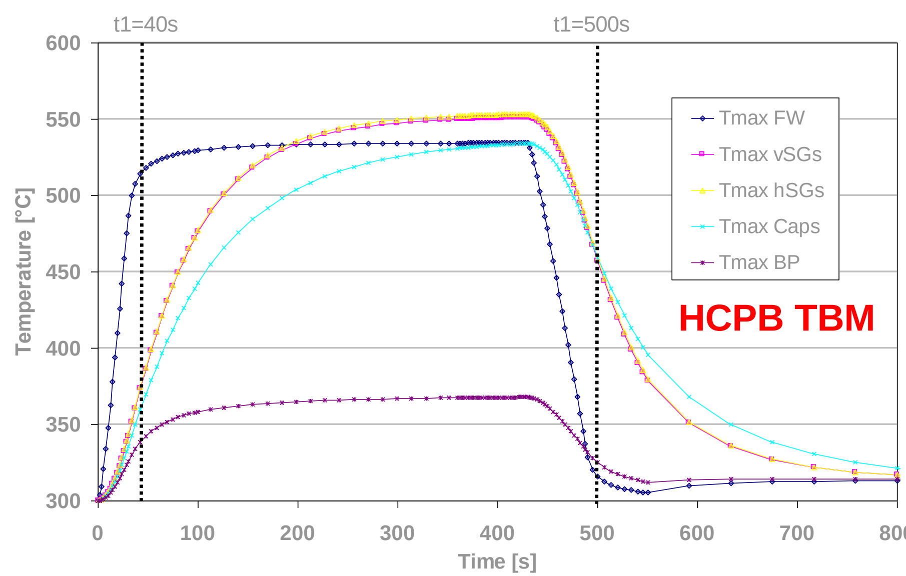
- By the end of the pulse the BU works in steady state condition
- Helium outlet temperature at the end of the plasma pulse ~500°C.
- Inversion of the thermal gradient between the FW and the BZ

Time instants significant for the mechanical analyses:

t1=40s, FW reaches nearly stationary conditions
t2=500s: cooling phase, inversion of the temperature difference between FW and Manifold region is maximal

Evolution of maximum temperature in TBM subcomponents during a typical ITER plasma pulse.





Thermal fields calculated at these instants have been used as input for the thermo-mechanical analysis.

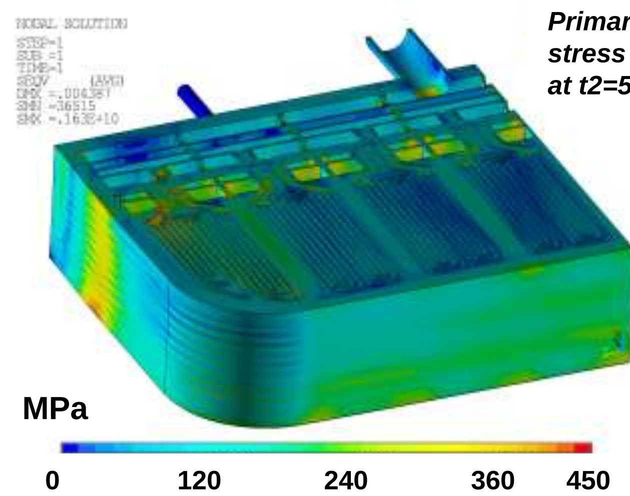
Transient thermo-mechanical analyses

HCPB TBM

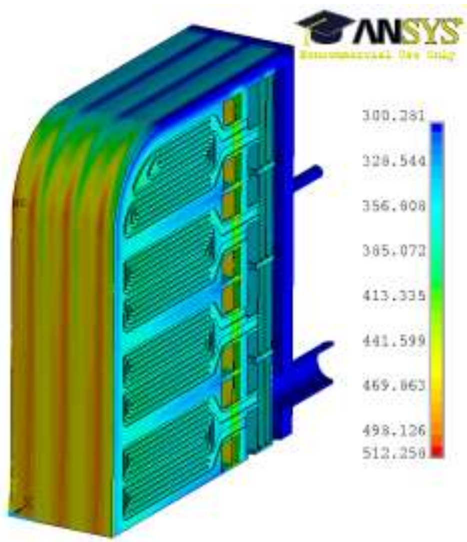
The most demanding condition for the structural integrity of the manifold region is the inversion of the thermal gradients during the plasma ramp-up and ramp-down phases.

Even in steady state conditions the horizontal SGs in the manifold region undergo high stresses (primary stresses) with peak values up to 850MPa.

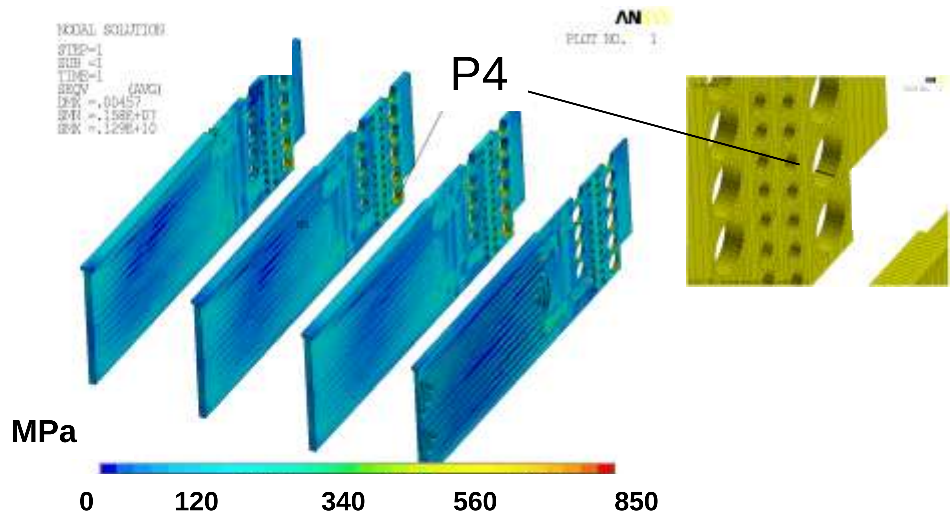
Primary + secondary stress field on the TBM at t2=500s



Temperature distribution at t1=40s.

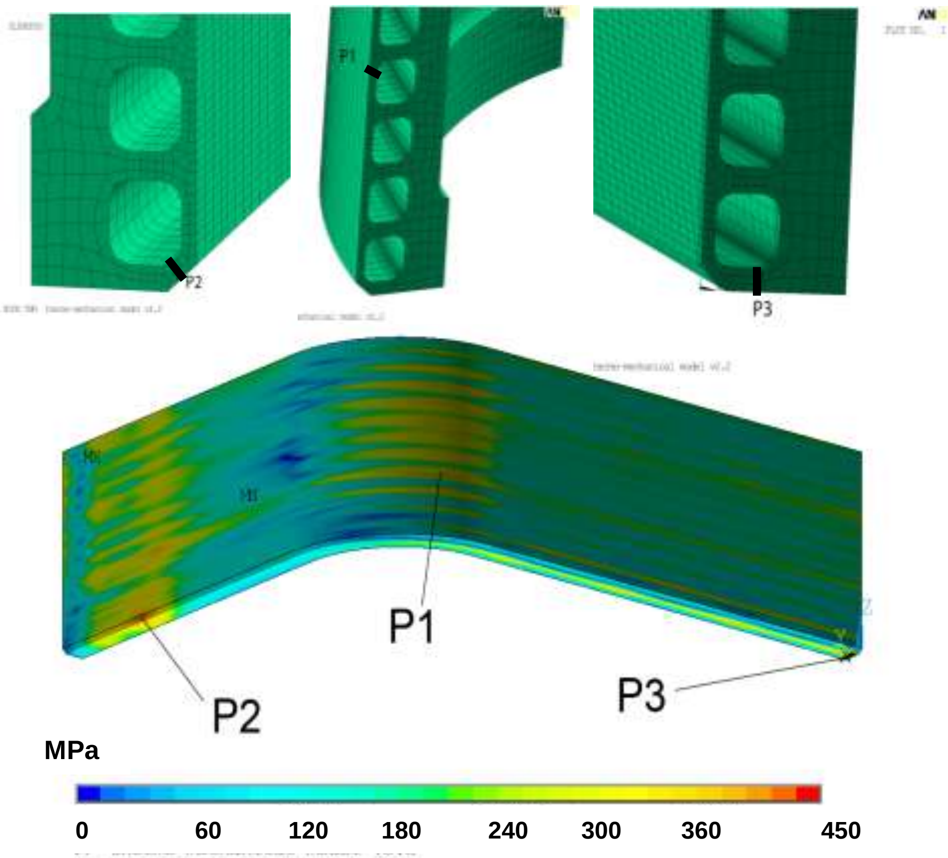


HCPB TBM transient thermo-mechanical model



Transient thermo-mechanical analyses

Karlsruhe Institute of Technology



Immediate plastic flow localization

	T (°C)	$\overline{P_m+Q_m}$ t_1	(MPa) t_2	Limit (MPa)	Margin
Line 2	360	169	442	200	-121%
Line 3	384	70	248	174	-43%
Line 4	307	551	673	258	-161%

Ratcheting

	T (°C)	$\overline{P_L+P_b}+\overline{\Delta Q}$ (MPa) t_1-t_0	t_2-t_0	t_2-t_1	Limit (MPa)	Margin
Line 1	434	252	196	247	495	49%
Line 2	360	198	496	323	543	9%
Line 3	384	265	254	422	528	20%
Line 4	307	593	736	246	567	-30%

Good behavior of the FW against ratcheting and primary stresses

Problematic behavior of the manifolds region: In P4 limits for immediate plastic collapse and instability and creep are largely exceeded.

Primary stresses + creep

		Immediate plastic collapse and instability						Creep					
		$\overline{P_m}$ (MPa)			$\overline{P_m+P_b}$ (MPa)			$\overline{P_m}$ (MPa)			$\overline{P_m+P_b/k_t}$ (MPa)		
	T (°C)	Value	Limit	Margin	Value	Limit	Margin	Value	Limit	Margin	Value	Limit	Margin
Line 1	493	21	147	86%	25	220,5	89%	21	249	92%	36	249	86%
Line 2	458	21	159	87%	27	238,5	89%	21	315	93%	38	315	88%
Line 3	448	22	162	86%	44	243	82%	22	322	93%	36	322	89%

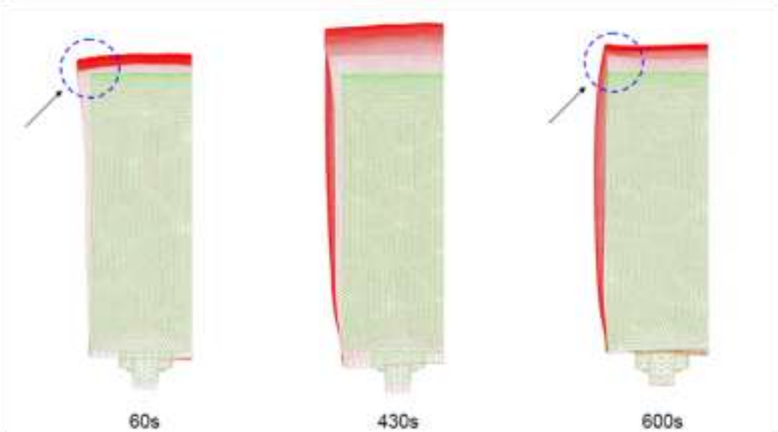
Transient thermo-mechanical analyses

HCLL TBM

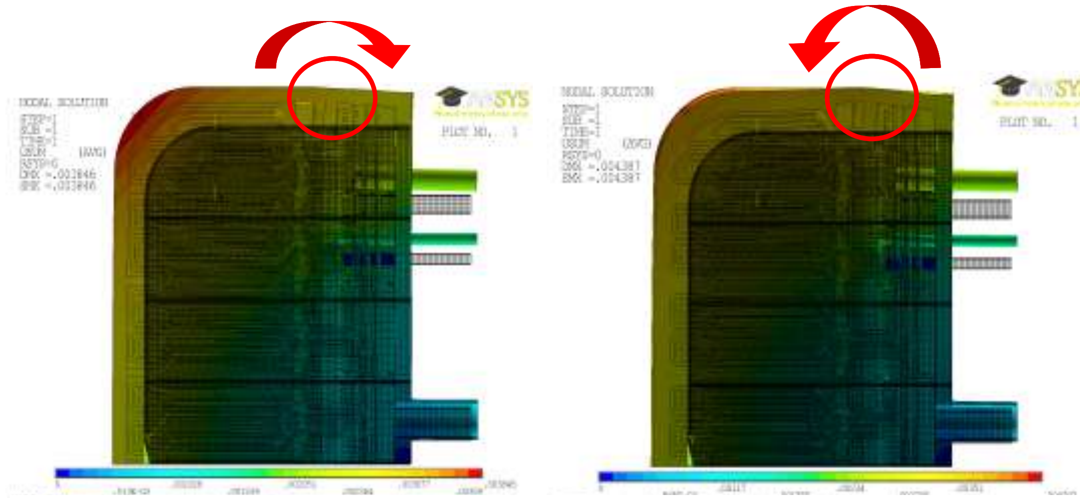
Most demanding condition for the structural integrity of the box: alternation between tensile and compressive stress states in the FW.

HCPB TBM

Most demanding condition for the structural integrity of the box: inversion of the thermal gradients during plasma ramp-up and ramp-down in the manifold region associated to the weakness of the horizontal SGs.



Deformation pattern of the FW at the selected time instants during the plasma pulse



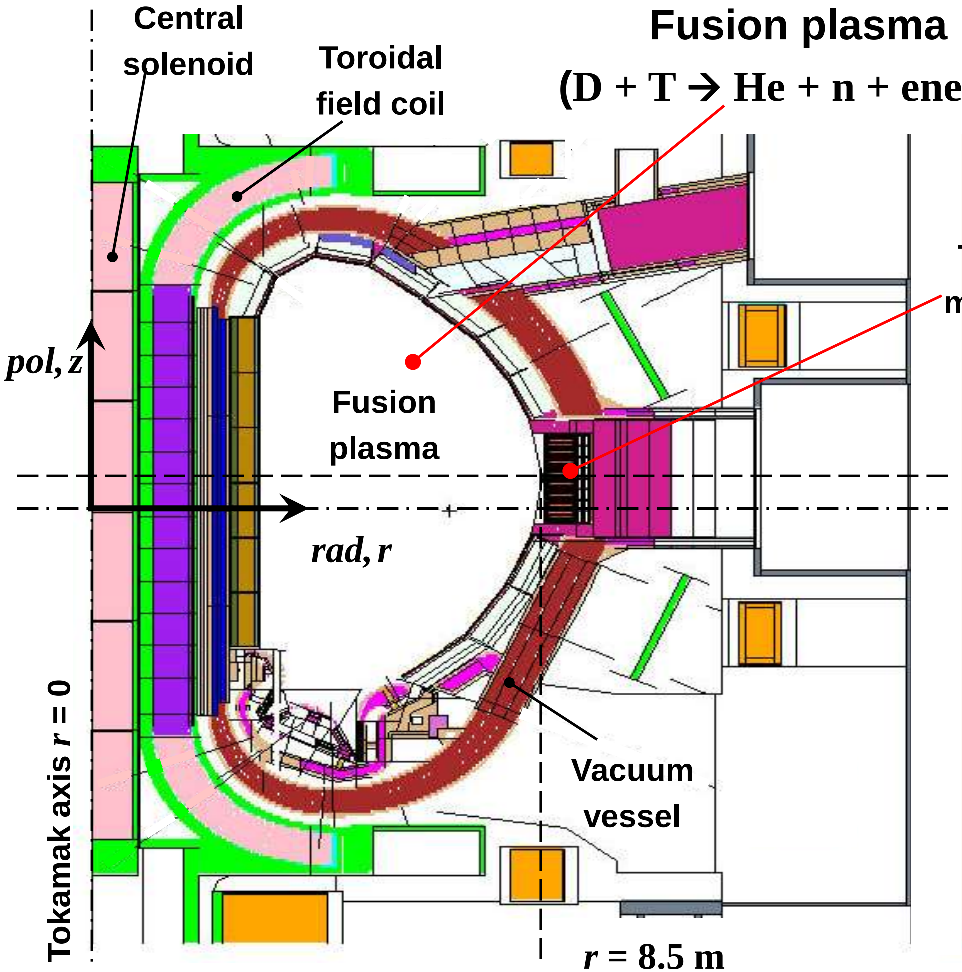
Deformation pattern of the TBM box at 40s (left) and 500s (right) during the plasma pulse

Solution: FW design of the HCPB TBM + Manifold design of the HCLL TBM. The FW higher bending radius (HCPB design) compensates the tension/compression states, the stiffening rods (HCLL design) release the stresses in the manifold region.

Open issues:

Design rules developed for austenitic-type steels (i.e. 316L(N)-IG ITER shielding steel), Limited experience with martensitic steel in a fusion relevant environment. Concerns regarding the validity/degree of conservatism of the C&S rules when taking into account Eurofer97 mechanical properties.

Liquid metal flows in fusion blankets



Blanket

- Radiation shielding
- Breeding of tritium
  ^6Li + n → He + T + energy
- Cooling of the first wall
- Conversion of nuclear power
- Heat removal

Requirements can be accomplished with Li-containing liquids as breeder and coolant

⇒ Eutectic PbLi

Liquid metal magnetohydrodynamics (MHD)

What is MHD?

Movement of electrically conducting fluids in a magnetic field

Fluid dynamics

Conservation of

- **Mass**
- **Momentum**
- **Energy**

Navier-Stokes

Electrodynamics

Conservation of

- **Electric charge**
- **Energy**

Induction

Ohm's law

Maxwell (Ampère, Faraday)

Lorentz-force ←

induced electric field →

Governing equations

Karlsruhe Institute of Technology

Conservation of

Lorentz-force

Mass

$$\nabla \cdot \mathbf{v} = 0$$

Momentum

$$\frac{1}{N}\left(\frac{\partial}{\partial t} + \mathbf{v}\cdot\nabla\right)\mathbf{v} = -\nabla p + \frac{1}{Ha^2}\nabla^2\mathbf{v} + \mathbf{j}\times\mathbf{B}$$

Nondimensional groups

Interaction parameter

$$N = \frac{\sigma L B^2}{\rho u_0}$$

El.magn. force / Inertia force

Hartmann number

$$Ha^2 = \frac{\sigma L^2 B^2}{\rho \nu}$$

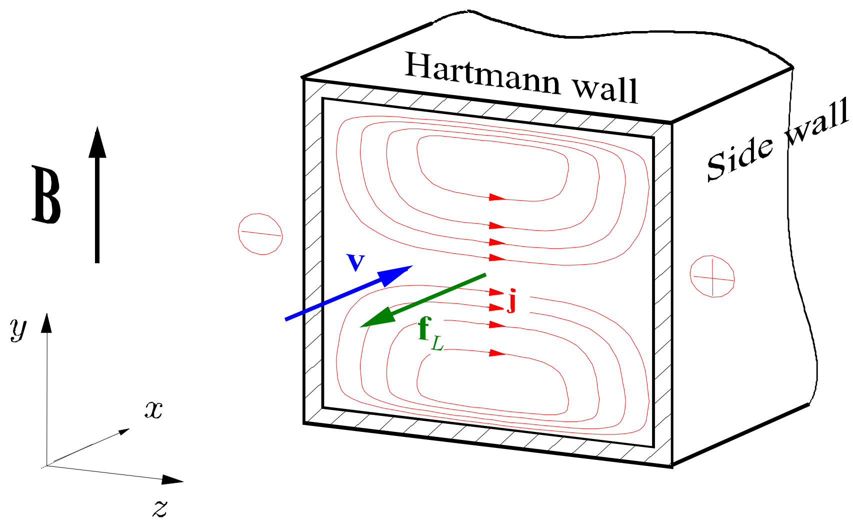
El.magn. force / Viscous force

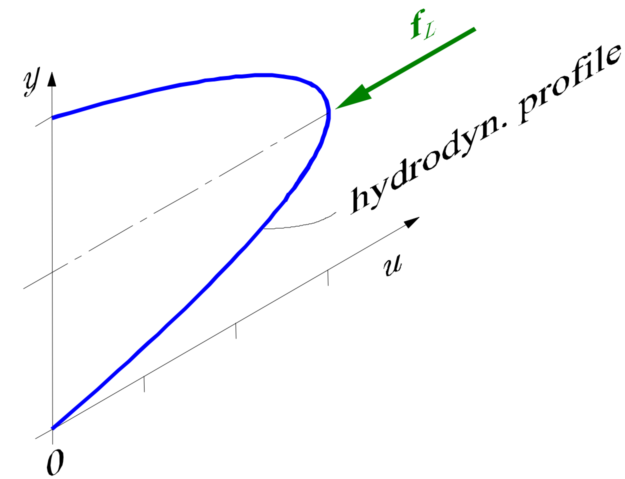
Reynolds number

$$Re = Ha^2 / N$$

Inertia force / Viscous force

MHD channel flows





$$\mathbf{j} = \sigma(-\nabla\phi + \mathbf{v}\times\mathbf{B})$$

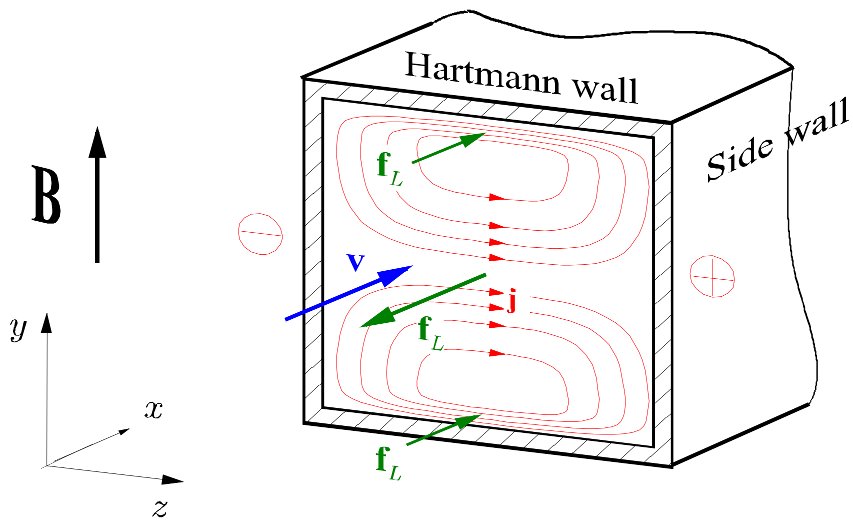
Induced electric field

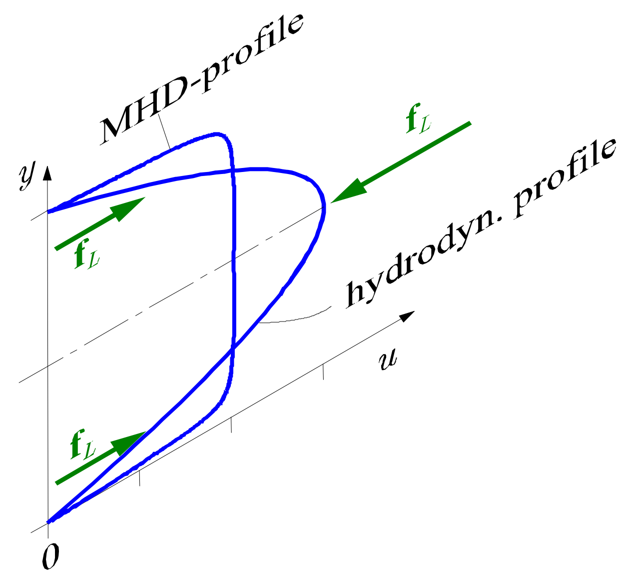
Lorentz force

$$\mathbf{f}_L = \mathbf{j}\times\mathbf{B}$$

MHD channel flows

Karlsruhe Institute of Technology





$$\mathbf{j} = \sigma(-\nabla\phi + \mathbf{v}\times\mathbf{B})$$

Induced electric field

Lorentz force

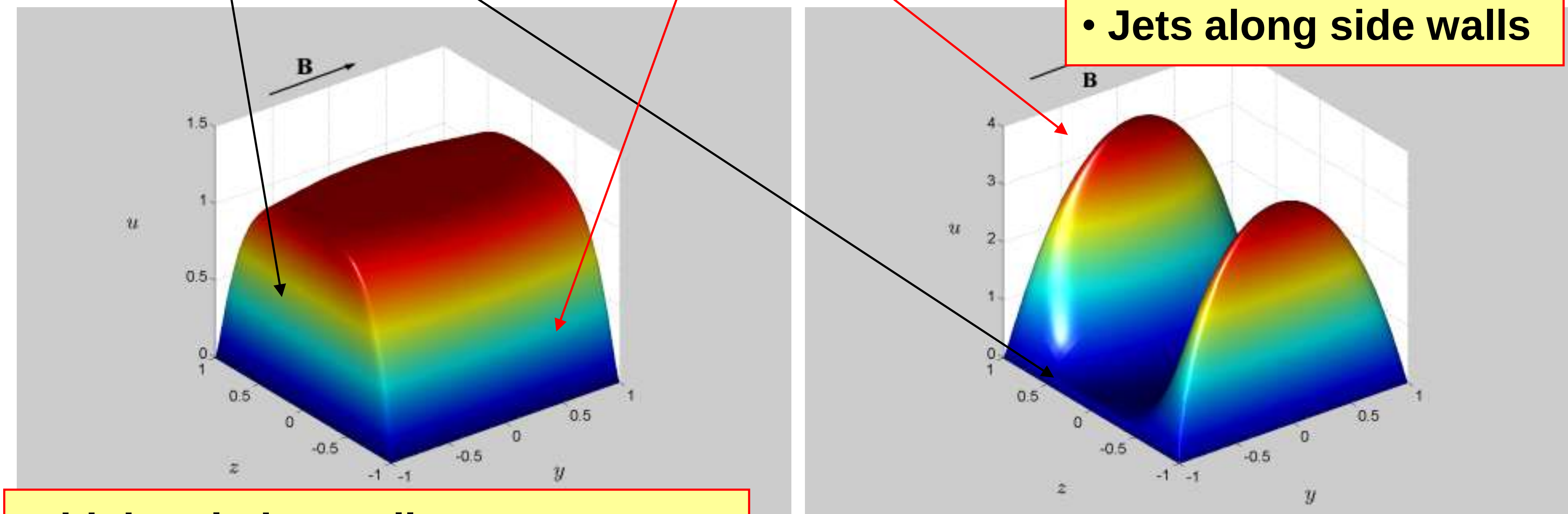
$$\mathbf{f}_L = \mathbf{j}\times\mathbf{B}$$

MHD flows in rectangular ducts, *Ha* = 50

Hartmann layer $d_H \sim Ha^{-1}$

Side layer $d_S \sim Ha^{-1/2}$

With conducting walls:
- **Higher currents**
- **Reduced core flow**
- **Jets along side walls**



With insulating walls:
- **Uniform core**
- **Thin Hartmann and side layers**

Things to remember!

Magnetic fields affect the flow of electrically conducting fluids

Utility: measuring, pumping, braking, stirring, melting, ...

Disadvantage: high pressure drop in channel flows

Channel flows in <u>strong magnetic fields</u>

- Core flow with uniform velocity
- Thin Hartmann layers perpendicular to B, $d_H \sim Ha^{-1}$
- Side layers parallel to B, $d_S \sim Ha^{-1/2}$
- Strong braking of flows perpendicular to B
- Turbulence suppressed or strongly damped (laminarisation)
  - Time dependent structures highly correlated and aligned with B
  - Deterioration of heat transfer

Helium Cooled Lead Lithium (HCLL) blanket

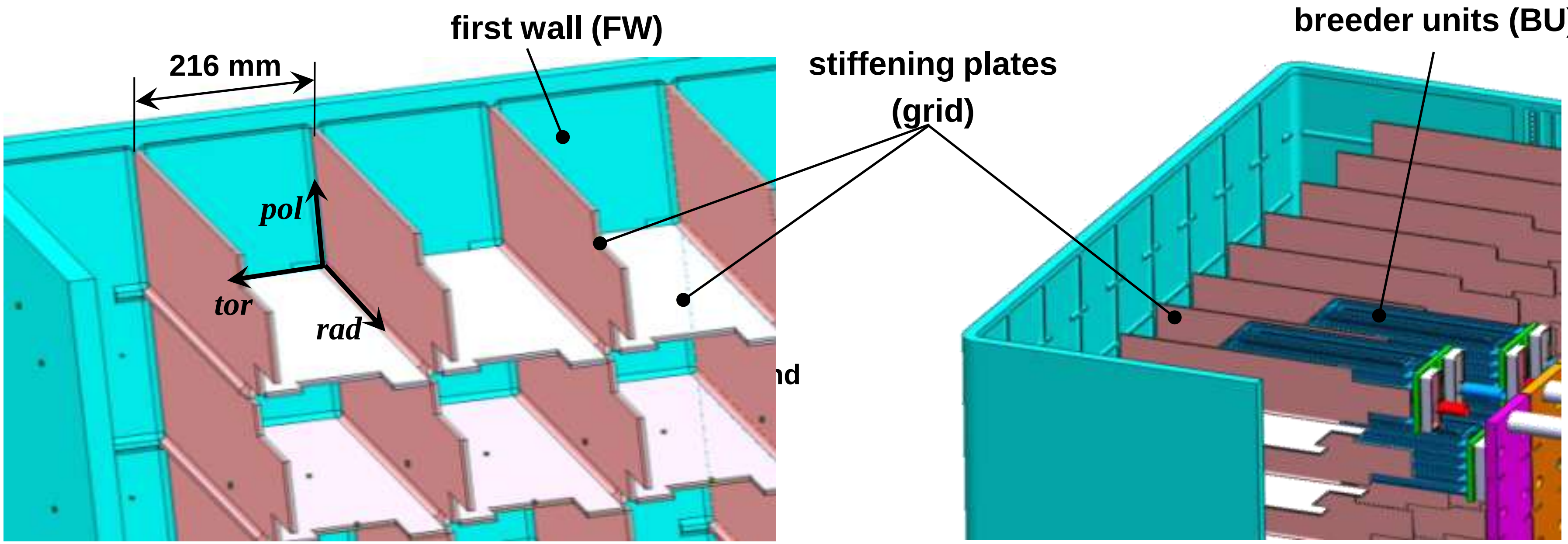
Separately - cooled concept

- Liquid metal used only as breeder
  - ⟹ Small velocities (1mm/s)
- Heat removed by helium (thermal conductance)

HCLL blanket features

⟹ **Modular concept**

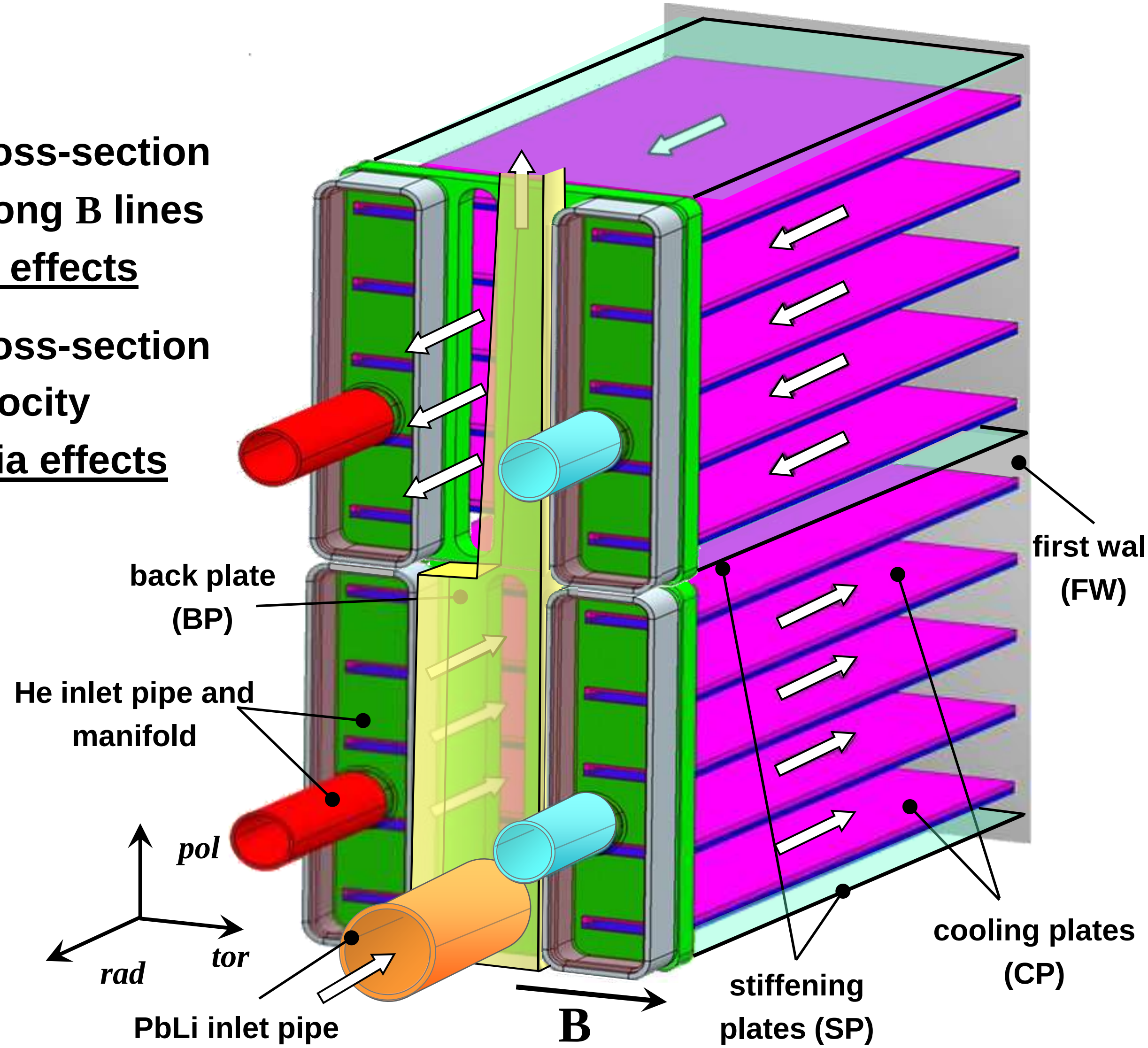
- Stiffening plates forming a grid
- Frame - array of rectangular cells → breeder units (BU)



Helium Cooled Lead Lithium (HCLL) blanket

Blanket ⟷ MHD issues

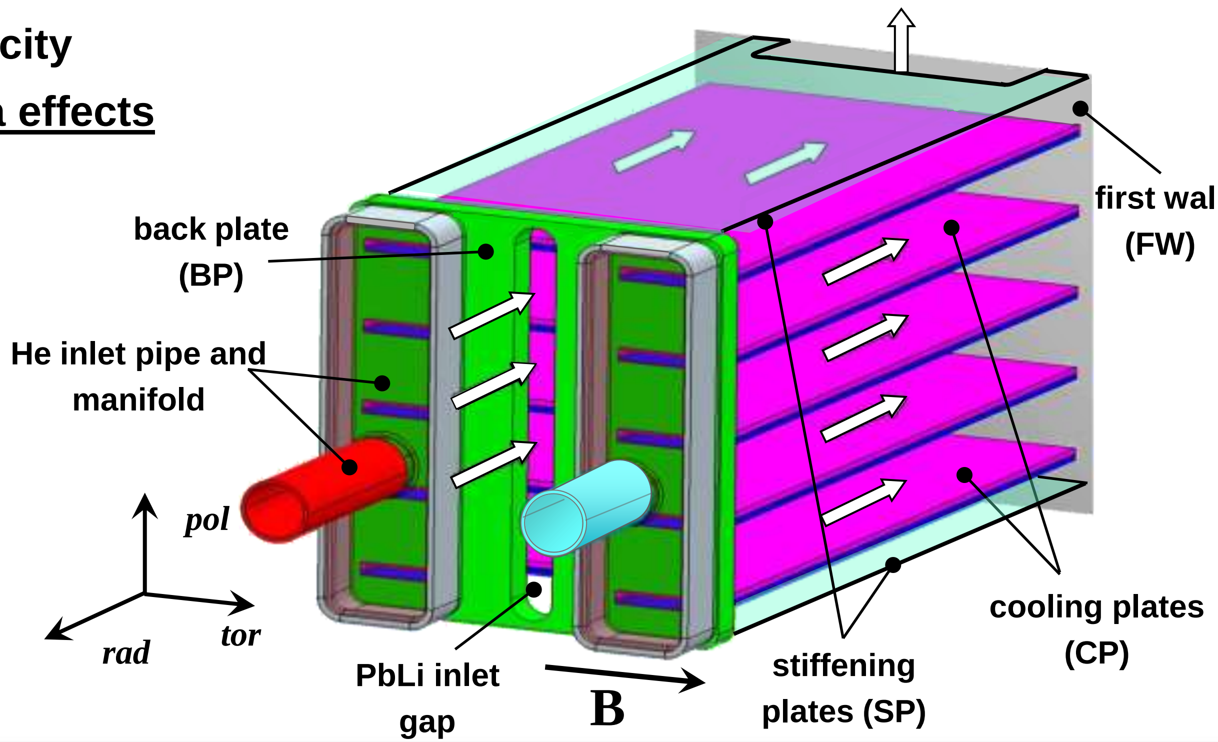
- **Gap at BP** → ♦ **Change of cross-section**
  ♦ **Expansion along B lines**
  → **strong MHD effects**
- **Gap at FW** → ♦ **Change of cross-section**
  ♦ **Increased velocity**
  → **strong inertia effects**



Helium Cooled Lead Lithium (HCLL) blanket

Blanket ⟷ MHD issues

- **Gap at BP** → ♦ **Change of cross-section**
  ♦ **Expansion along B lines**
  → **strong MHD effects**
- **Gap at FW** → ♦ **Change of cross-section**
  ♦ **Increased velocity**
  → **strong inertia effects**



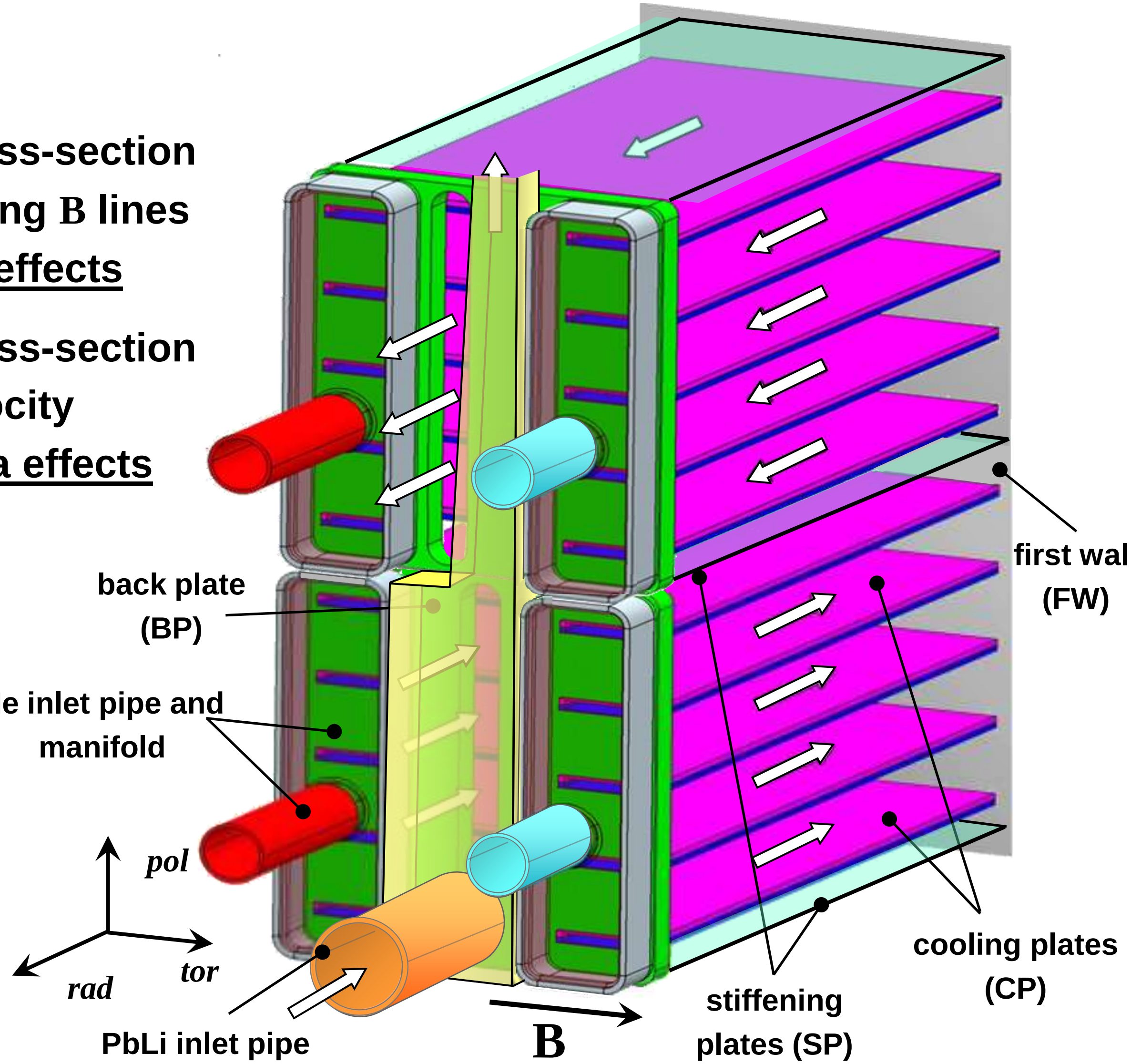
Helium Cooled Lead Lithium (HCLL) blanket

Blanket ⟷ MHD issues

- Gap at BP → ♦ Change of cross-section
  ♦ Expansion along B lines
  → <u>strong MHD effects</u>
- Gap at FW → ♦ Change of cross-section
  ♦ Increased velocity
  → <u>strong inertia effects</u>
- Manifolds → ♦ High velocity
  ♦ Long path
- <u>Electric flow coupling</u>

❖ Flow distribution

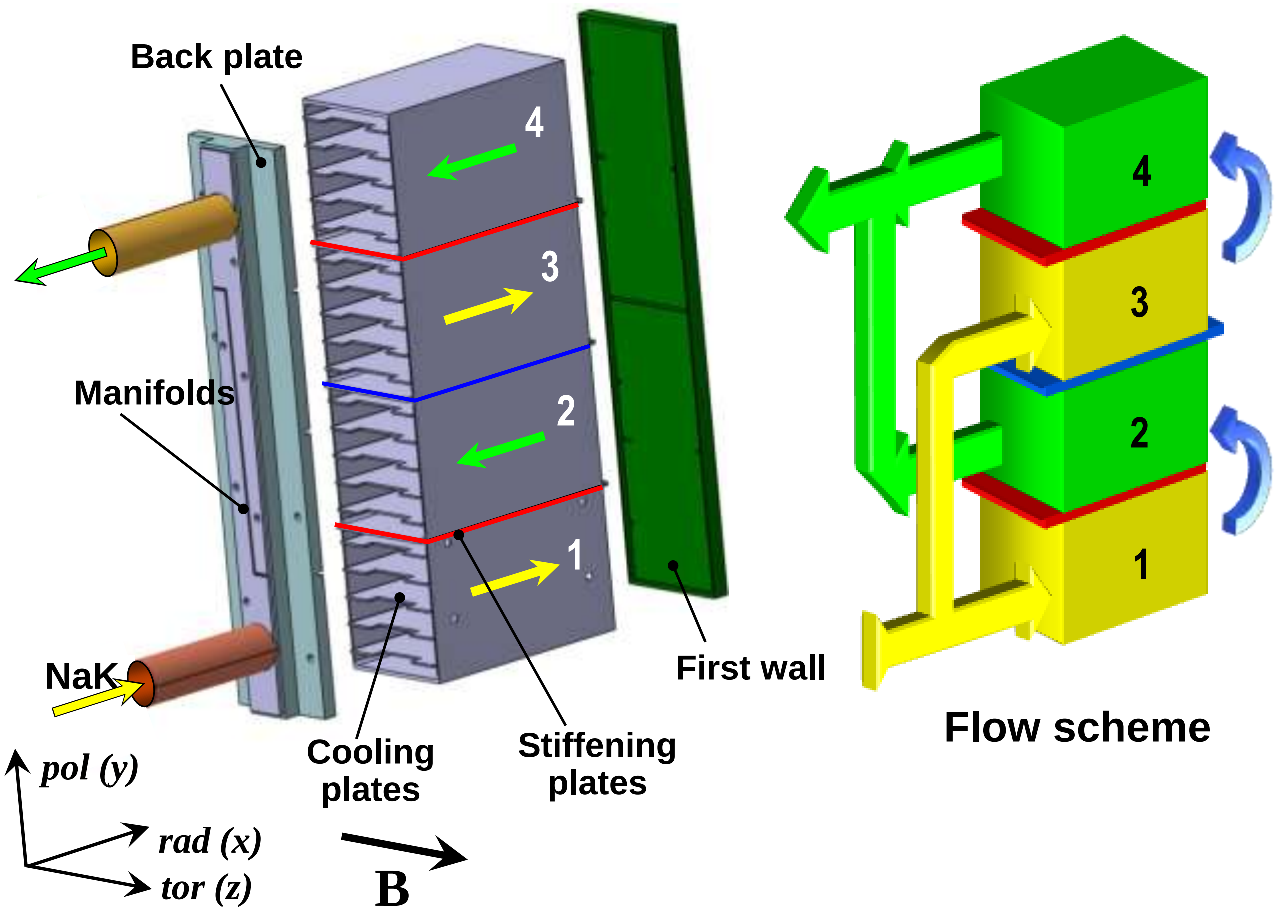
❖ Pressure drop



Mock-up of an HCLL blanket

❖ Mock-up scaled 1:2 compared to original TBM (4 breeder units)

❖ Model fluid: sodium potassium alloy NaK ($\sigma = 2.88\ 10^6\ 1/\Omega m$)

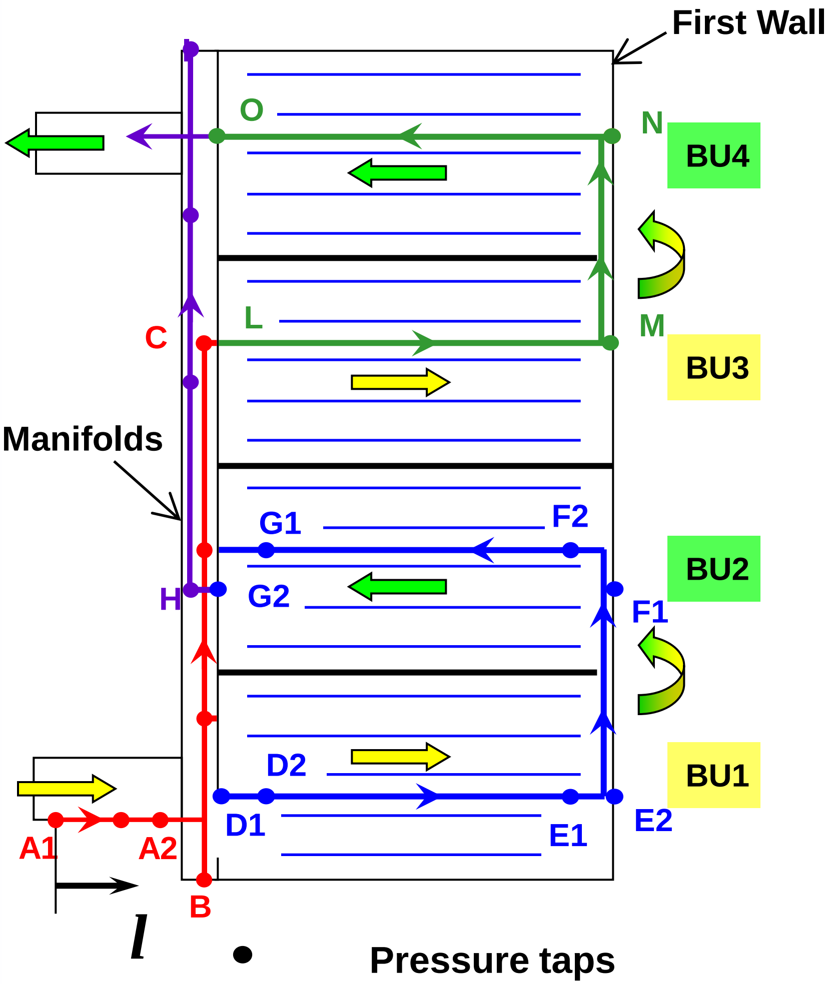


Objectives

- Measurements of
- → Pressure
- → Electric potential

Contributions to the total pressure drop

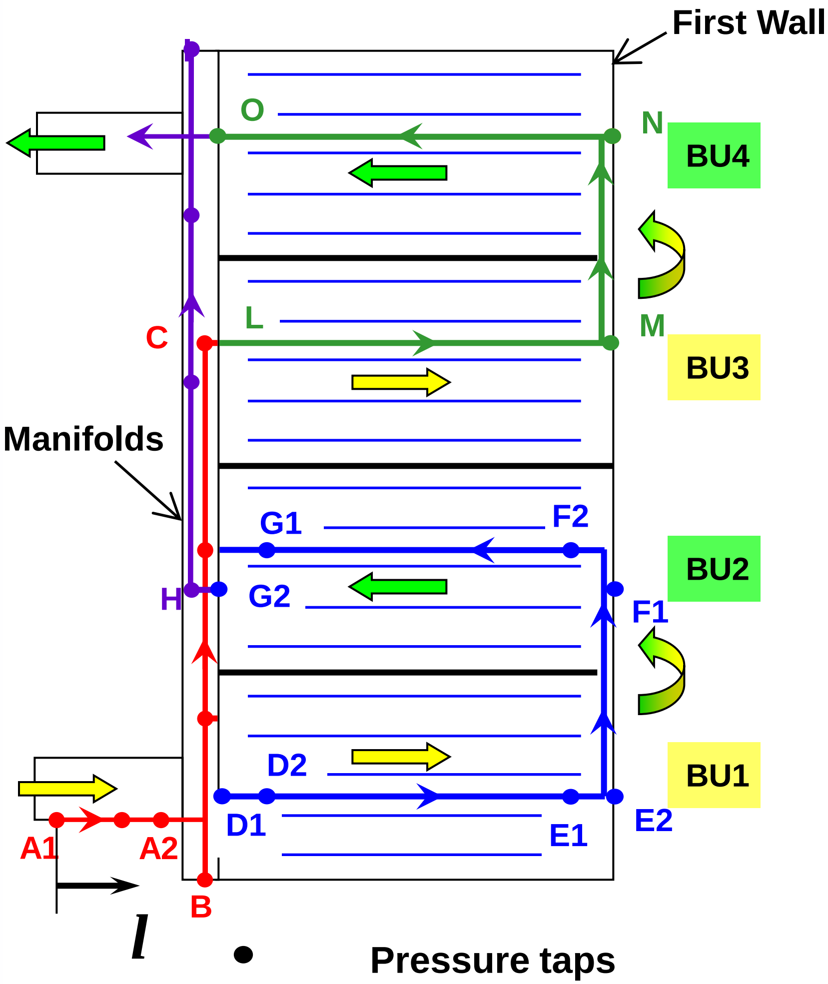
- Identify critical elements / locations
- Defining scaling laws

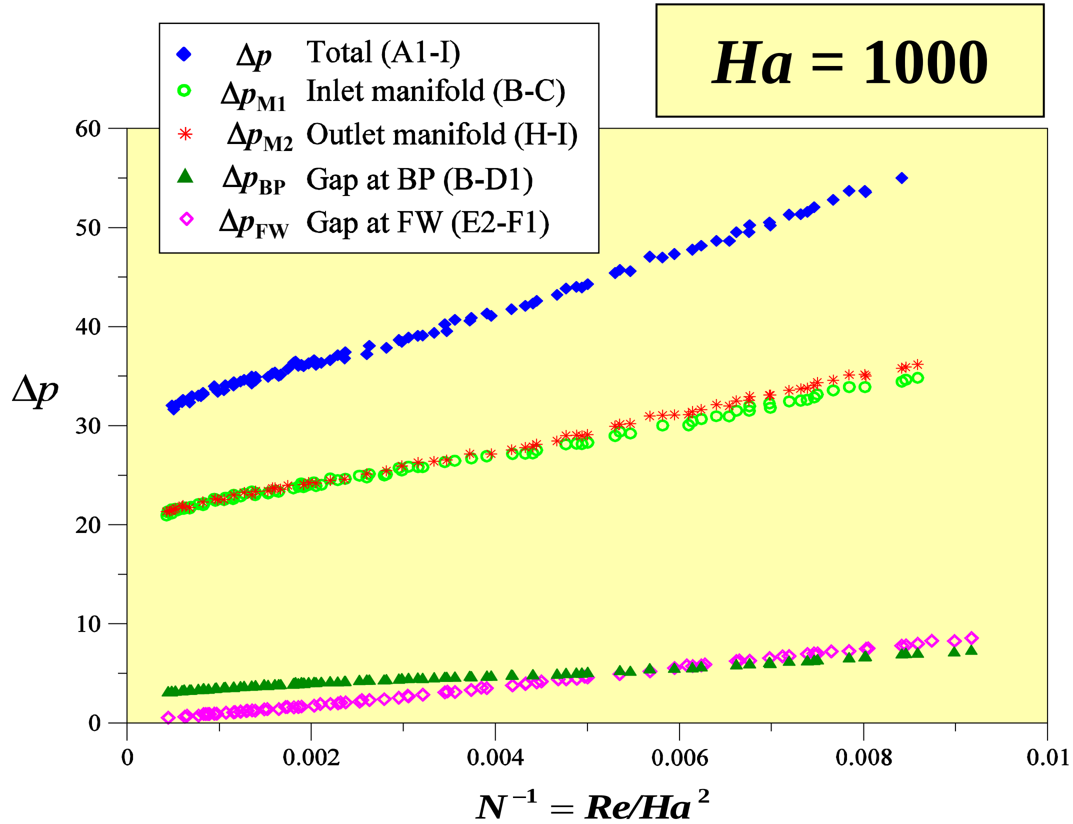


- Main pressure drop in manifolds and gaps
- All Δp contributions increase linearly with N^{-1}
- Strong MHD effects across BP gap
- Intense inertia effects are present at the FW
- Pressure almost unform in breeder units

Contributions to the total pressure drop

- Identify critical elements / locations
- Defining scaling laws

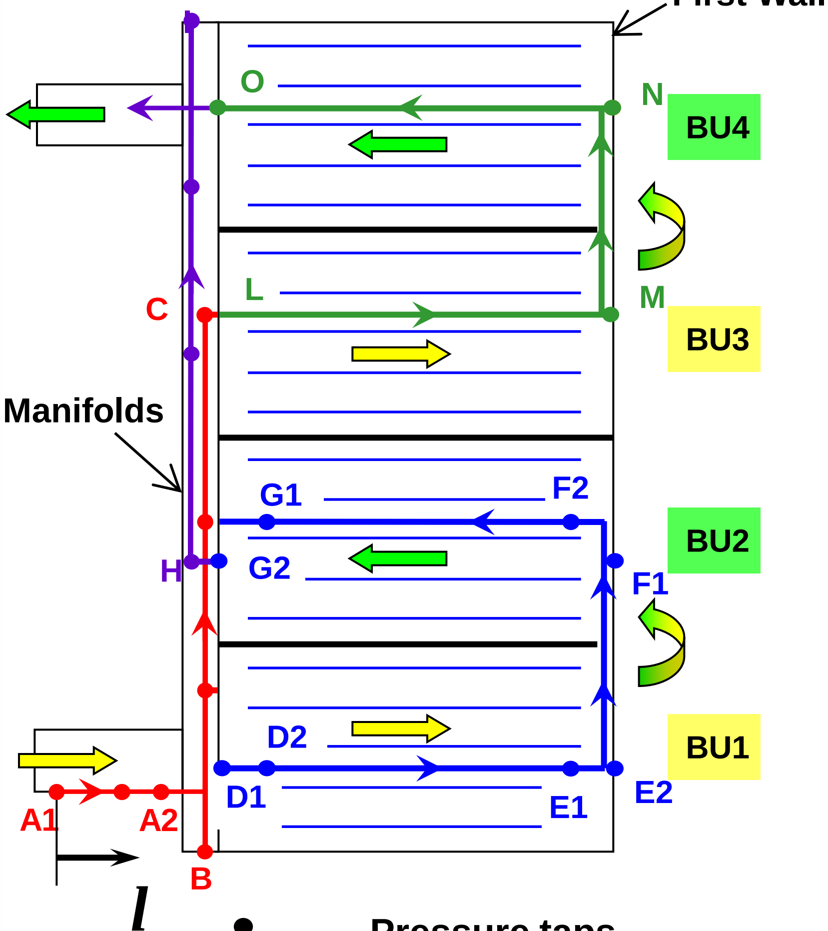




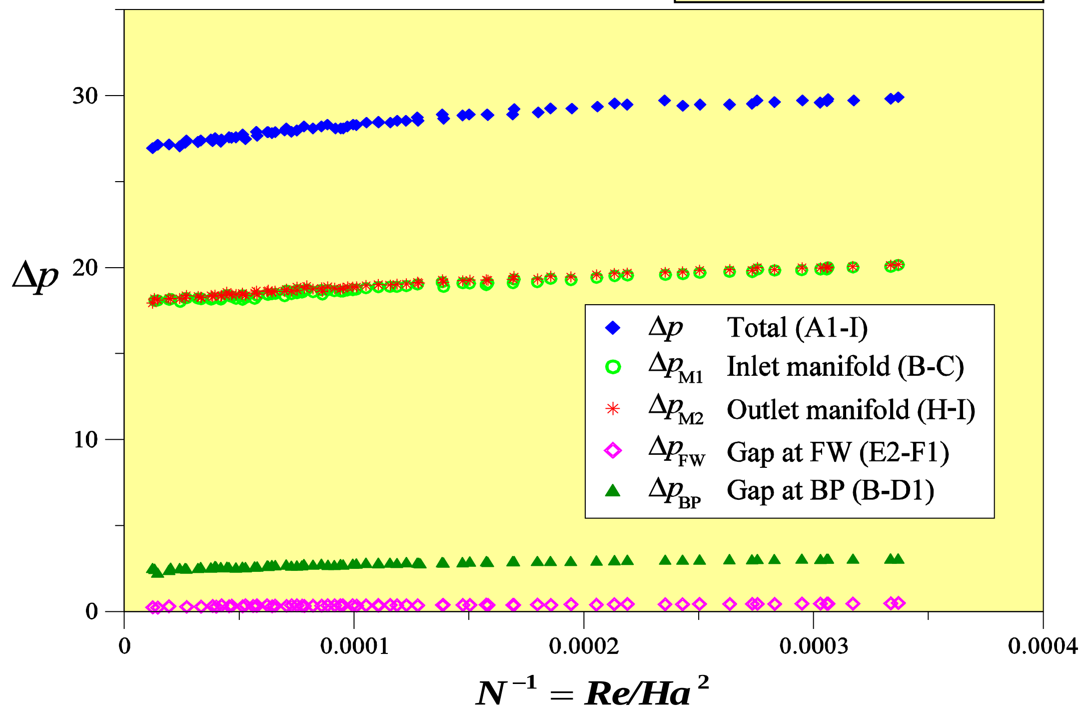
- Main pressure drop in manifolds and gaps
- All Δp contributions increase linearly with N^{-1}
- Strong MHD effects across BP gap
- Intense inertia effects are present at the FW
- Pressure almost unform in breeder units

Contributions to the total pressure drop

- **Identify critical elements / locations**
- **Defining scaling laws**

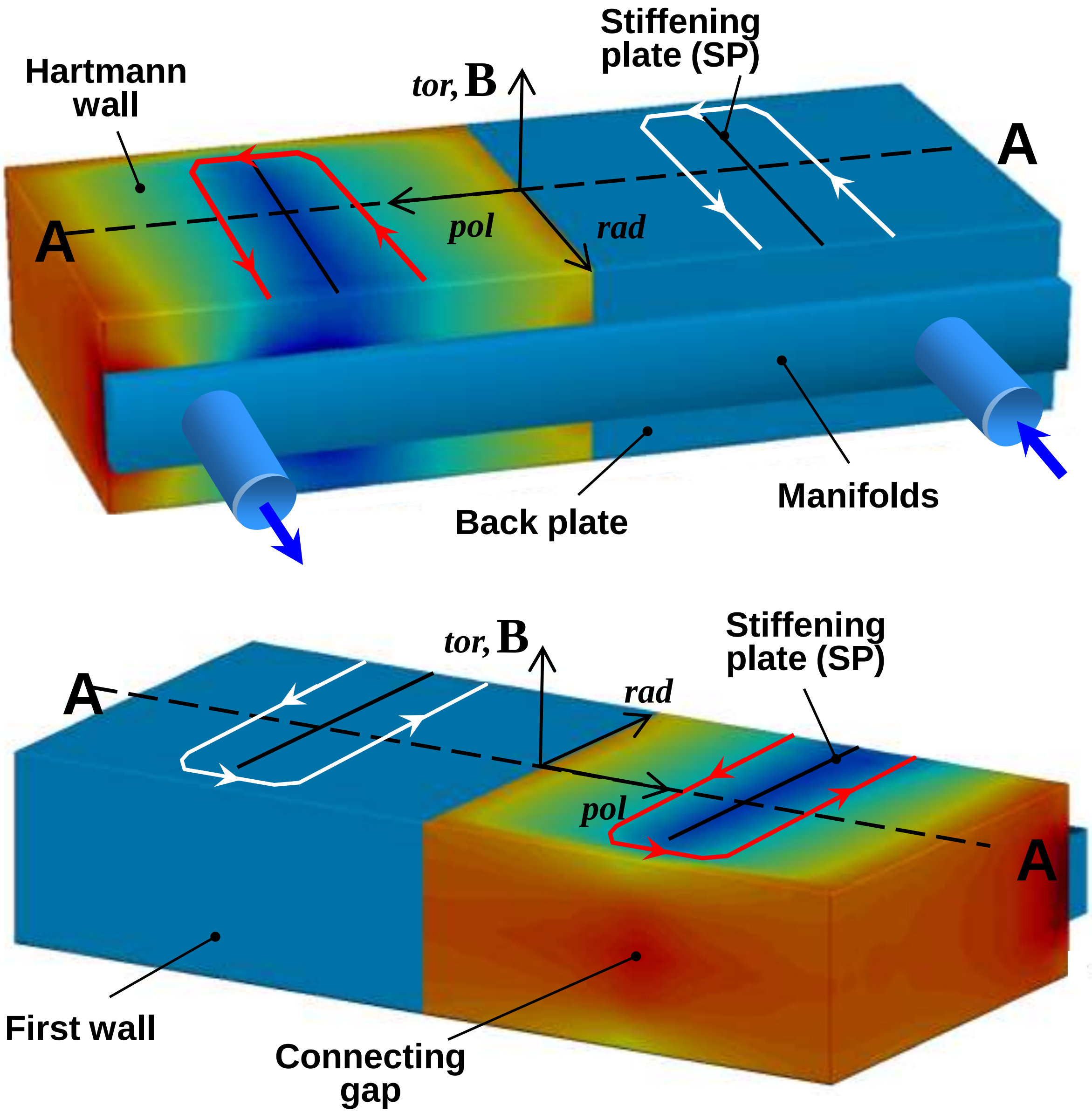


Ha = 3000



❖ **For ITER conditions Δp is inertialess**

Measured surface potential



Measured electric potential at
Ha = 3000, *Re* = 1000

Potential measurements

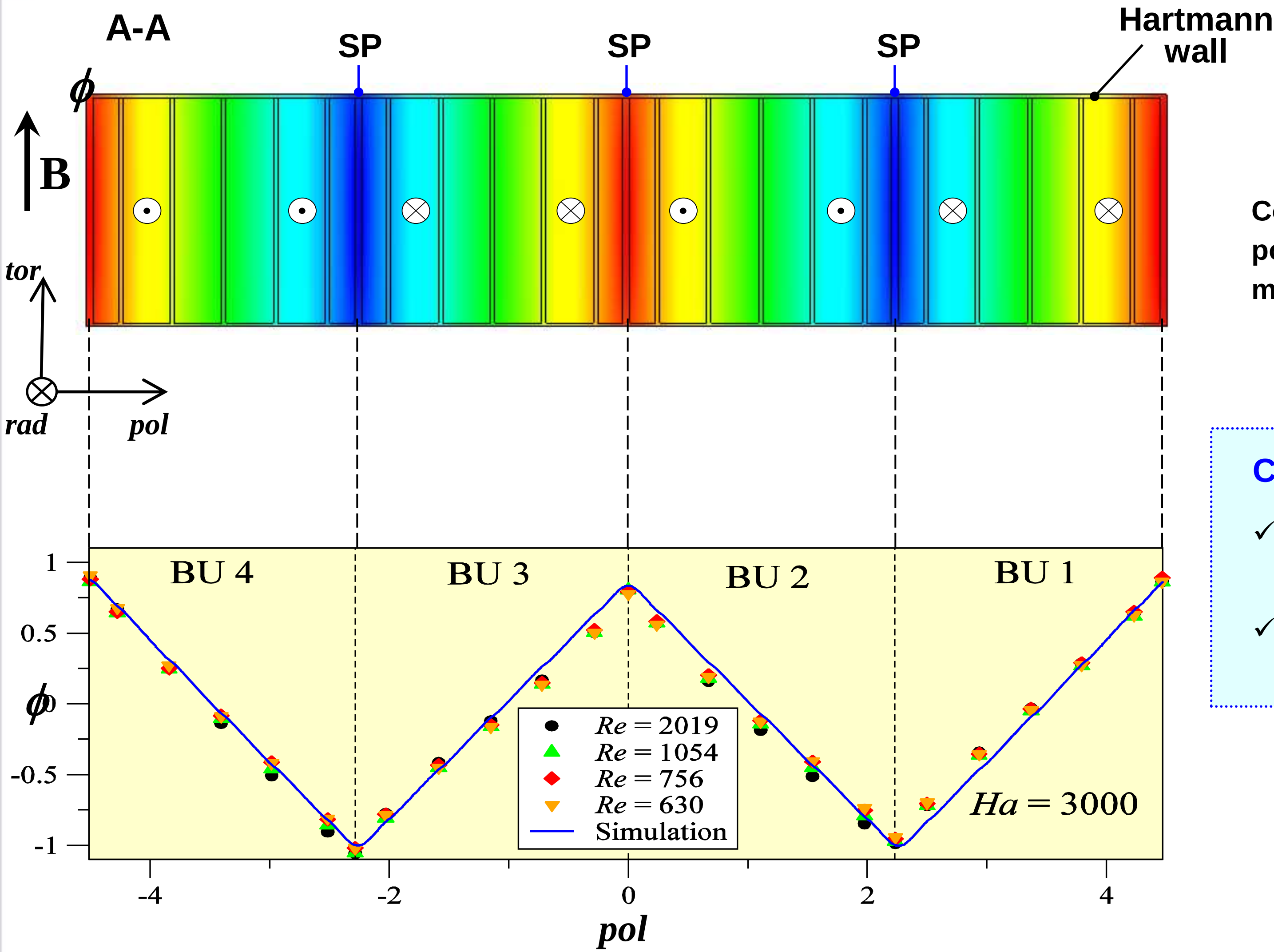
They serve as indicators for *flow distribution* in mock-up:

- Lines of constant colour are streamlines
- Fully developed flow conditions along AA

⇩

Assumption for numerical calculations

Experiments and numerical results



Comparison of potential profiles along the Hartmann wall

***Ha* = 3000**

Contours of calculated electric potential on the MHD mock-up middle plane (AA).

Comparison

- ✓ **Validity of FDF assumption (weak *Re* - dependence)**
- ✓ **Good quality of measuring technique for potential**

Things to remember!

- **HCLL blanket and MHD issues:**

  MHD flow through geometries with different-cross sections, long manifolds, electric flow coupling

  ⇒ Influence on pressure and flow distribution

- Experiments in a mock-up of a HCLL blanket:

  - Measurements of pressure differences and surface electric potential

- **Pressure measurements:**

  - Main pressure drop in manifolds and across BP gap (3D MHD effects)

  - **Pressure drop correlation** derived from experimental data

- **Electric potential measurements:**

  Contour plots of potential give overview of flow distribution (ϕ streamfunction)

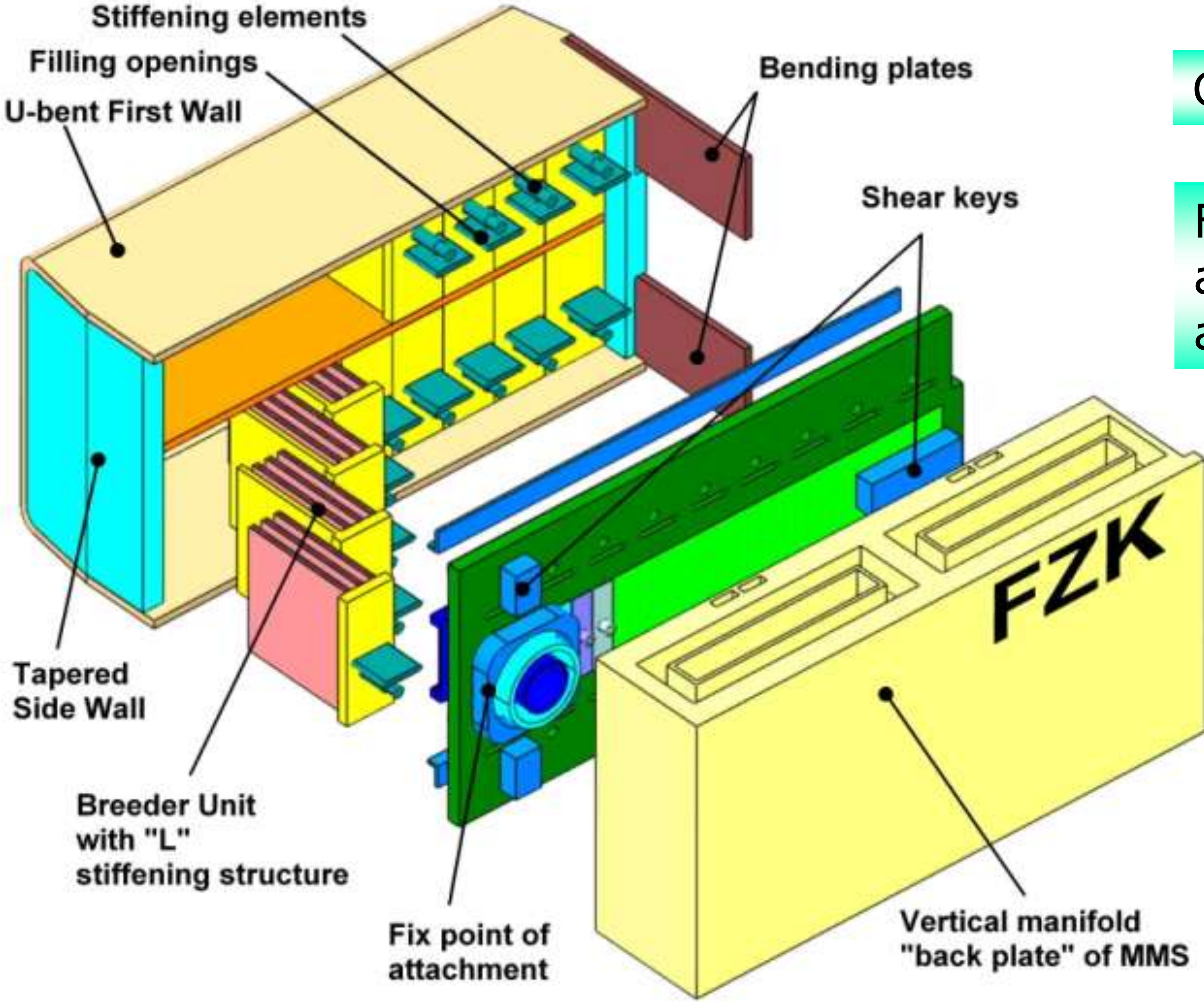
- **Fundamental role of numerical calculations:**

  - Support definition of scaling and extrapolation laws

  - First overview of flow phenomena: position and number of sensors

  → Need of high-performance parallel computing

Development of HCPB sub module concept for DEMO



Compatible with MMS concept.

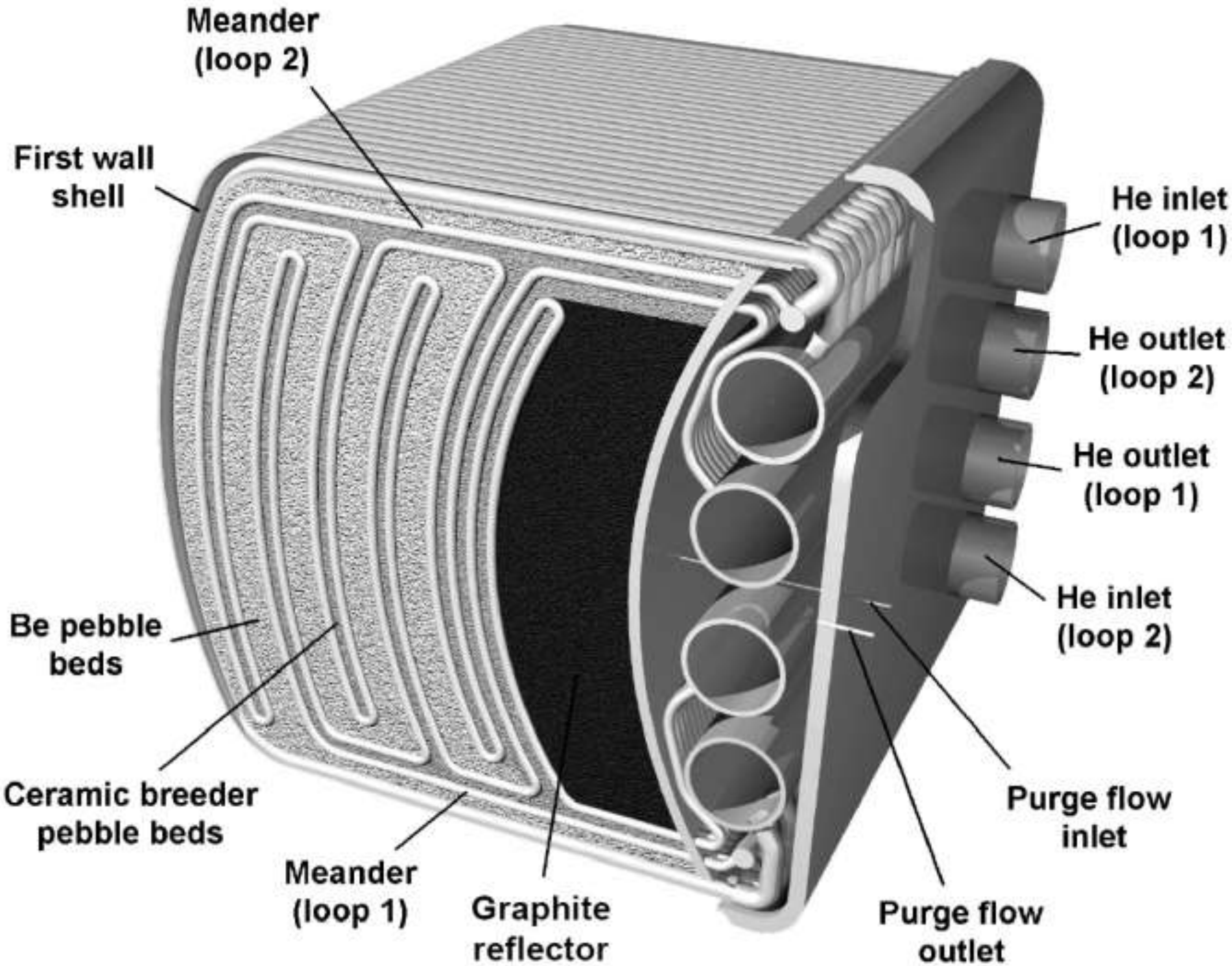
Flexible attachment concept adaquate for transient thermal and electromagnetic loads.

Reduced number of single parts and welds. (improved feasibility)

Reduced Helium pressure drop.

Advanced HCPB approach with SiC_f/SiC structures

KIT Karlsruhe Institute of Technology

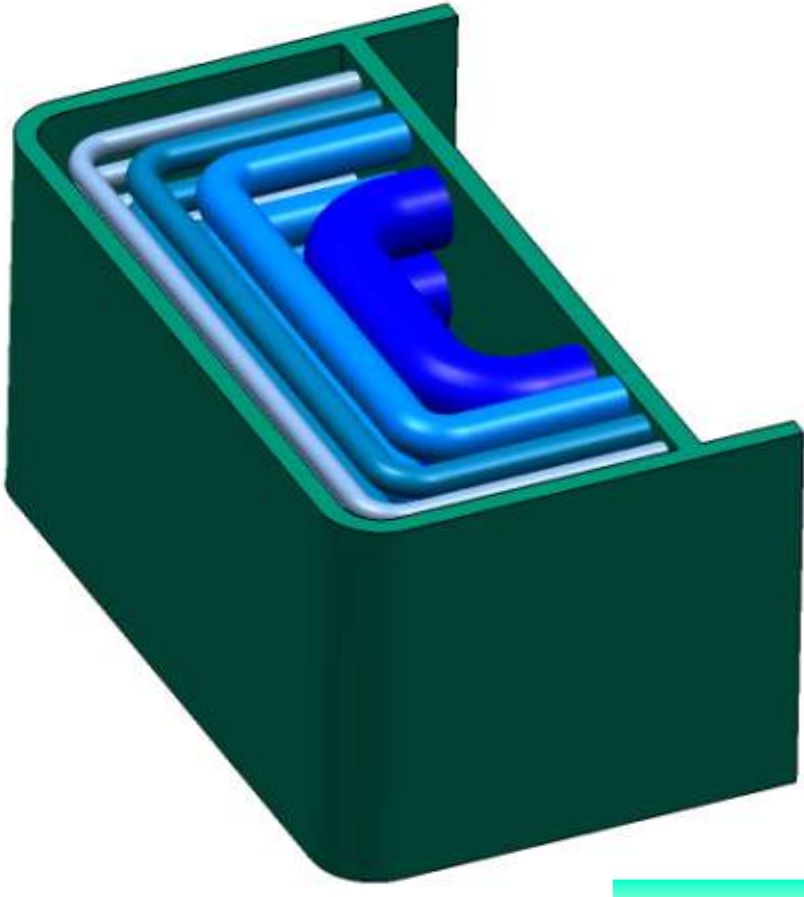


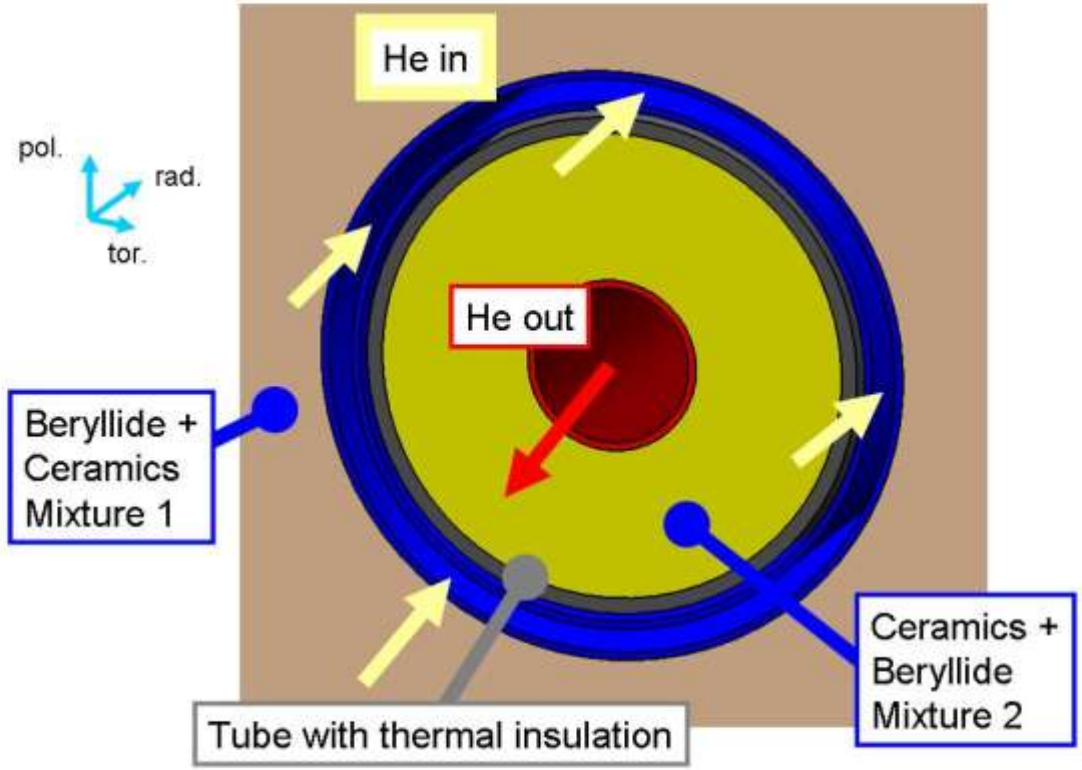
FW and cooling tubes From SiC/SiC

Helium operated up to 700°C at the outlet

Advanced HCPB approach with mixed beds and SiC inserts

Karlsruhe Institute of Technology

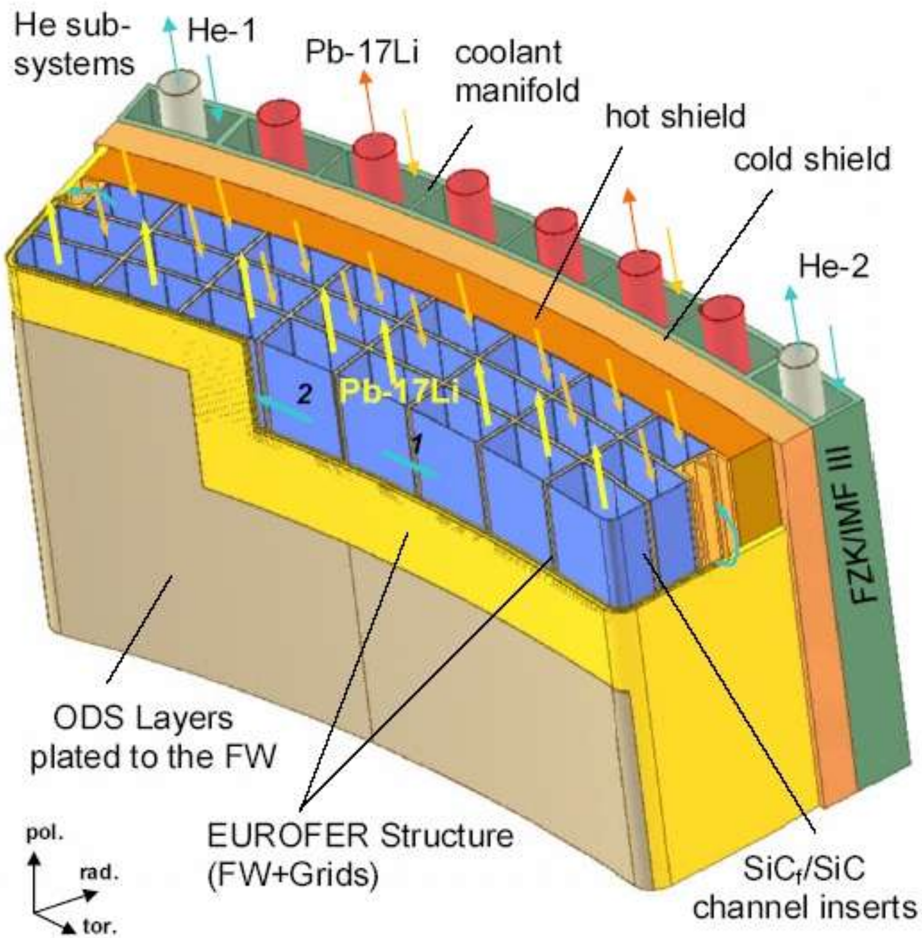


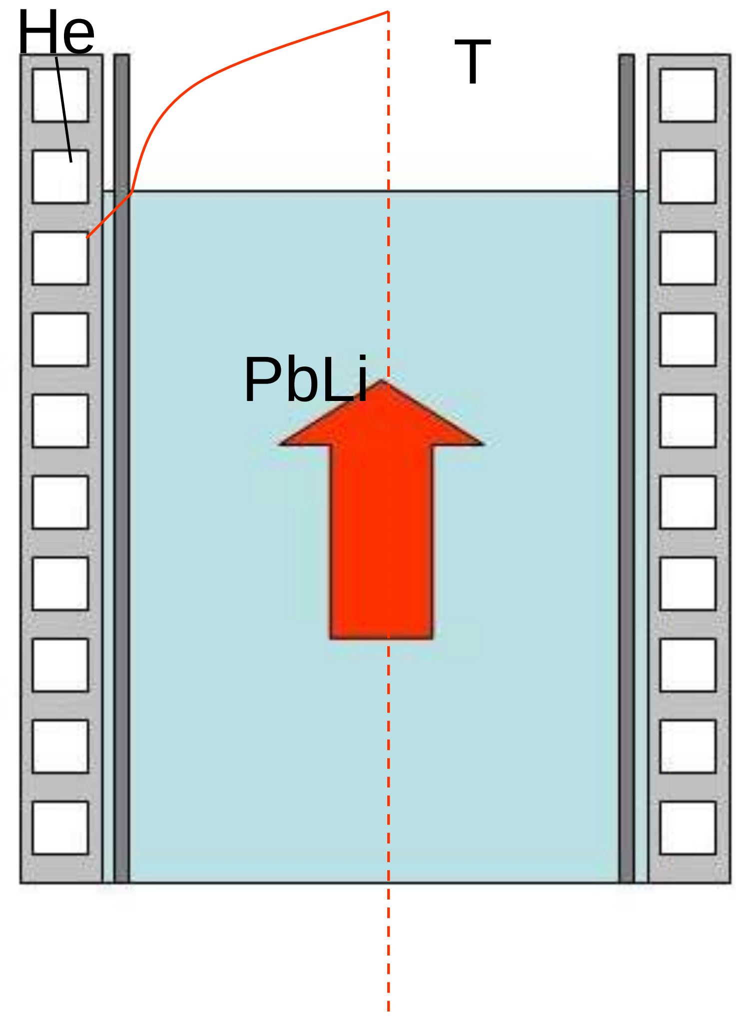


Concentric cooling tubes with inserts from SiC/SiC

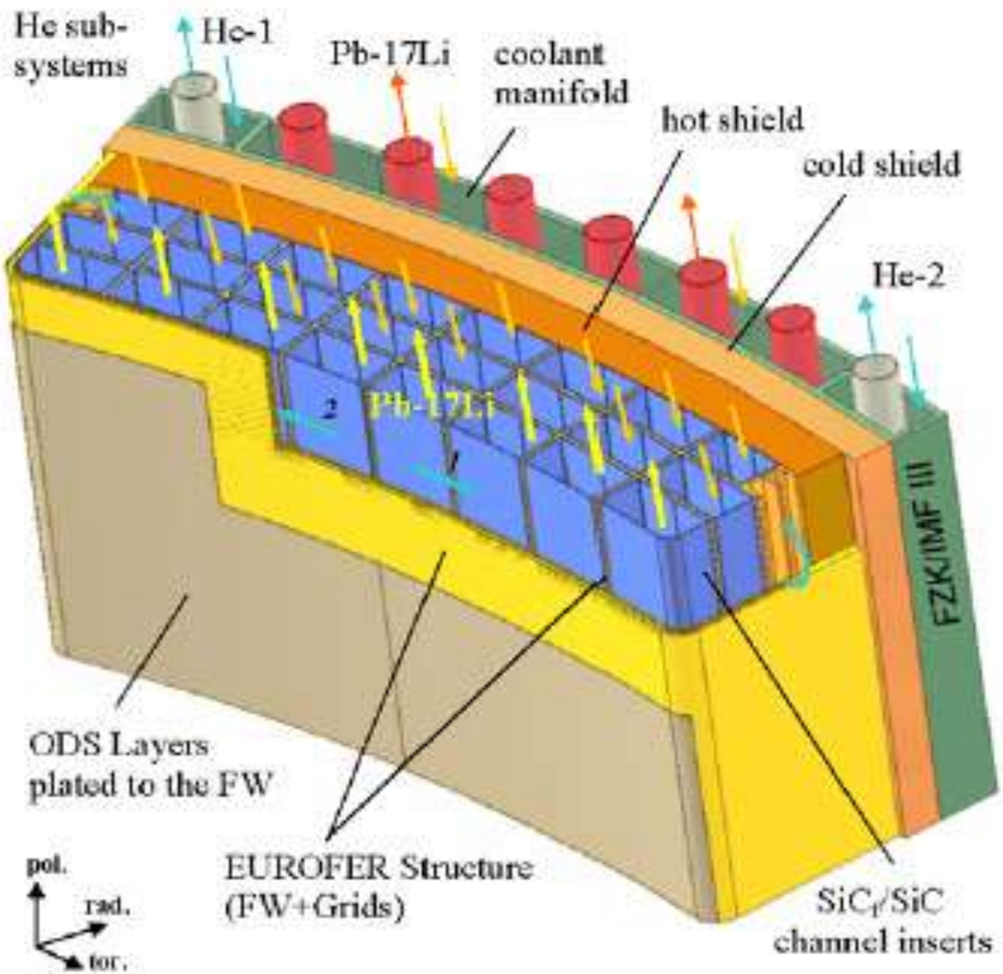
Helium operated up to 700°C at the outlet

FZK DCLL Blanket (EU-PPCS Model C, 2002)





FZK DCLL Blanket (EU-PPCS Model C, 2002)



Main features:

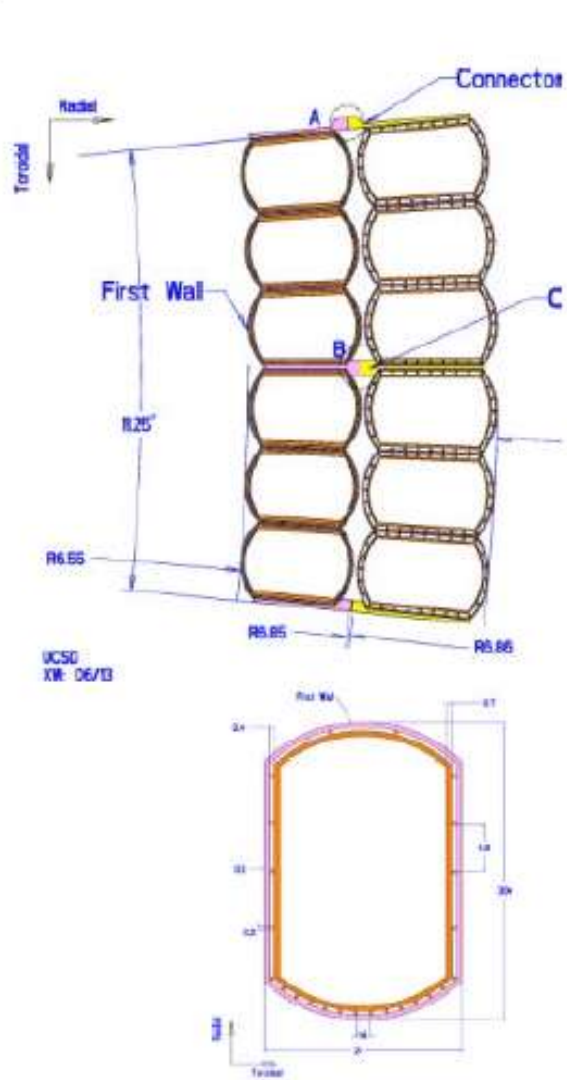
- helium-cooled RAFM steel structures (EUROFER)
- ODS plated FW to use the high-temperature strength of ODS
- self-cooled breeding zone with Pb17Li as breeder and coolant
- SiC$_f$/SiC flow channel inserts as electrical (MHD) and thermal insulators leading to high exit temperature and high thermal efficiency

Dual Coolants	T_{Inlet} (°C)	T_{Outlet} (°C)	ΔT (K)
Helium (8 MPa)			
Overall blanket	300	480	180
FW	300	450	150
Grids	450	480	30
Pb-17Li	480	700	220

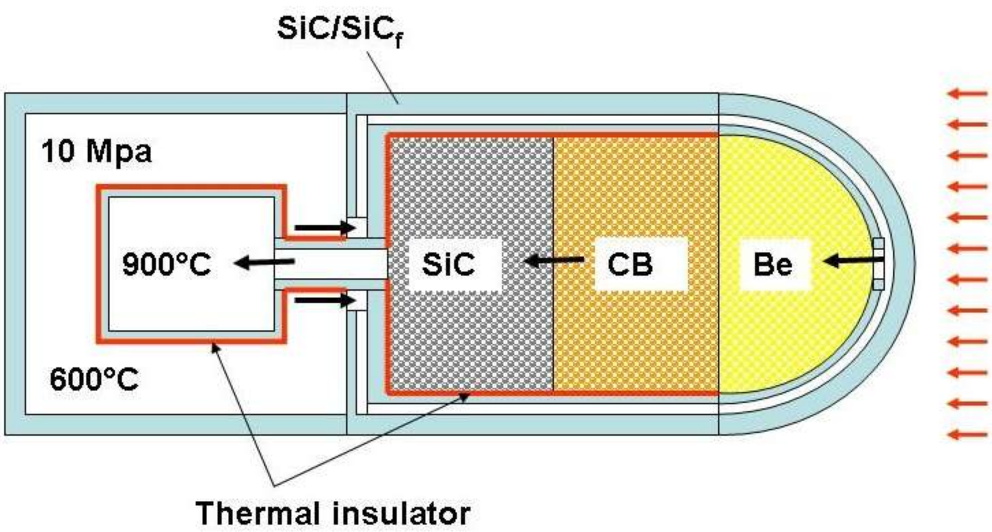
US ARIES Blanket system

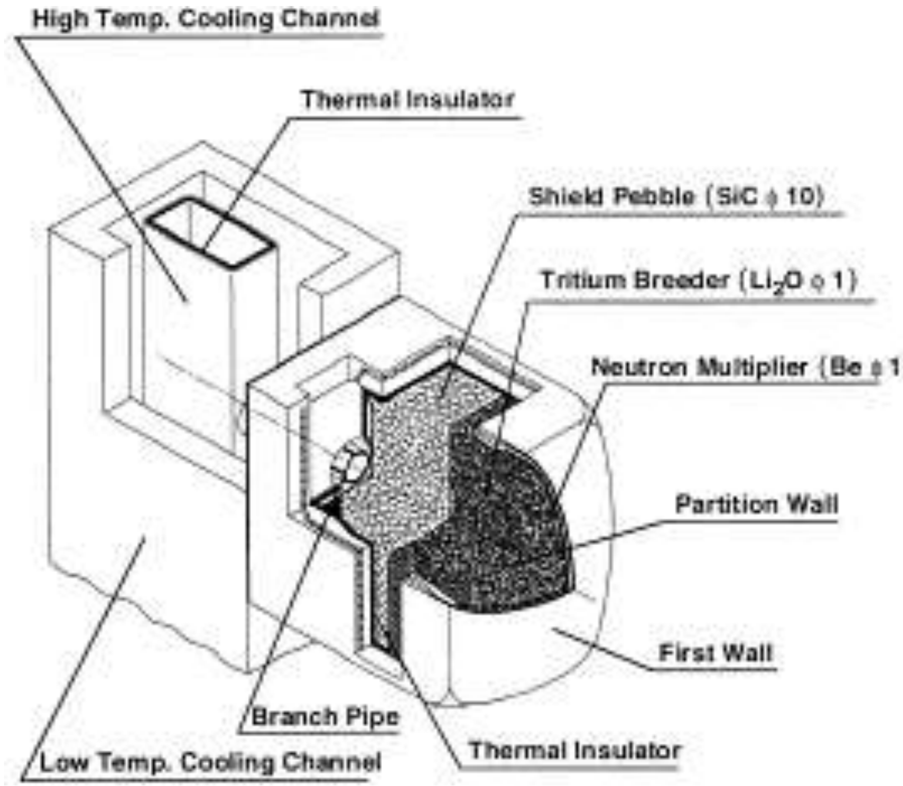
- Simple, low pressure design with SiC structure and LiPb coolant and breeder.
- Innovative design leads to high LiPb outlet temperature (~1100°C) while keeping SiC structure temperature below 1000°C leading to a high thermal efficiency of ~ 60%.
- Simple manufacturing technique.
- Very low afterheat.
- Class C waste by a wide margin.
- LiPb-cooled SiC composite divertor is capable of 5 MW/m^2 of heat load.

Outboard blanket & first wall



(Very) Advanced Solid Breeder concepts: JA Dream





Concept	Structural Material	Breeder/ Multiplier	Coolant	T-Extraction
HT-HCSB	Sic/Sic$_f$	CB / Be-alloy	He	Coolant He

Ceramic breeder blanket design

Blanket has to optimize: That neutrons from the plasma
1.) are causing neutron multiplication with Be and
2.) are absorbed in ^{6}Li

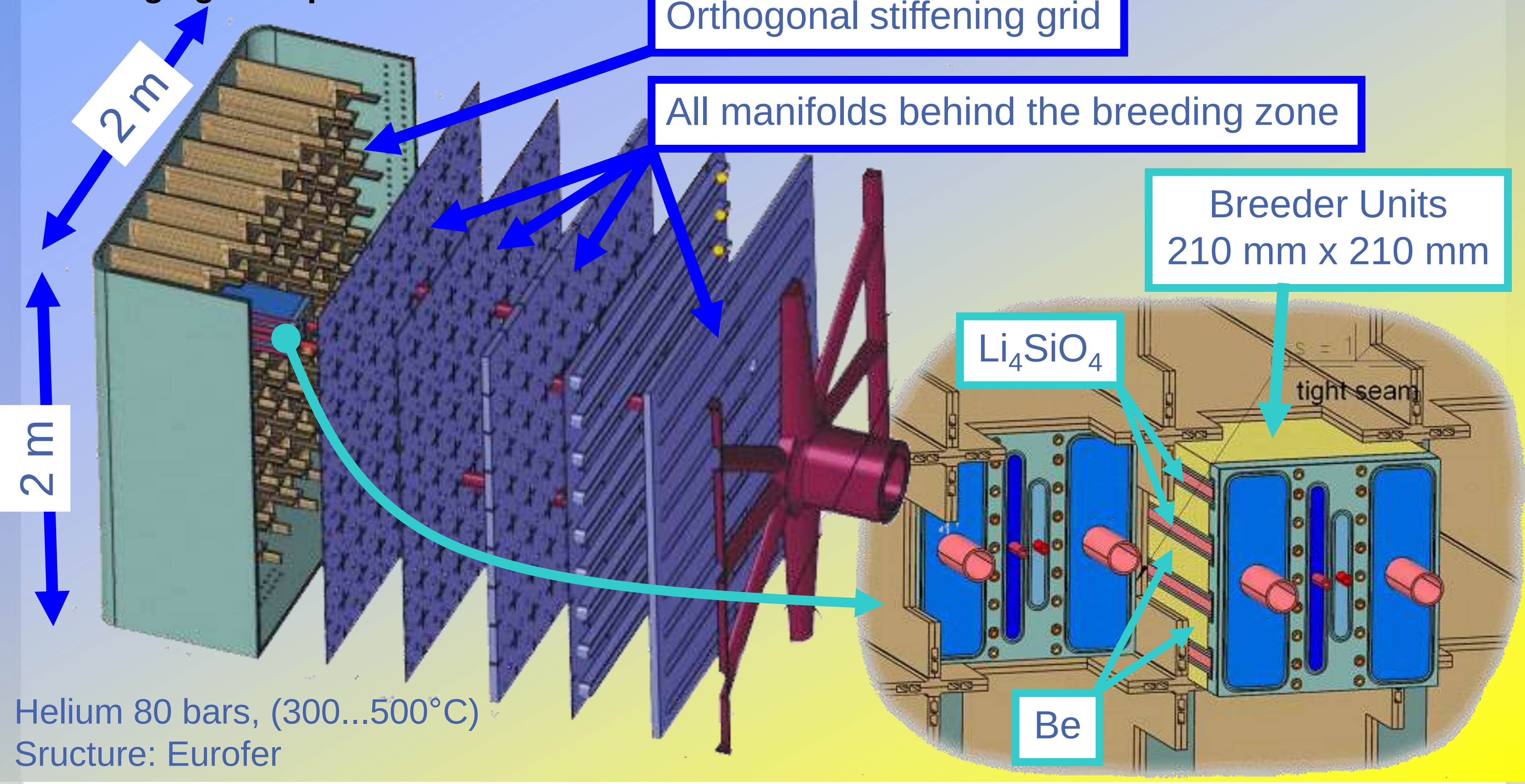
→ Avoid inelastic scattering with and absorption in iron
→ Small amount of steel structure, especially thin first wall
→ Enrichment with ^{6}Li (e.g. 30%), especially where slow neutrons are present

↕

But safety and from this strength of the blanket has to be optimized, too

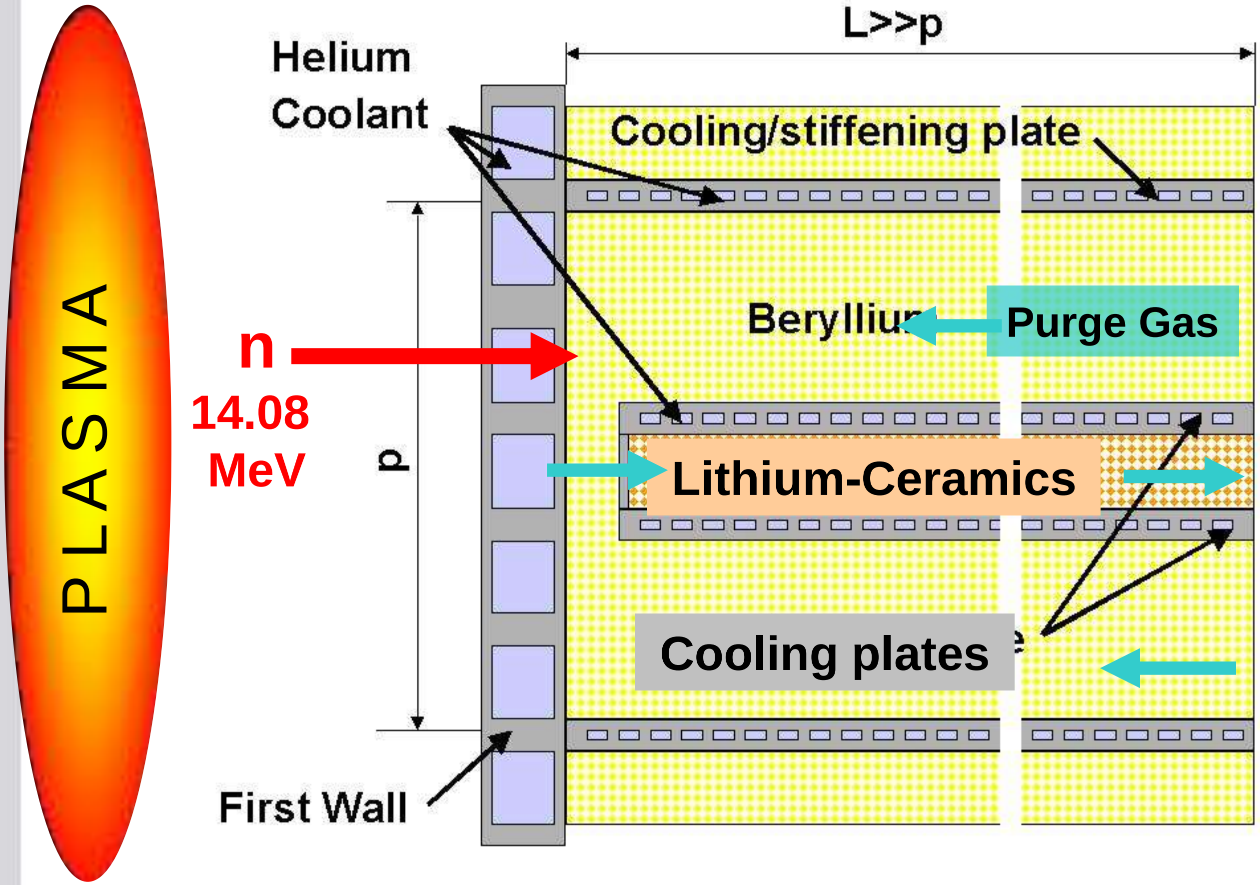
HCPB blanket design for DEMO

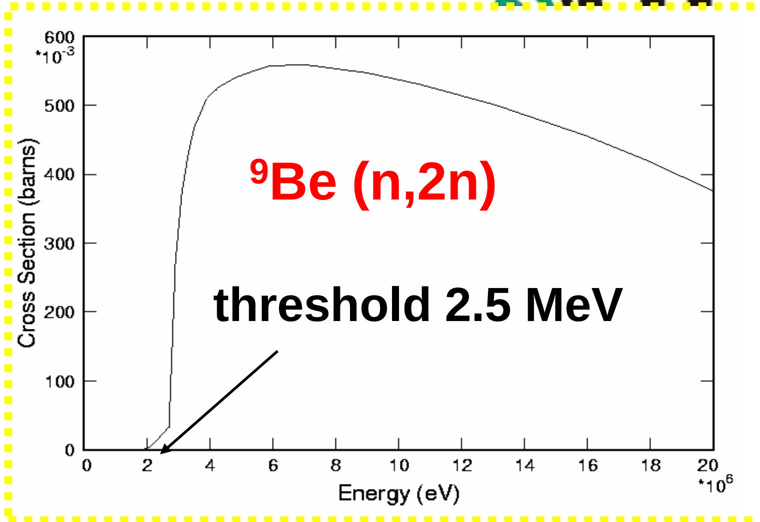
Strong against pressurization

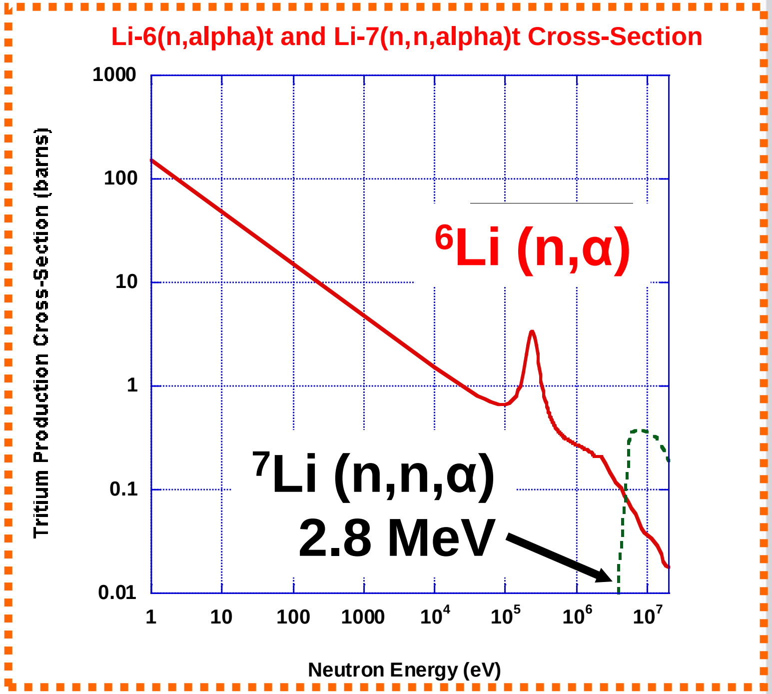


Helium 80 bars, (300...500°C)
Sructure: Eurofer

HCPB blanket design for DEMO







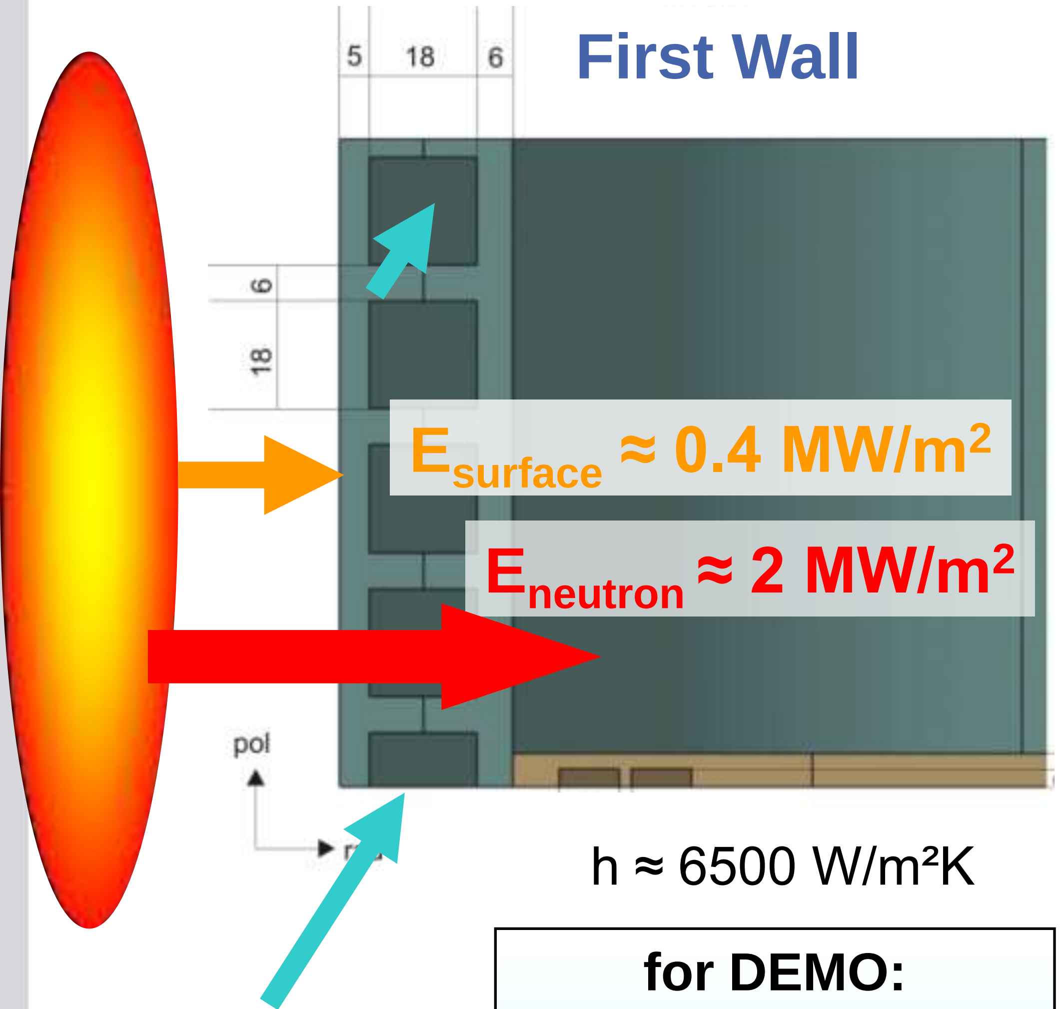
Main solid breeder blanket material

Materials	
Solid Breeder	Li_2O, Li_4SiO_4, Li_2TiO_3, Li_2ZrO_3
Multiplier	Beryllium/Beryllides**
Structure	Ferritic or austenitic (ITER base)
Coolant	Helium or water
Purge	Helium + %H_2
Material form	
Solid breeder and multiplier	Sphere-pac or sintered block
Configuration	BIT, BOT, layers

***High temperature capability and less reactivity*

First Wall cooling

First Wall

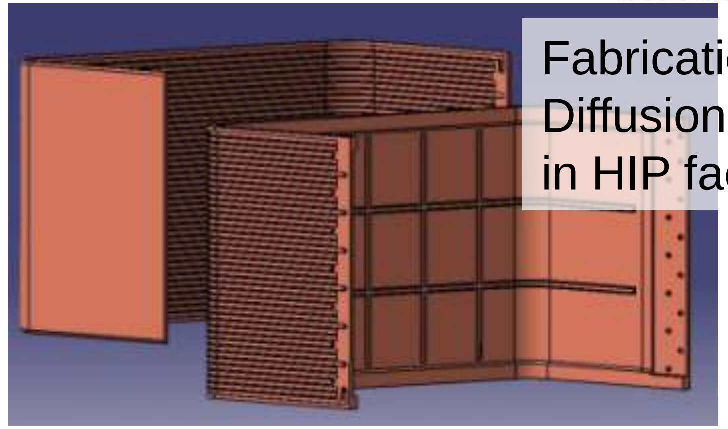


He, 8 MPa, 84 m/s

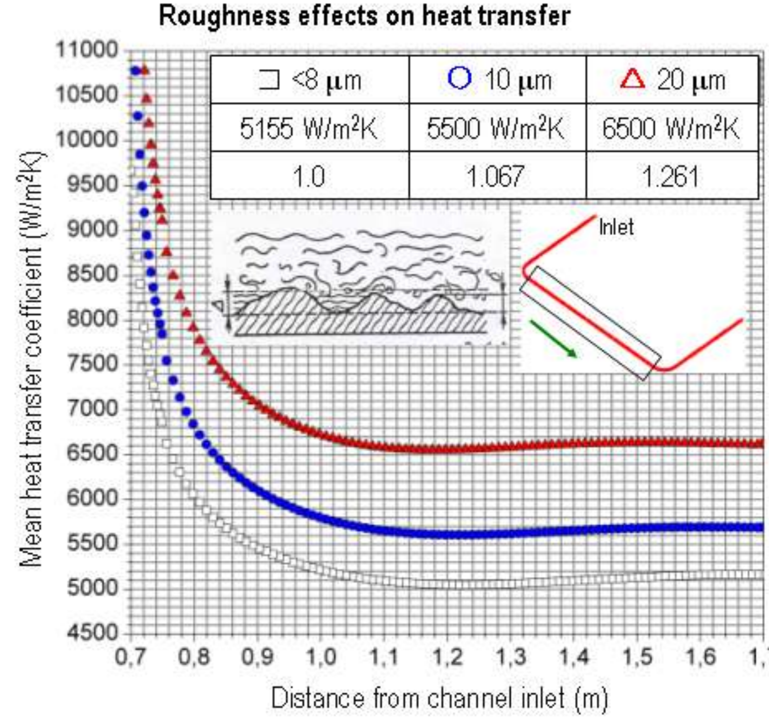
h ≈ 6500 W/m²K

for DEMO:

Δp ≈ 117 kPa (20 μm)



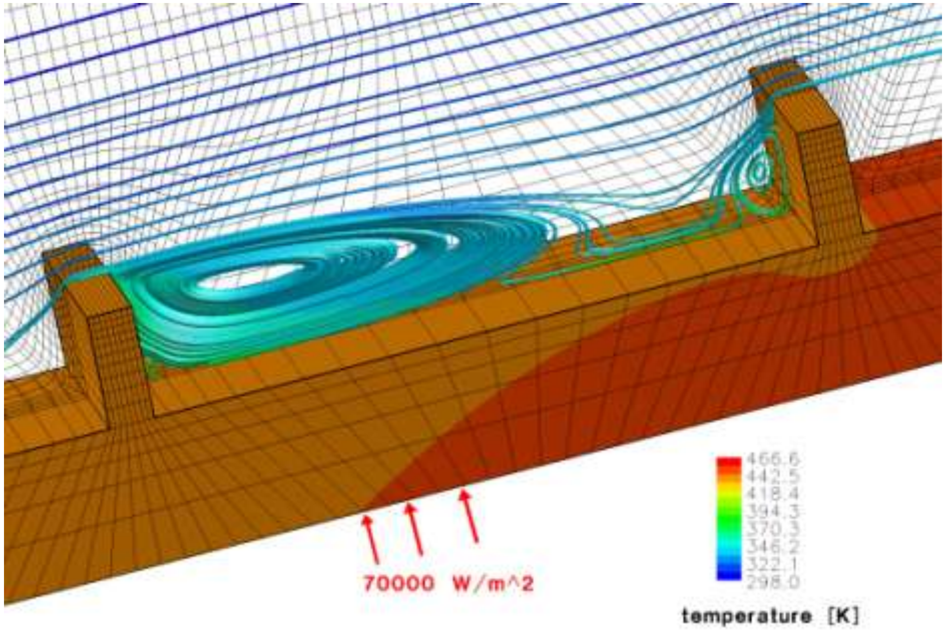
Fabrication by Diffusion welding in HIP facility

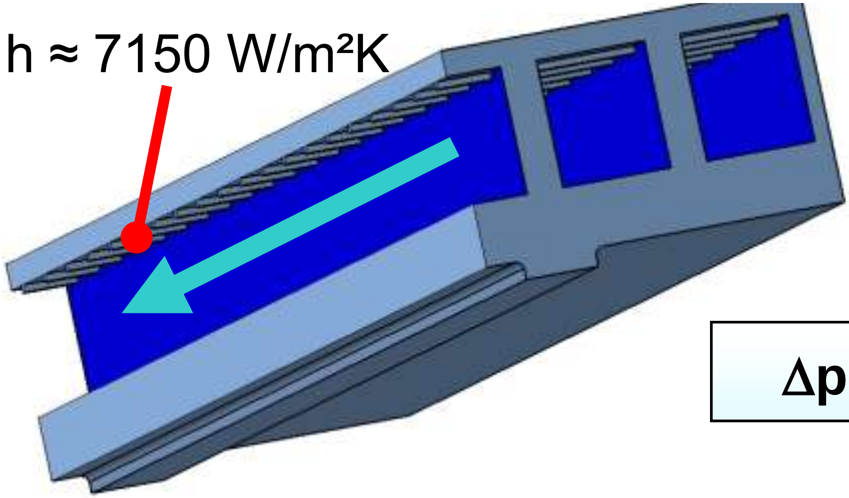


□ <8 μm	O 10 μm	Δ 20 μm
5155 W/m²K	5500 W/m²K	6500 W/m²K
1.0	1.067	1.261

First Wall rib cooling

Pr_{air} = 0.71
Pr_{He} = 0.67





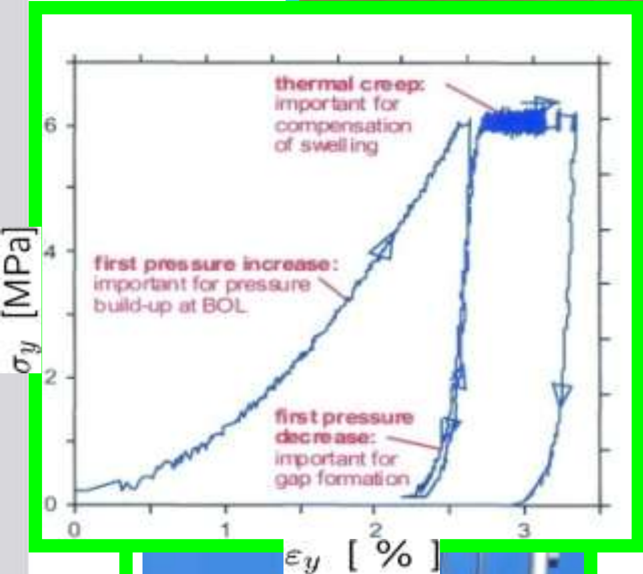
Gasturbine blade cooling

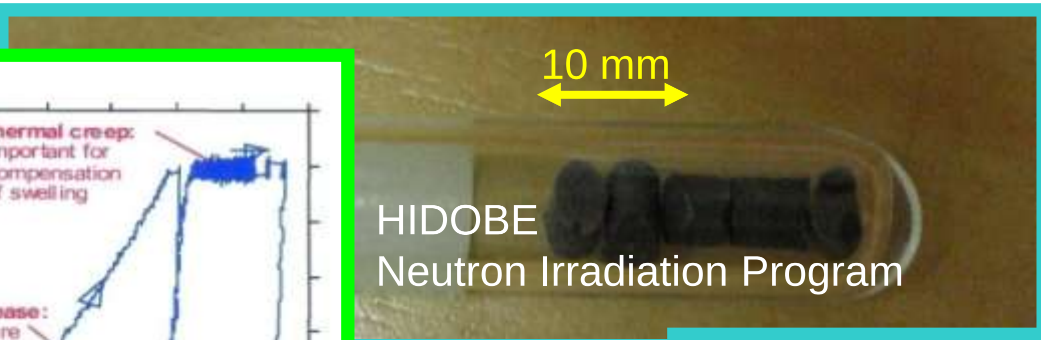
He, 8 MPa
39 m/s

Δp ≈ 38.3 kPa

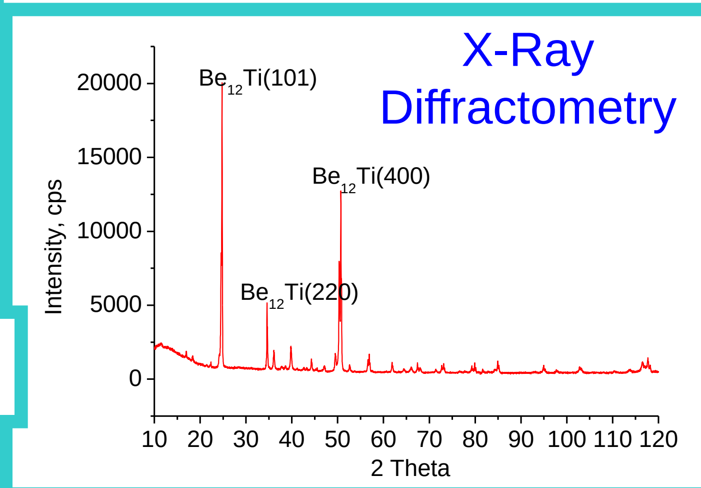
R&D on pebble beds at KIT: overview

KIT Karlsruhe Institute of Technology



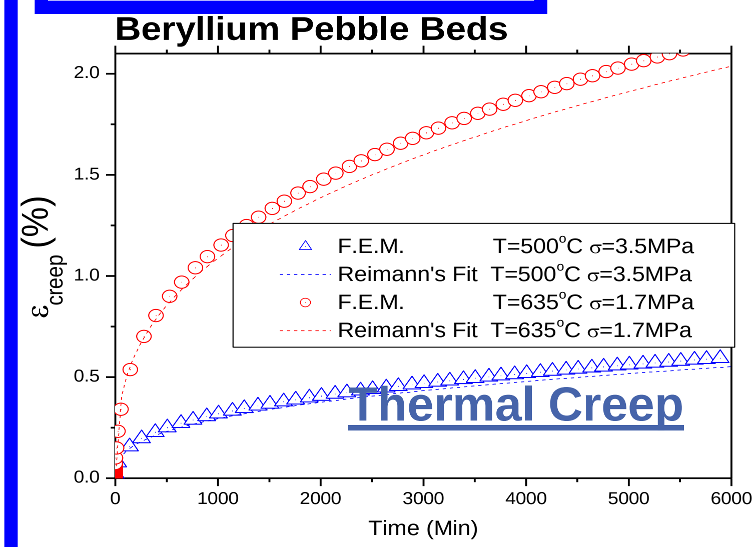


Berylite $Be_{12}Ti$



Experiments Data Base

Numerical Tools



Li_4SiO_4

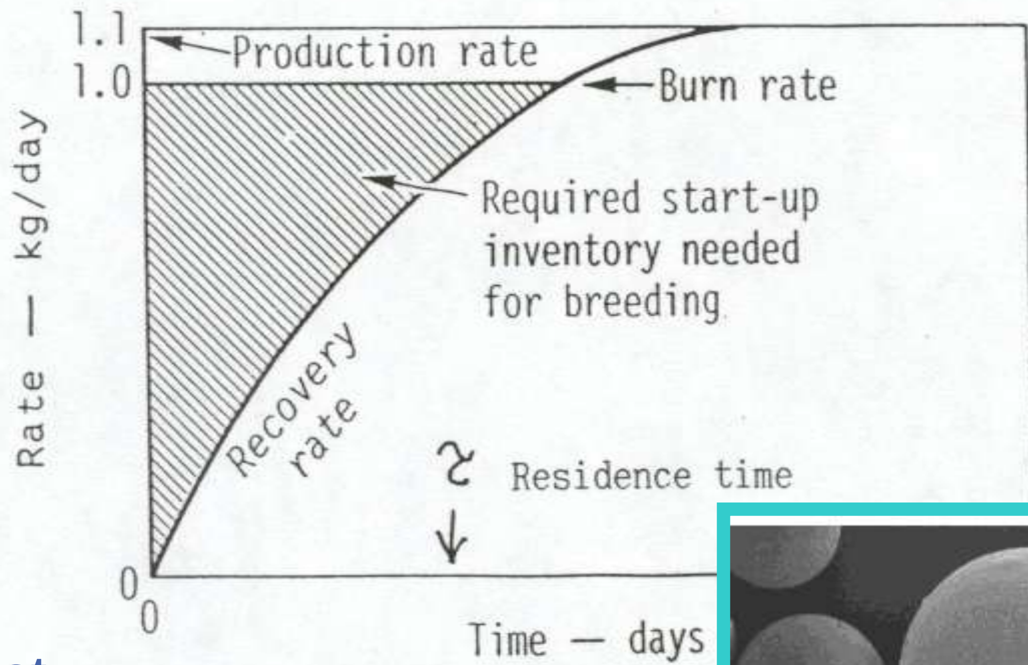
Fabrication

Tritium inventory

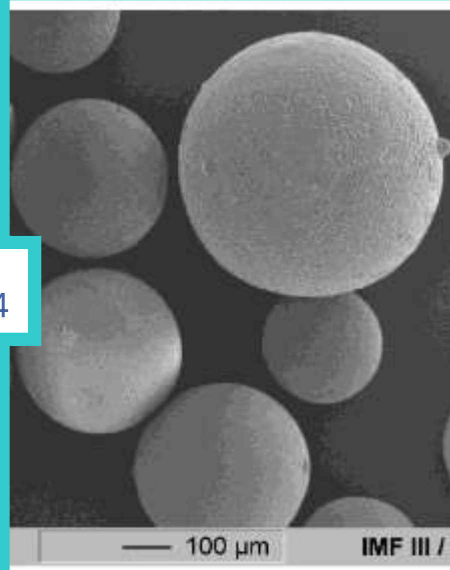
Tritium generation rate **G** and its recovery rate **R** must satisfy self-breeding and start-up **TBR > 1**

Tritium inventory **I = ∫(G-R)dt**

Tritium residence time **τ = I/G**



Tritium inventory in the blanket should be small → Tritium should not stay long in the breeder. (safety and start-up issues)

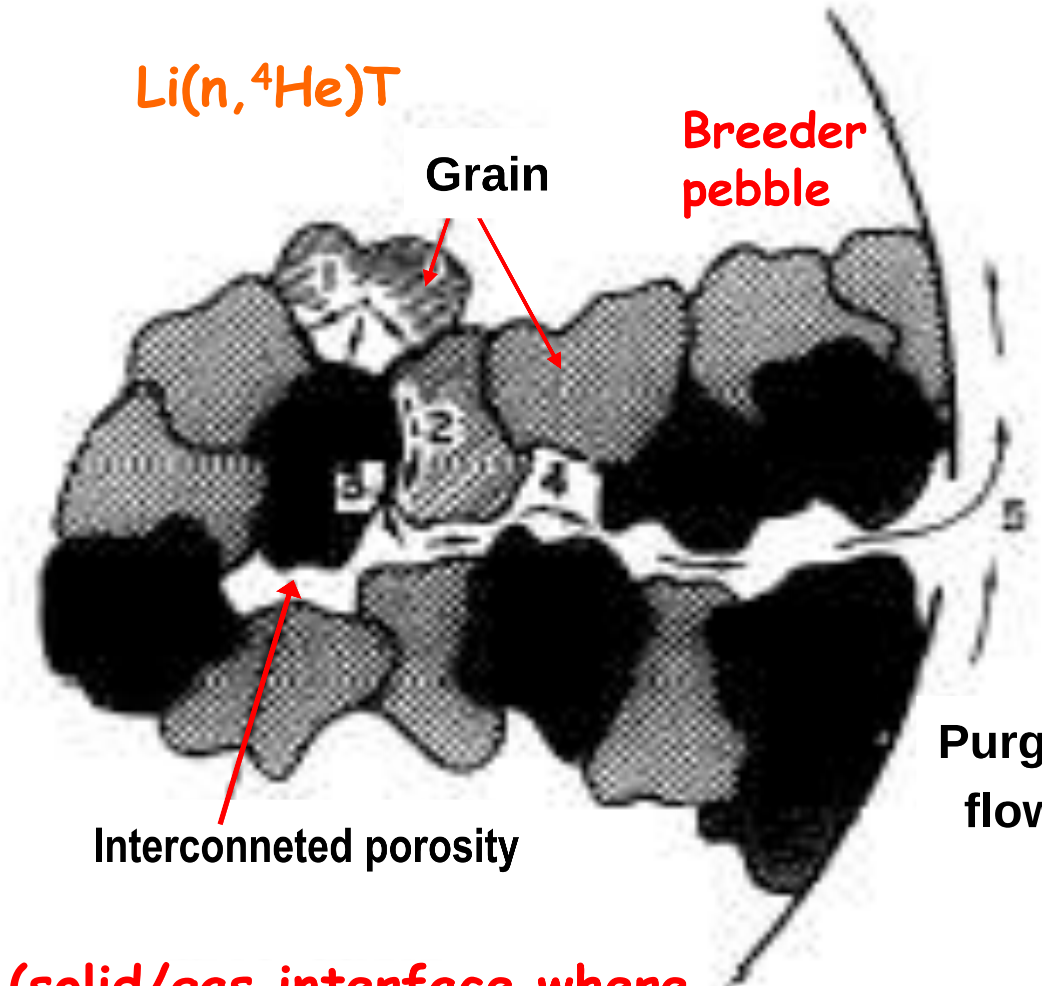


Li_4SiO_4

→ Small pebbles with porosity > 30 %, reduce τ
typical size of breeder pebbles: d = 0.2 mm

→Temperature shall not be to small as this would reduce the diffusion of Tritium in the material (for Li_4SiO_4 : T > 300°C)

Mechanism of Tritium transport



(solid/gas interface where adsorption/desorption occurs)

Mechanisms of Tritium transport

1) Intragranular diffusion
2) Grain boundary diffusion
3) Surface Adsorption/desorption
4) Pore diffusion
5) Purge flow convection

Purge gas composition:

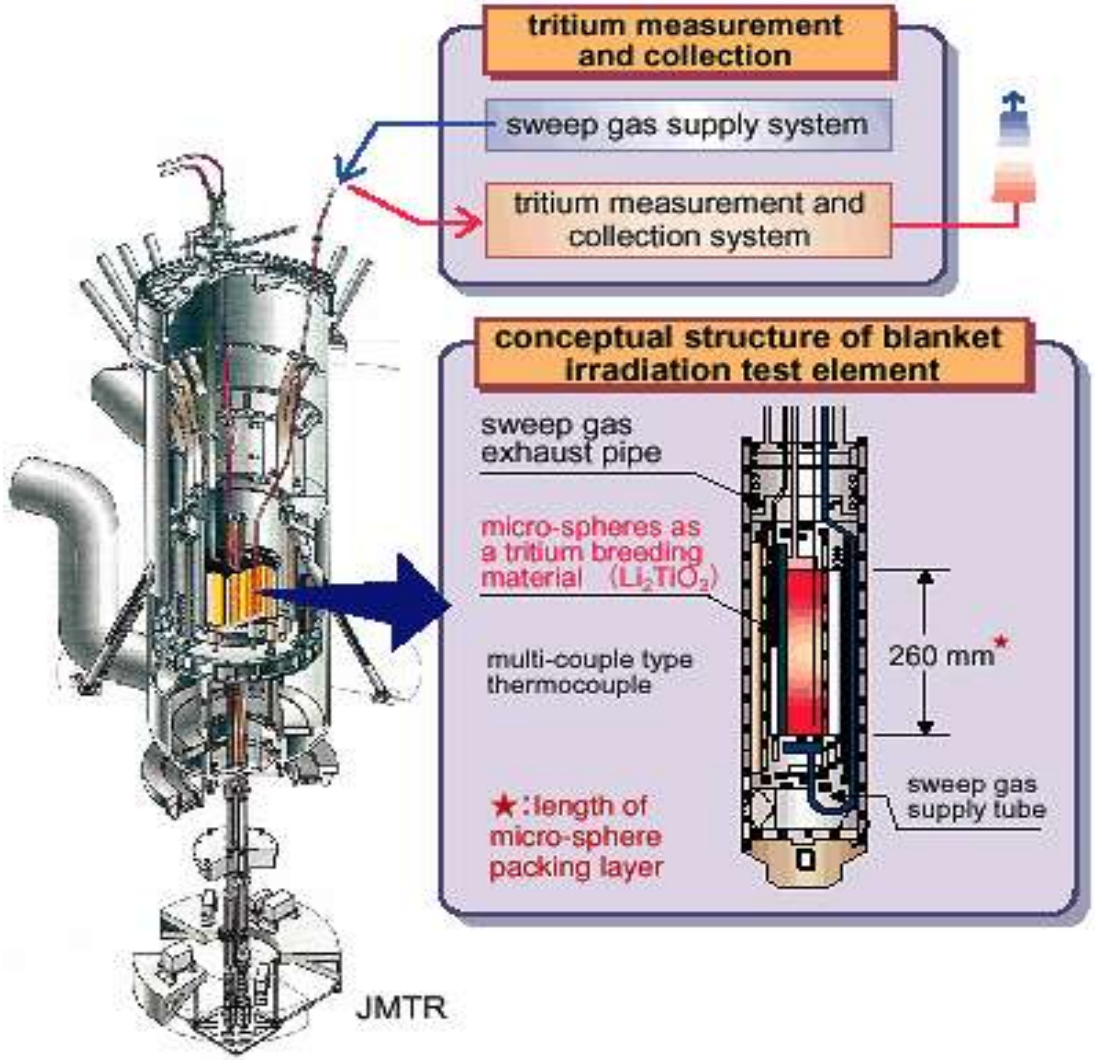
He + 0.1% H_2

Tritium release composition:

T_2, HT, T_2O, HTO

Tritium breeding modules tested in High Flux fission reactors

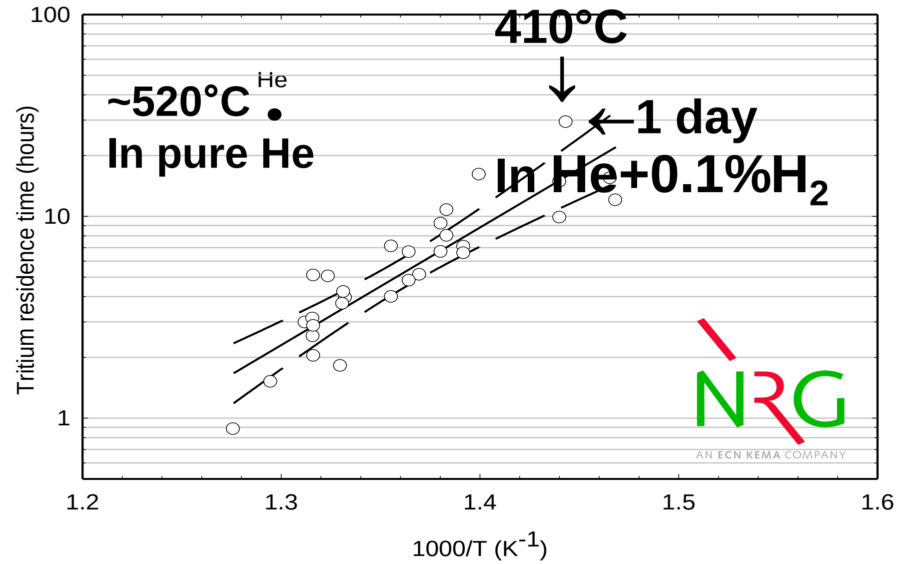
TBM with ^{6}Li-tailored ceramics are being irradiated in representaive environment (neutron flux, dose, BU and dpa):
In EU (in HFR-Petten),
In JAERI (in JMRT-Oarai).



Effect of the average temperature

Irradiation in HFR-Petten:
R, I =∫(G-R)dt and **τ = I/G**, are evaluated by step-changing the temperature in purge gas He+0.1%H_2

For $\mathbf{Li_2TiO_3}$ $\mathbf{T_{min}}$ = 410°C for **τ** = 1 day
Note the increase of **τ** in pure He



Expressions used for **τ** in design calculations:

$$\tau = 1.280 \cdot 10^{-5} \exp\left(\frac{9720}{T}\right) \qquad for\ Li_4SiO_4$$

$$\tau = 1.995 \cdot 10^{-5} \exp\left(\frac{10315}{T}\right) \qquad for\ Li_2TiO_3$$

Tritium recovery from Li-ceramics

- Pellets or pebbles are swept by He flowing during the reactor operation.
- Tritium in gaseous forms are carried by the He purge, adding H_2 (as isotope swamping) to He the removal rate is improved
- T_2, DT (or HT in the experiments) are preferred to water vapor condensable forms T_2O or DTO (or HTO).
- He doped with D_2 (0.1% as H_2 in the experiments) is the "reference" purge gas to get tritium in DT (or HT) form

It is generally accepted that **τ < 1** day states the minimum operative temperature $\mathbf{T_{min}}$

Li-orthosilicate fabrication

Melt-Spraying Facility at Schott Glas, Mainz

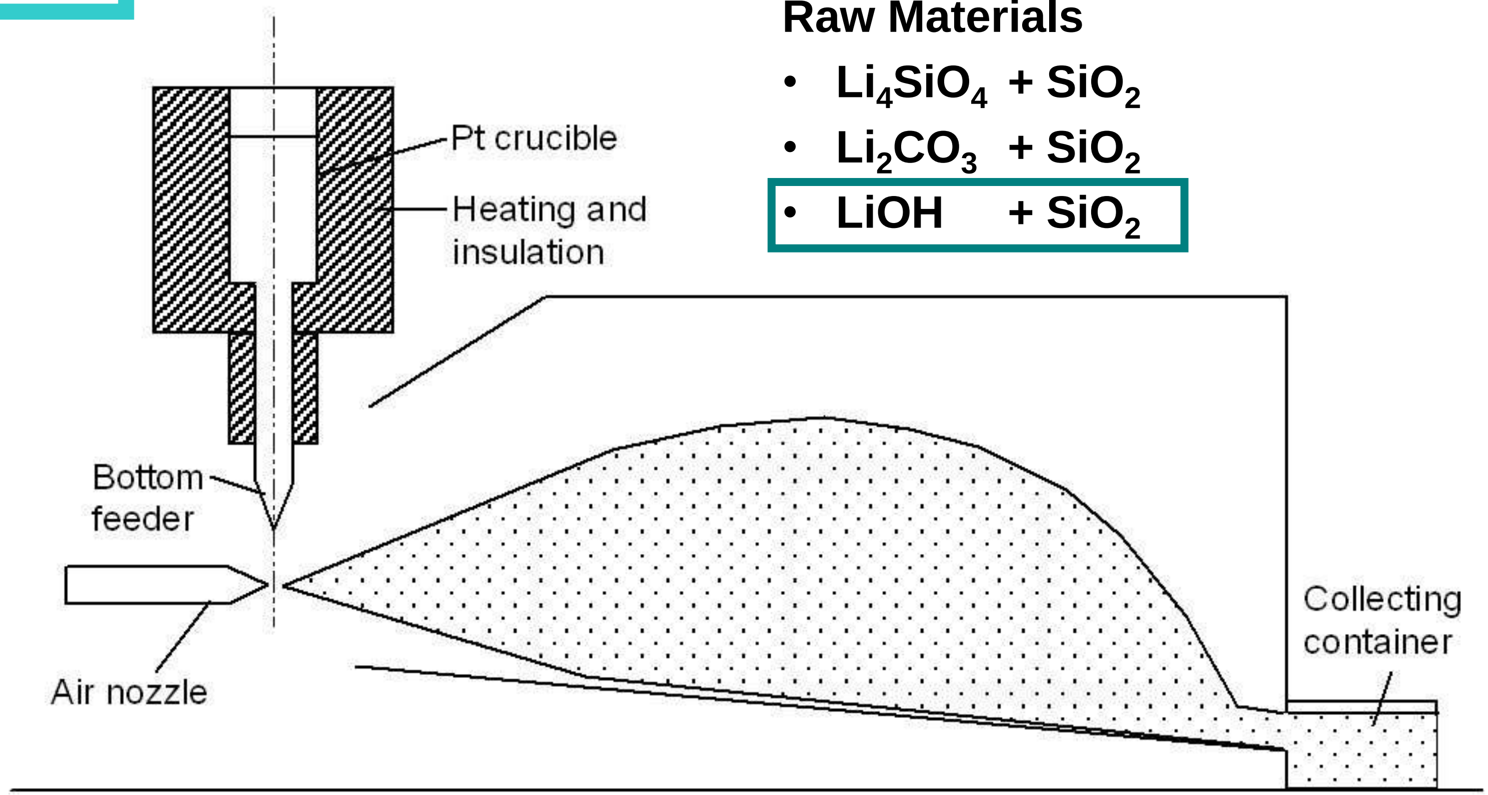
➔ **Aim** Li_4SiO_4 + 2.5 wt% SiO_2

Raw Materials

- Li_4SiO_4 + SiO_2
- Li_2CO_3 + SiO_2
- LiOH + SiO_2

1450°C

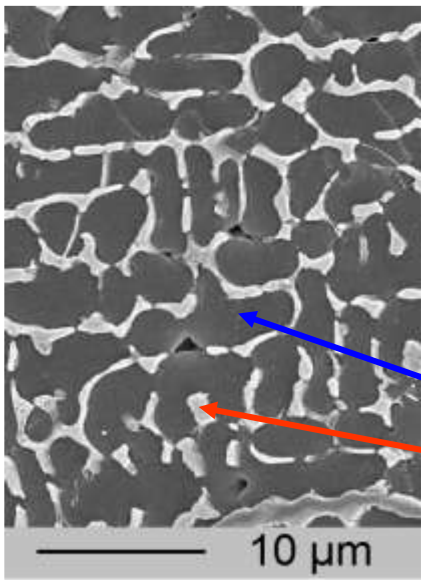
~ 1350°C



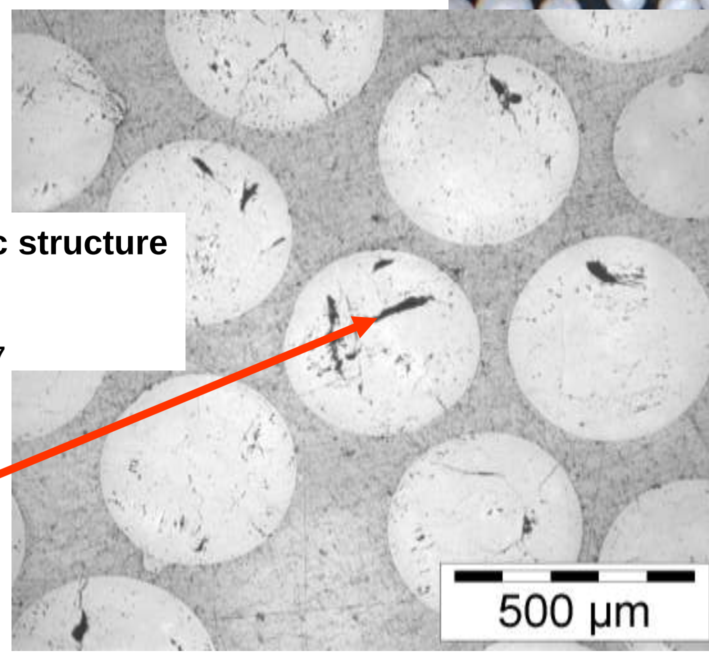
Li-orthosilicate fabrication

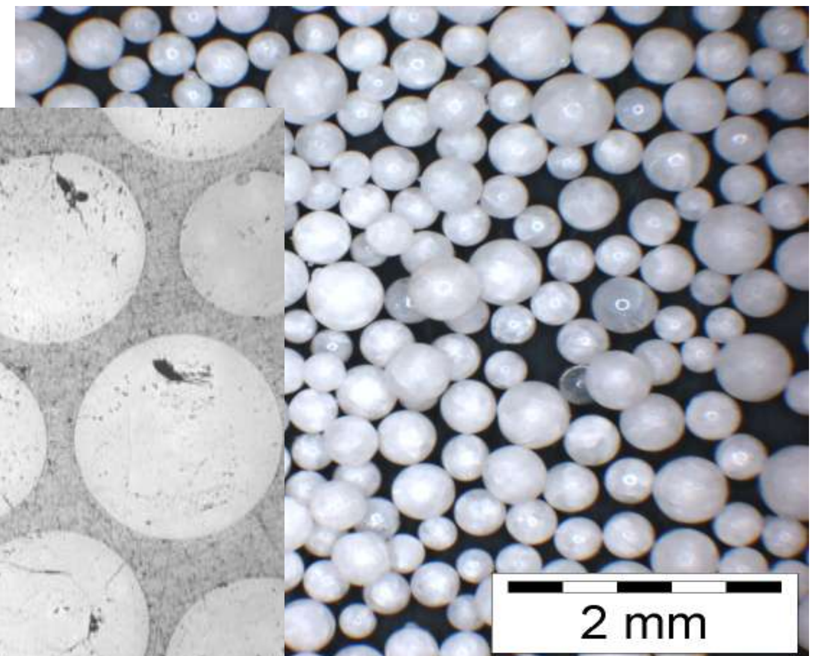
Melt-Spraying Facility at Schott Glas, Mainz

Production	2 x 1.5 kg per day
Yield of screened pebbles	50 % (250 – 630 µm)
	200 – 300 kg per year
Drawbacks	Batch processing
	Limited control of fabrication parameters
➔	Variation of batch properties
Advantage	Recycling of material



pebbles cross section





Dendritic structure

Li_4SiO_4

$Li_6Si_2O_7$

micropores

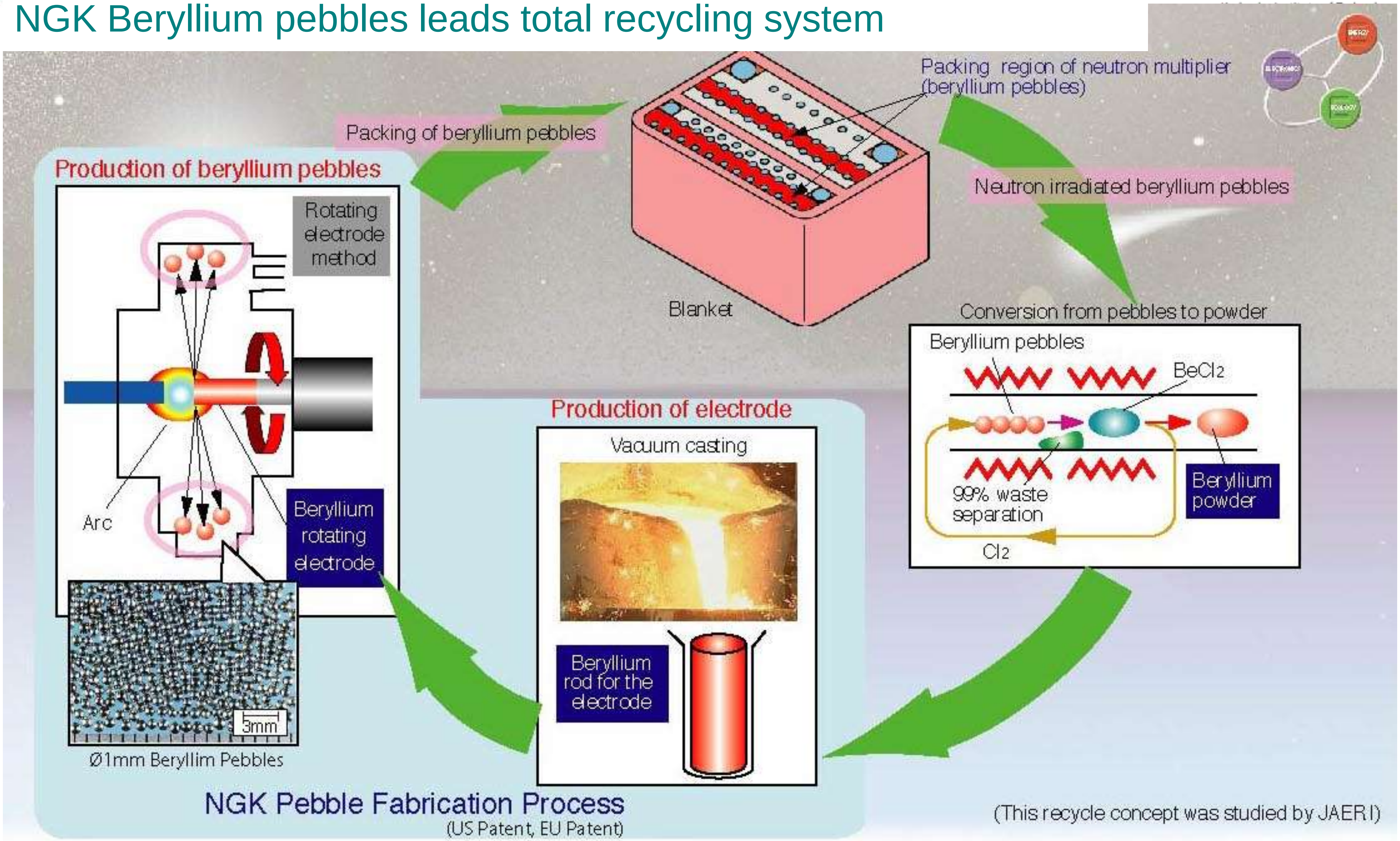
Li-orthosilicate fabrication

Fabrication of lithium orthosilicate pebbles using LiOH and SiO_2 as raw materials in a melt-sprying process

- material meets the specification of HCPB
- single process for all required ^{6}Li enrichments
- low impurities by high-purity raw material
- rejections and irradiated material can be recycled
- variation in batch properties are due to batch processing and will be reduced by a continuous process

Fabrication of neutron multiplier

NGK Beryllium pebbles leads total recycling system



Pebble beds density and packing factor

ρ_{pb} **= pebble bed density** = ratio of pebble bed mass to pebble bed volume

γ **= packing factor** = ratio of pebble volume to pebble bed volume

$$\rho_{pb} = 1.455\, {}^{g}/_{cm^3}, \gamma = 64.5\% \qquad \textit{for } Li_4SiO_4$$

$$\rho_{pb} = 1.74\, {}^{g}/_{cm^3}, \gamma = 63.5 \qquad \textit{for Beryllium}$$

ρ_{pb} = important quantity for **nuclear calculations**

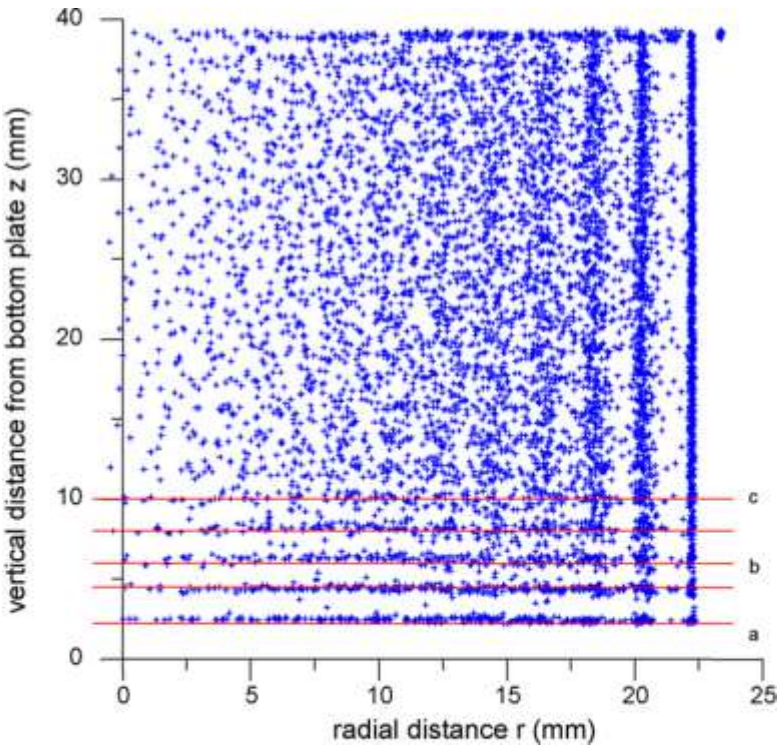
γ = characteristic quantity in **pebble bed engineering**

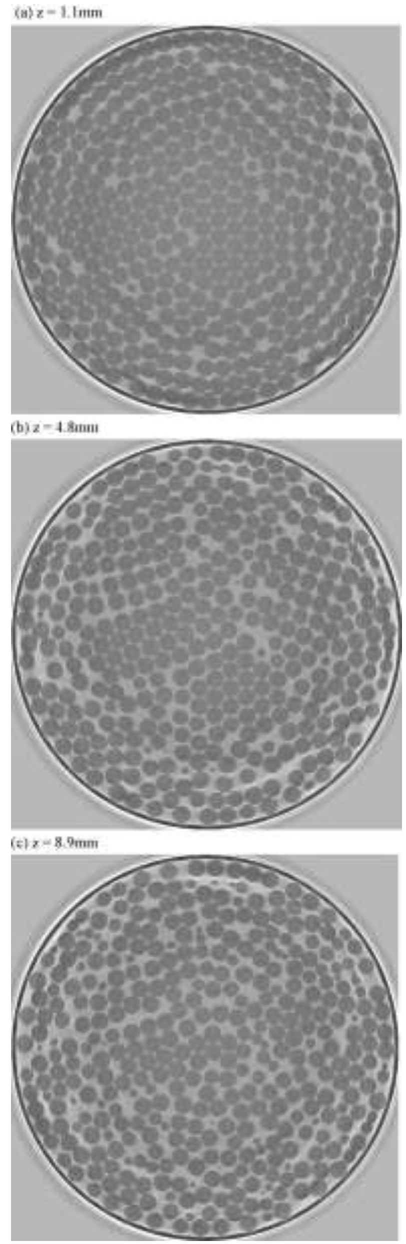
Pebble beds topology

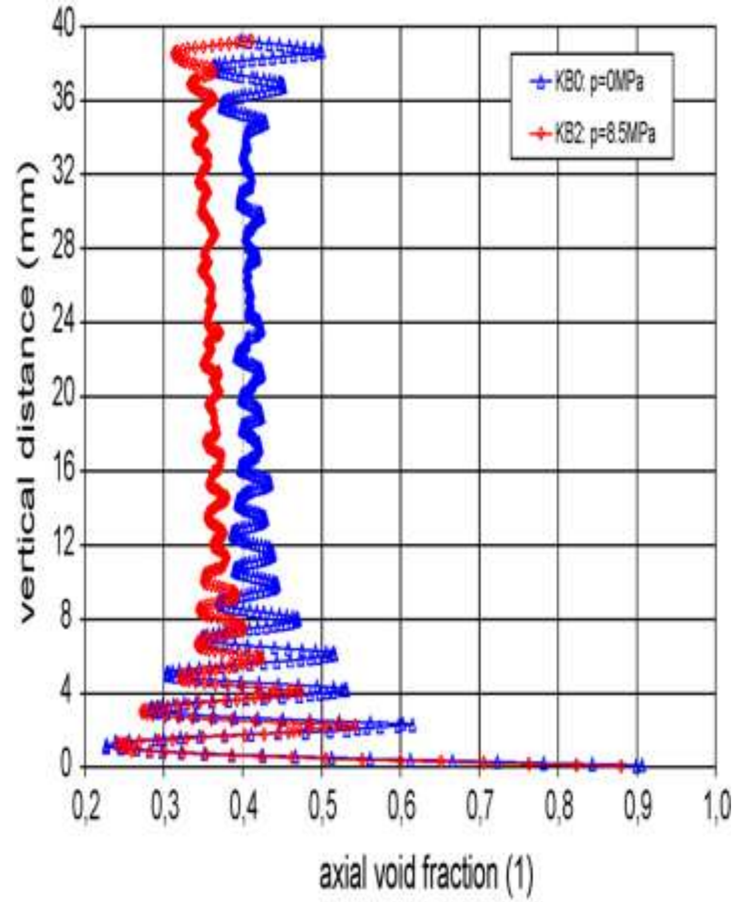
Karlsruhe Institute of Technology

X-ray tomography investigation on pebble beds structures in the ESRF

Vertical positions of sphere centers in a capsule

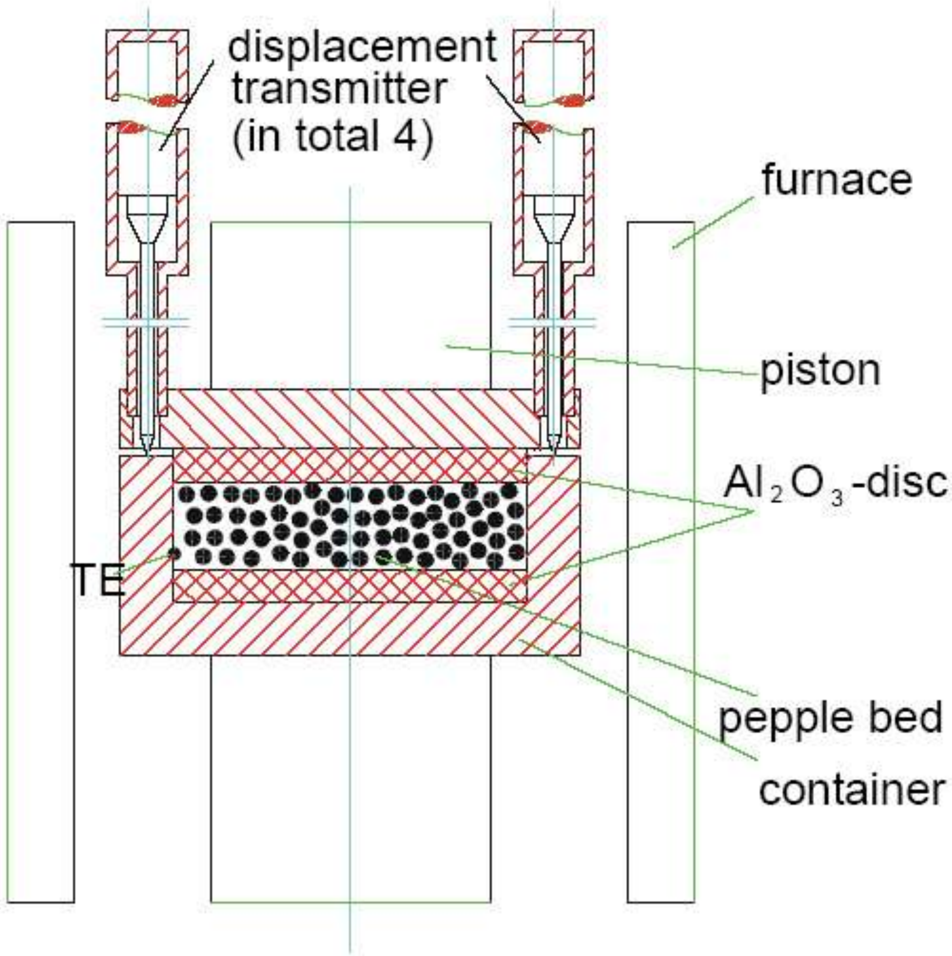






Pebble beds tests

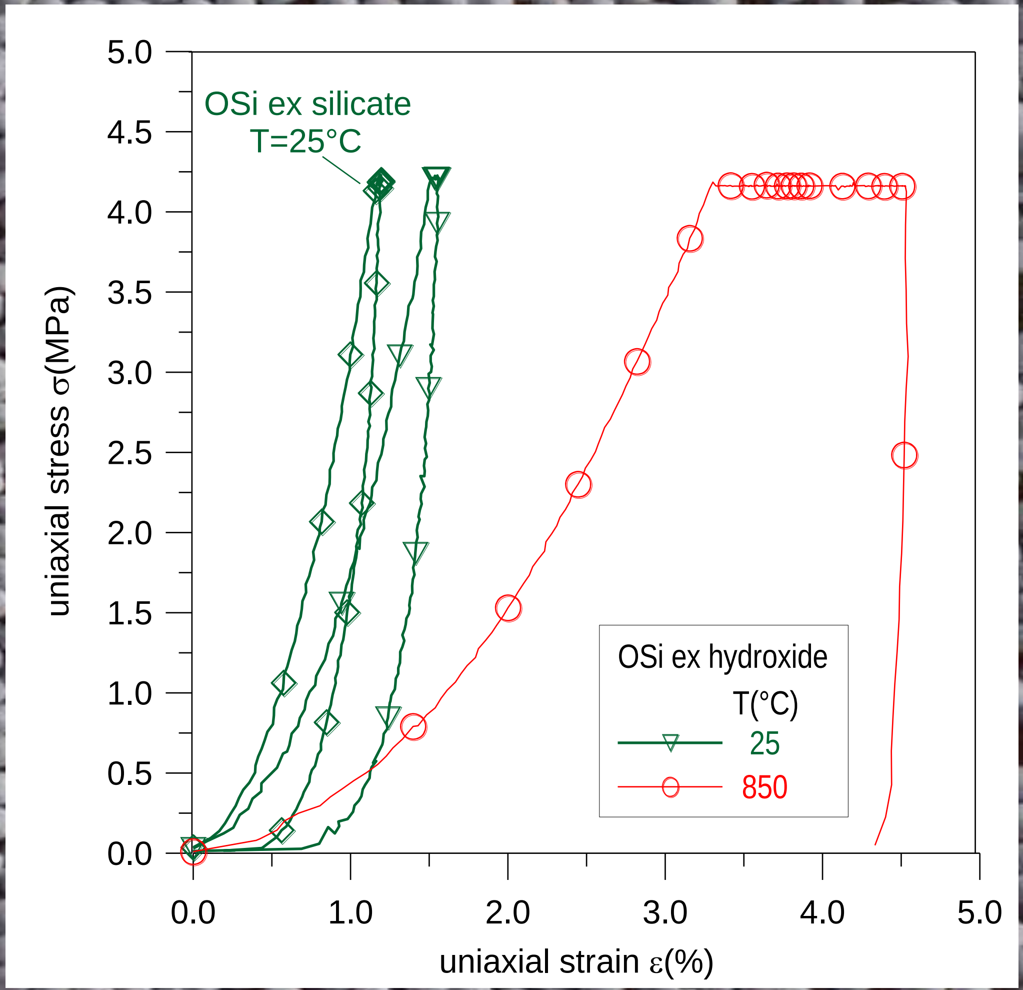
Uniaxial stress-strain and creep tests



Pebble beds tests: Young modulus

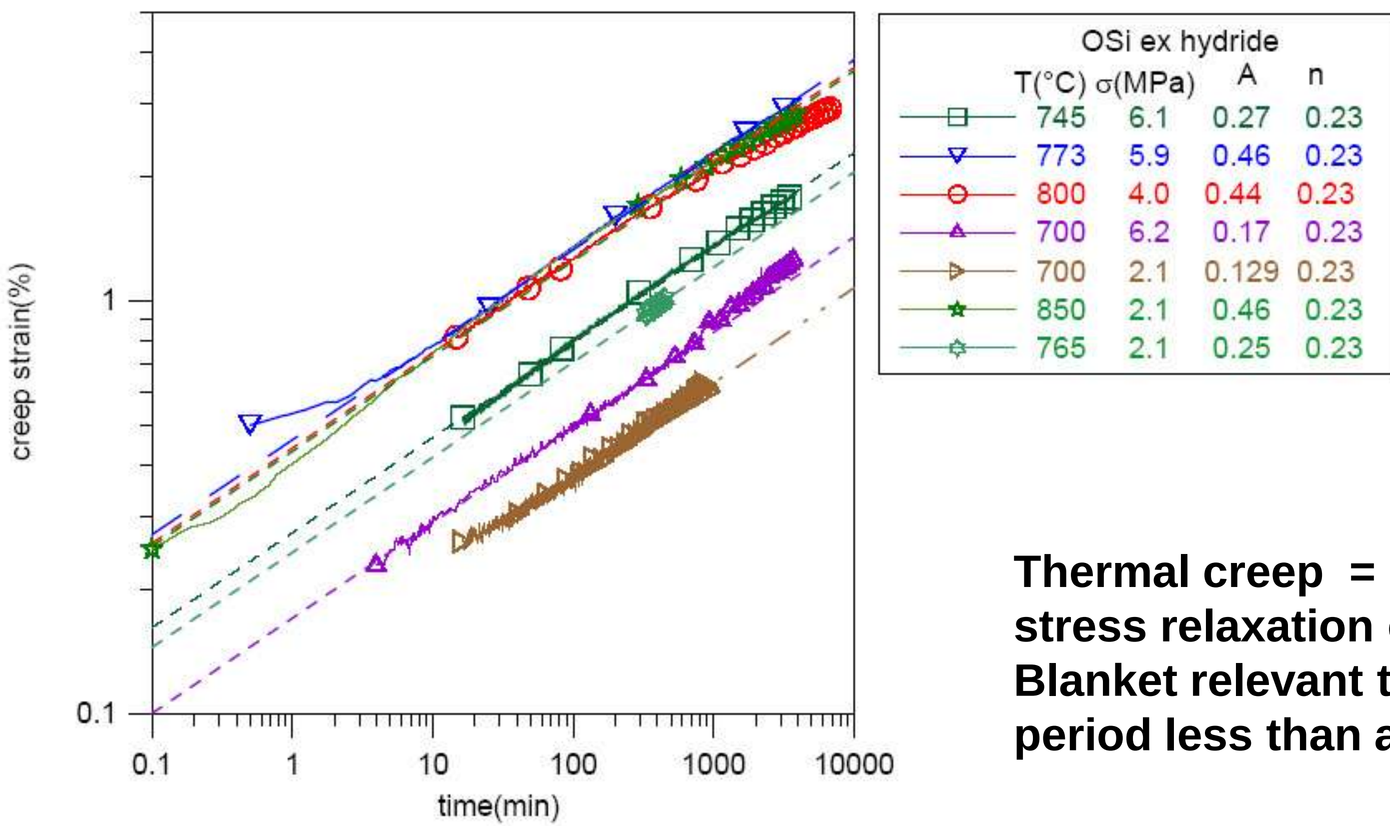
Stress-strain dependence for T = 25°C and T = 850°C

Thermal creep, an irreversible behavior to be known and controlled for the HCPB blanket design



Pebble beds tests: thermal creep

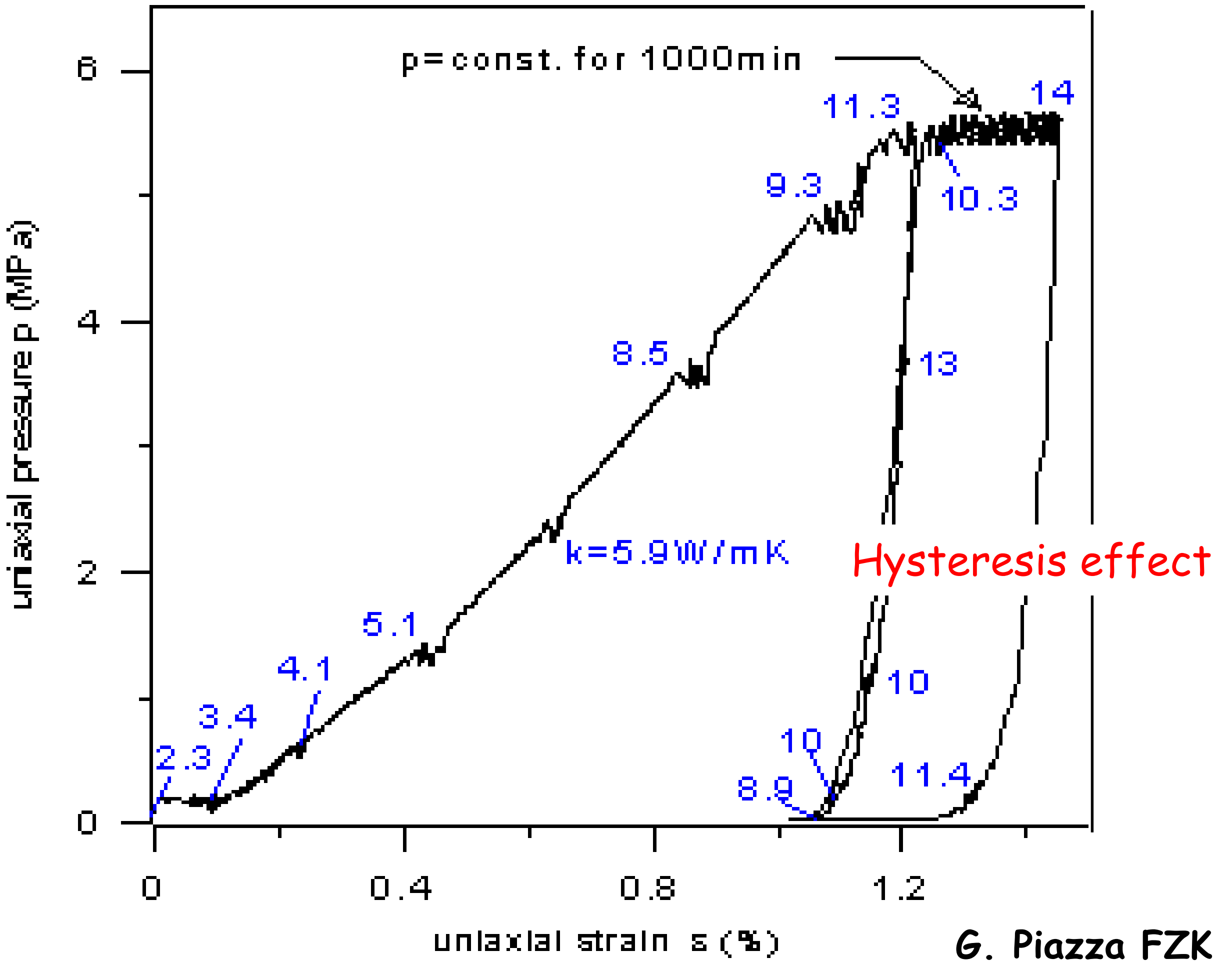
Thermal creep measured by UCT keeping constant stress at a given T.

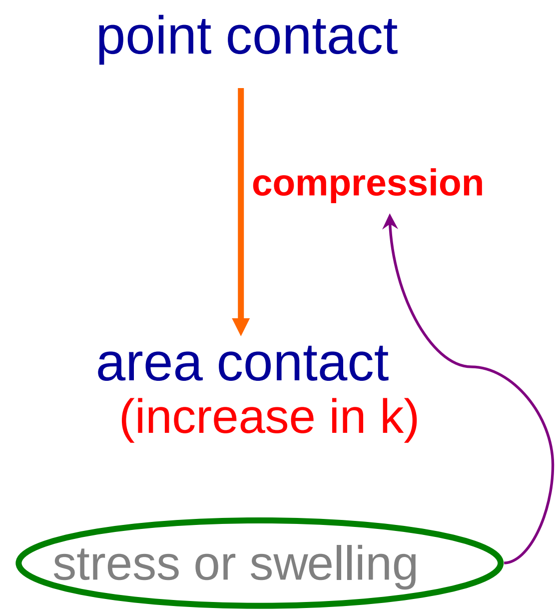


Thermal creep = stress relaxation effect. Blanket relevant time period less than a day!

Pebble beds tests: thermal conductivity

Effective thermal conductivity of 1 mm Be pebble bed (475 °C) depends on the compressive strain

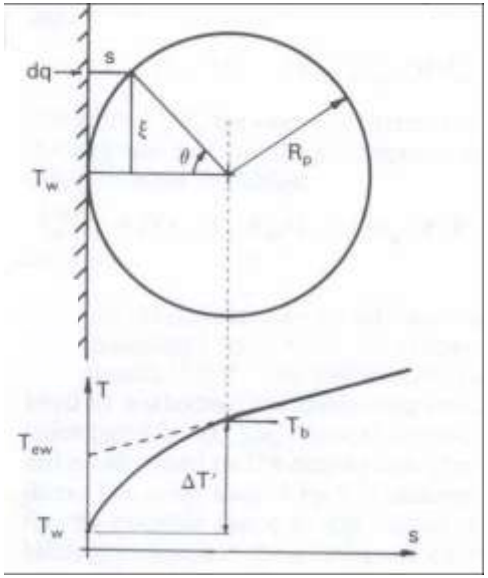




Pebble beds properties: heat transfer coefficient

No reliable measurement.
Difficulty to measure T differences between wall and pebble beds.

Model for Heat Transfer Coefficient



Yagi and Kunii model is recommended

$$h\left(\frac{W}{m^2K}\right) = 2577 + 4.327T(°C) - 8.91 \cdot 10^{-4}T(°C)^2 \qquad \textit{for } Li_4SiO_4$$

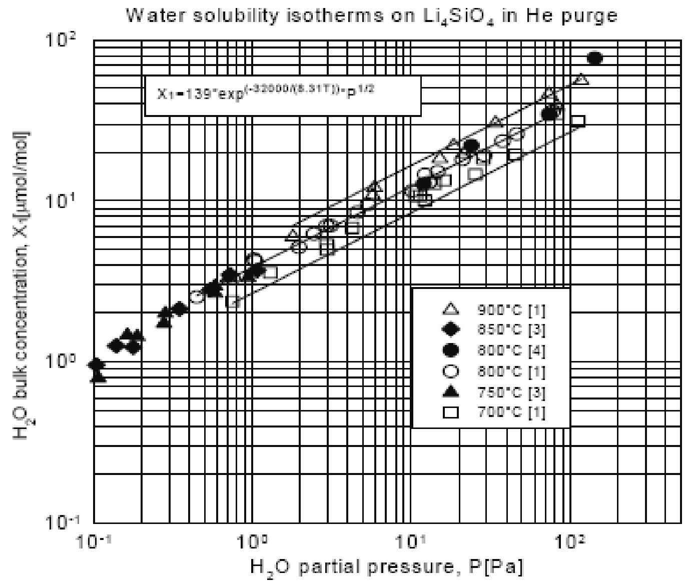
$$h\left(\frac{W}{m^2K}\right) = 2207 + 4.014T(°C) - 0.0004 \cdot 10^{-4}T(°C)^2 \qquad \textit{for Beryllium}$$

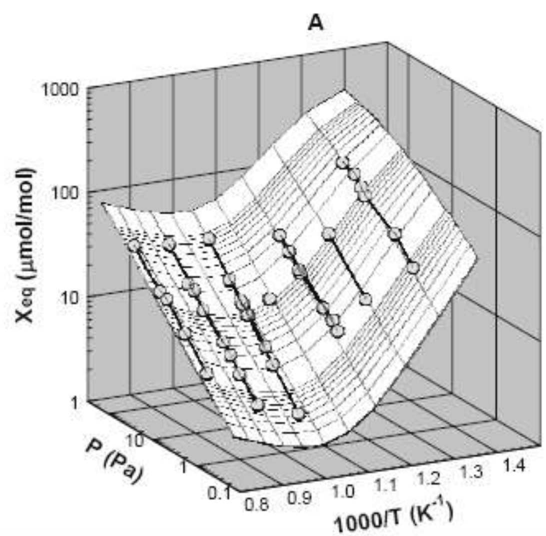
Pebble beds properties: Li_4SiO_4 interaction with H_2 and steam

Reaction with H_2:
after complete reduction process, no change in the T release properties.

Interaction with H_2O:
- **Surface adsorption**
- **Grain boundary adsorption**
- **Dissolution inside crystal**

Above 700°C dissolution is dominant.
Below 700°C microstructure plays an important role:
- $H_2$0 grain boundary absorption acts slowly but significantly

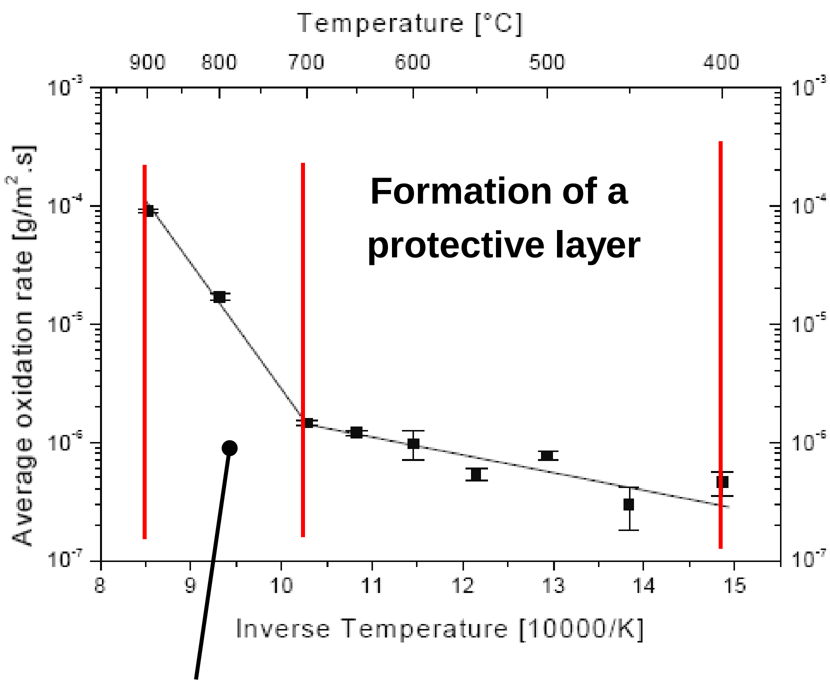




Arrhenius plot of H_2O solubility vs. P

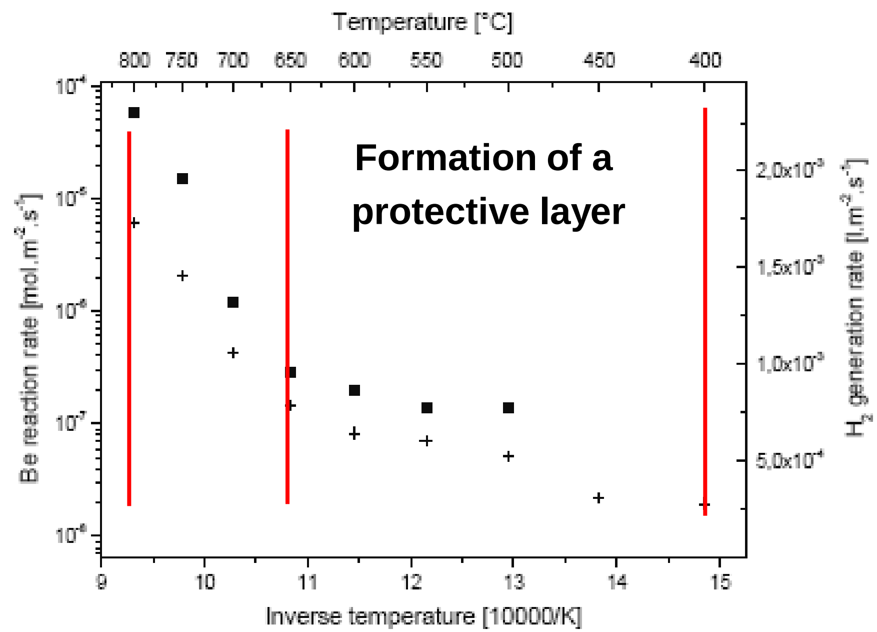
Pebble beds properties: Be interaction with air and steam

Chemical reactivity in air



Catastrophic oxidation

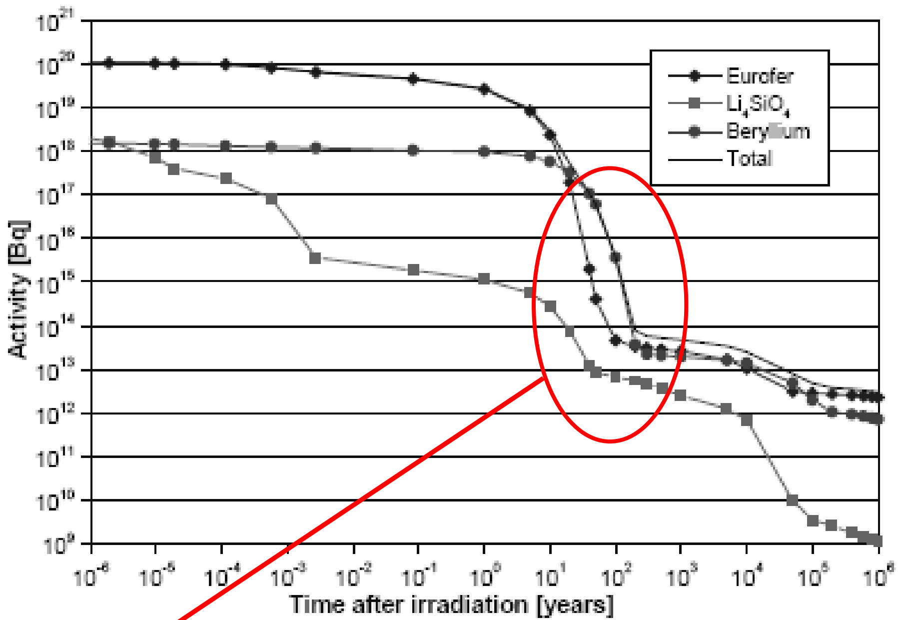
Chemical reactivity in steam



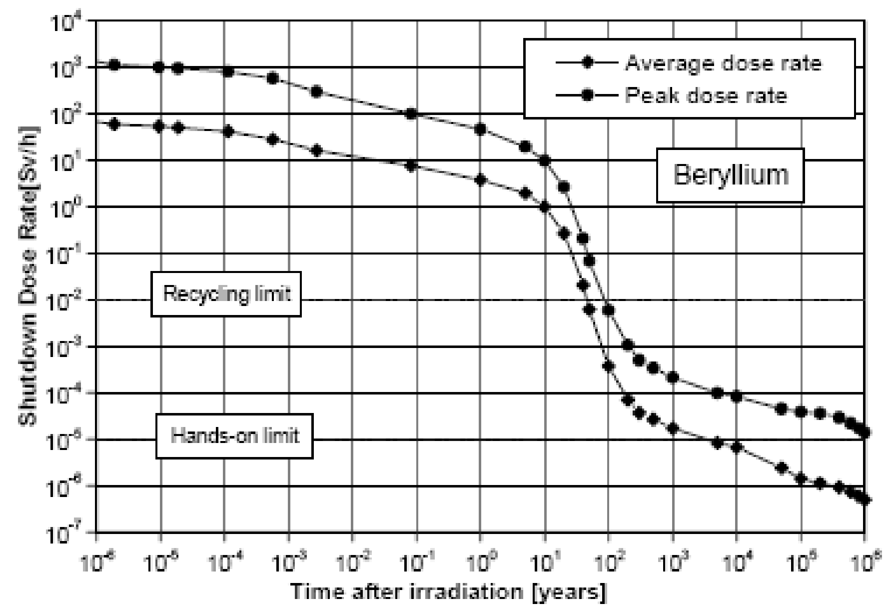
Pebble beds properties: activation under 14 MeV neutrons

3D activation calculation for a 2200 MW fusion power reactor operating at 20,000 hours.

Activity inventory of the HCPB DEMO BB



Shutdown dose rate in Be

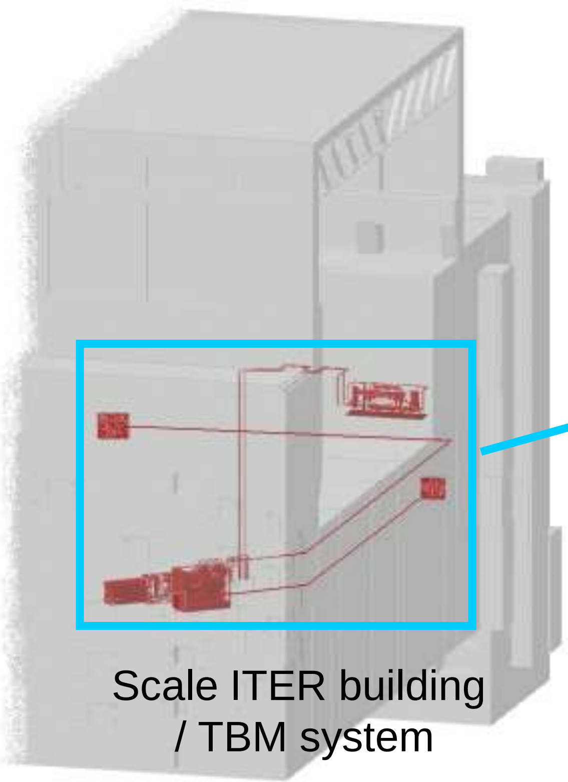


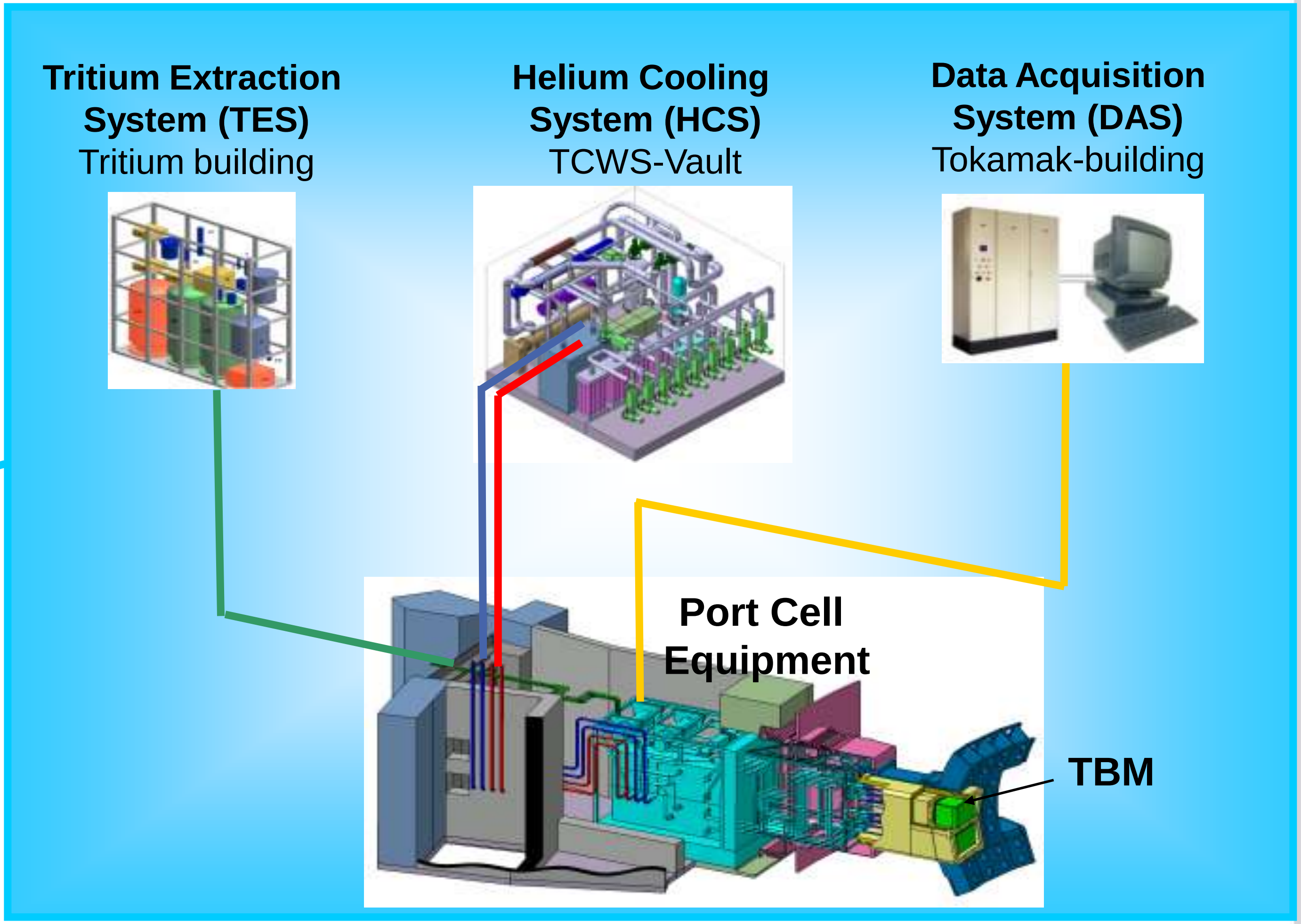
Activity dominated by T generated in Be

Major contribution of contact dose rate up to 50 years is ^{60}Co originating from ^{59}Co impurity

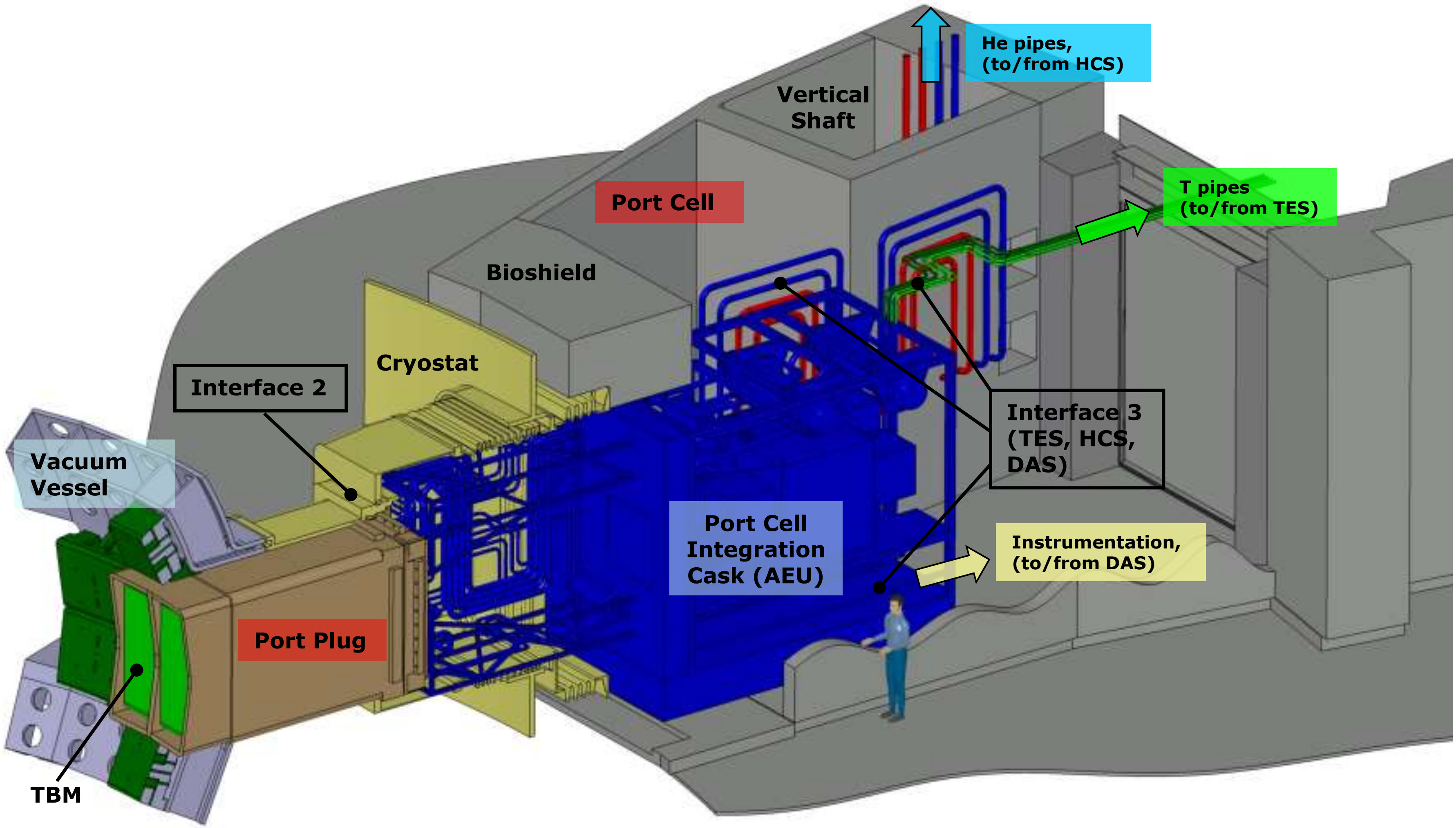
TBM System in ITER

ITER-Reactor building





TBM System in ITER



TBM system: development of Helium Cooling System for ITER (HELOKA as a prototype)

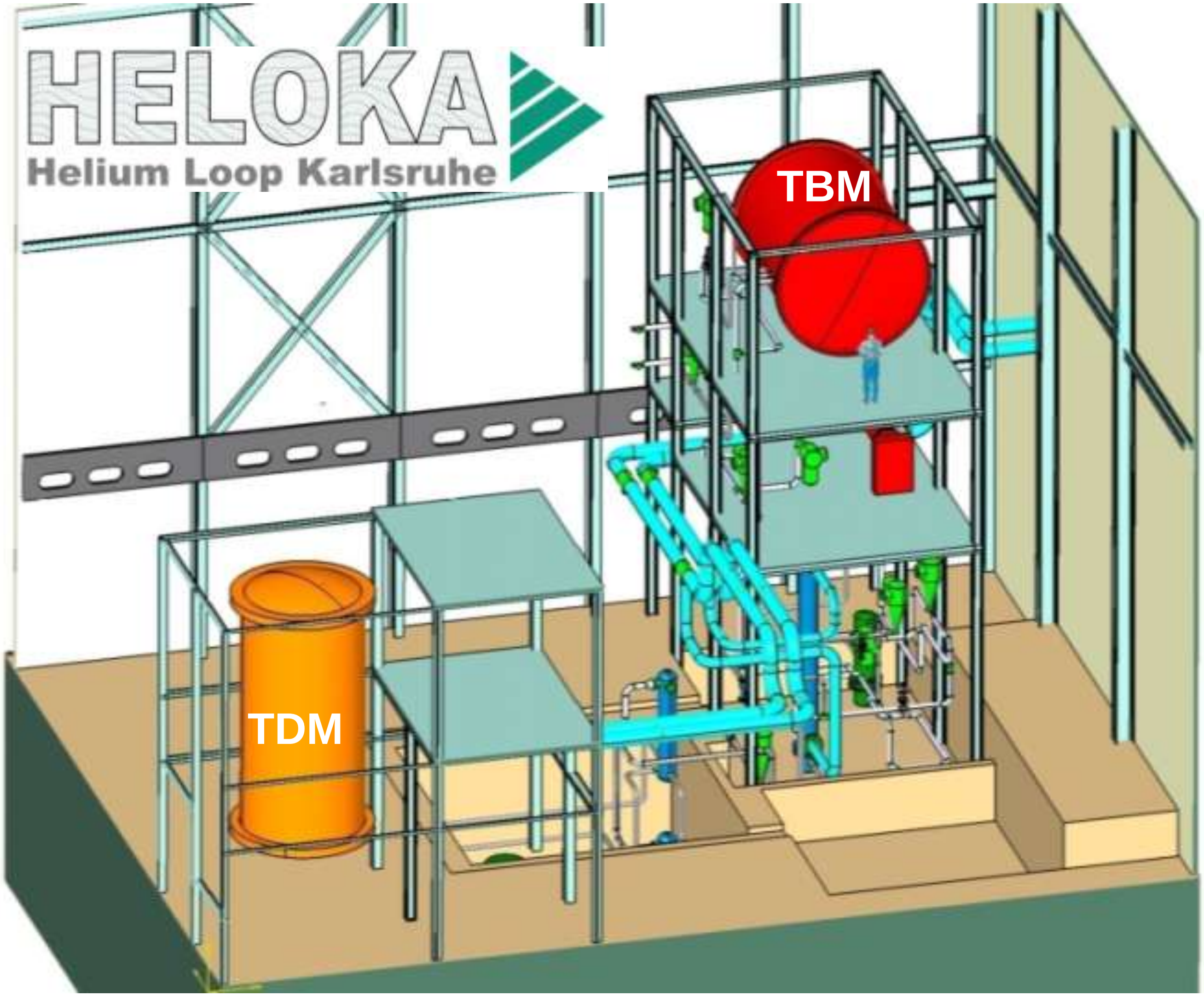
Karlsruhe Institute of Technology

HELOKA
Helium Loop Karlsruhe

Helium Loops for TBM, TDM, IFMIF

- Development of Components
- Qualification for use in ITER
- Development of Helium Loop Technologies
- TBM: up to 100 bars, 550°C, 1.4 kg/s
- TDM: up to 100 bars, 700°C, 5.5 kg/s,
- pulsed load operation *ITER scenarios
- long term operation

TBM system: development of HELOKA



HELOKA-HP/TBM

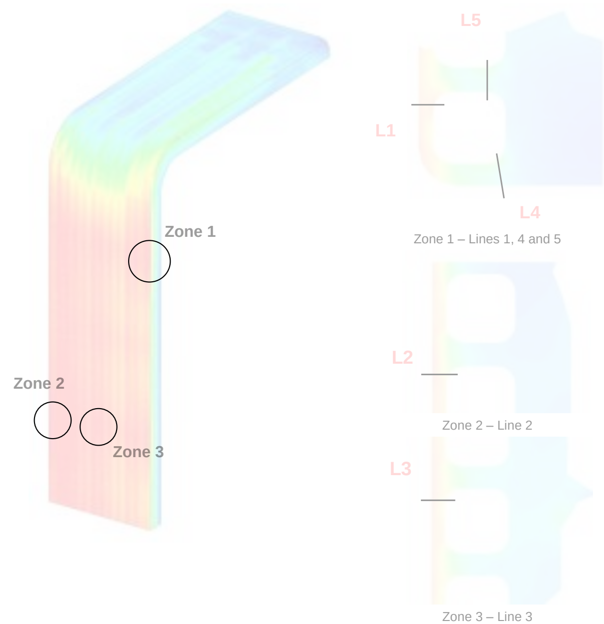
- Qualification for ITER
- Development of Helium Loop Technologies
- 80 bars, (max 100 bars)
- 500°C**
- 1.4 kg/s
- pulsed load operation *ITER scenarios
- long term operation
- Graphite radiation surface heaters

Transient thermo-mechanical analyses

HCLL TBM

The most demanding condition for the structural integrity of the FW is the inversion of the thermal gradients during the plasma ramp-up and ramp-down phases which causes an alternation between tensile and compressive stress states in the structure.

Stress intensity ranges between t3=600s and t1=60s (MPa).



Highest stress intensity range: relevant quantity for C-type damages!

Ratcheting: criteria exceeded in several zones of the FW

	T (°C)	$\overline{P_L+P_b+\Delta Q}$ (MPa) t_1-t_0	t_2-t_0	t_3-t_0	t_3-t_1	t_3-t_2	t_2-t_1	Limit (MPa)	Margin
Line 1	471	560	448	264	690	514	307	411	-68%
Line 2	484	518	322	205	673	474	247	406	-66%
Line 3	488	490	287	198	650	446	245	405	-60%
Line 4	376	458	541	243	454	427	279	534	-1%
Line 5	368	297	351	224	384	254	269	539	29%

Immediate plastic flow localization

	T (°C)	$\overline{P_m+Q_m}$ (MPa) t_1	t_2	t_3	Limit (MPa)	Margin
Line 4	376	128	262	243	182	-44%
Line 5	368	99	220	176	191	-15%

Primary stresses + creep

		Immediate plastic collapse and instability						Creep					
		$\overline{P_m}$ (MPa)			$\overline{P_m+P_b}$ (MPa)			$\overline{P_m}$ (MPa)			$\overline{P_m+P_b/k_t}$ (MPa)		
	T (°C)	Value	Limit	Margin	Value	Limit	Margin	Value	Limit	Margin	Value	Limit	Margin
Line 1	471	30	154	81%	70	231	70%	30	194	85%	62	194	68%
Line 2	484	33	150	78%	52	225	77%	33	181	82%	48	181	73%
Line 3	488	24	149	84%	40	223	82%	24	178	87%	37	178	79%
Line 4	376	22	178	88%	50	267	81%	NR	NR	NR	NR	NR	NR
Line 5	368	32	180	82%	44	269	84%	NR	NR	NR	NR	NR	NR

Conclusion

Main results achieved:

- Definition of C&S for TBM design and analyses
- Definition and analyses of main TBM specific loading conditions
- Analyses of LC1 (transient thermo mechanical analyses of a standard ITER pulse) presented in this work.

Important outcomes of the TBM transient analyses:

- Several junctions present peak stresses and an optimization of their geometry is necessary to remove sharp singularities.
- HCLL: problematic behavior of the FW
- HCPB : problematic behavior of the back manifolds
- **Solution envisaged: adopt the FW design of the HCPB and adapt the HCPB manifold design to the HCLL configuration**

Open issues:

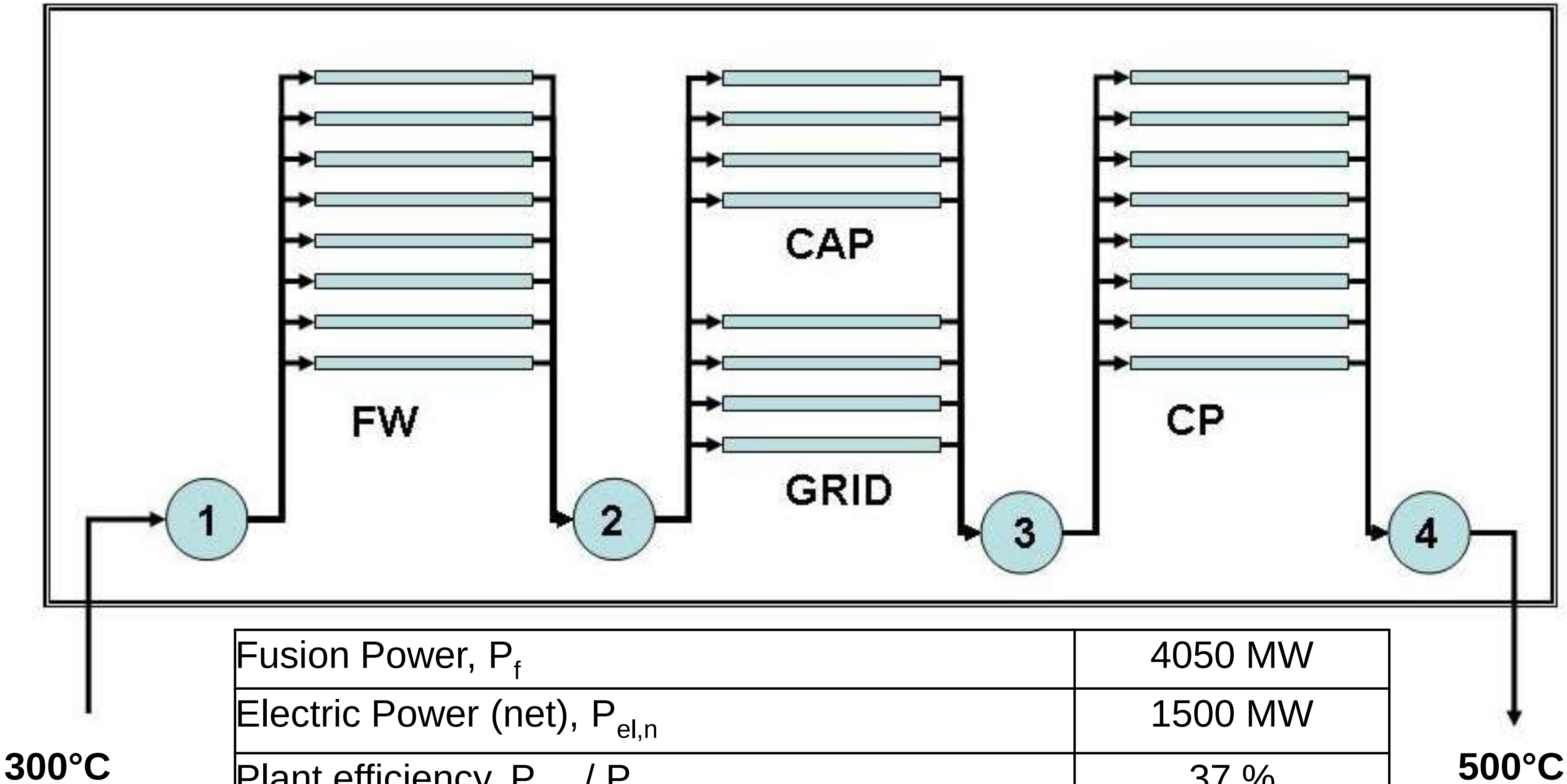
- Design rules developed mainly for austenitic-type steels (i.e. 316L(N)-IG ITER shielding steel)
- Limited experience with martensitic-type steel in a fusion relevant environment,
- Concerns regarding the validity/degree of conservatism of the C&S rules when taking into account Eurofer97 mechanical properties.

Next priorities:

- Develop dedicated models and studies addressing design geometrical issues
- Assess possible requirements and operating scenarios limiting the margins under which the design can evolve.

  - (i.e. thermal loads to be used for the TBM design are provided under conservative assumptions and they will not be reconsidered before starting of the ITER machine or uncertainties in the PS can strongly affect the design)

HCPB: Helium cooling



Fusion Power, P_f	4050 MW
Electric Power (net), $P_{el,n}$	1500 MW
Plant efficiency, $P_{el,n}$ / P_f	37 %
Pumping Power, P_p	400 MW
Thermal efficiency (gross), η_{th}	42 %

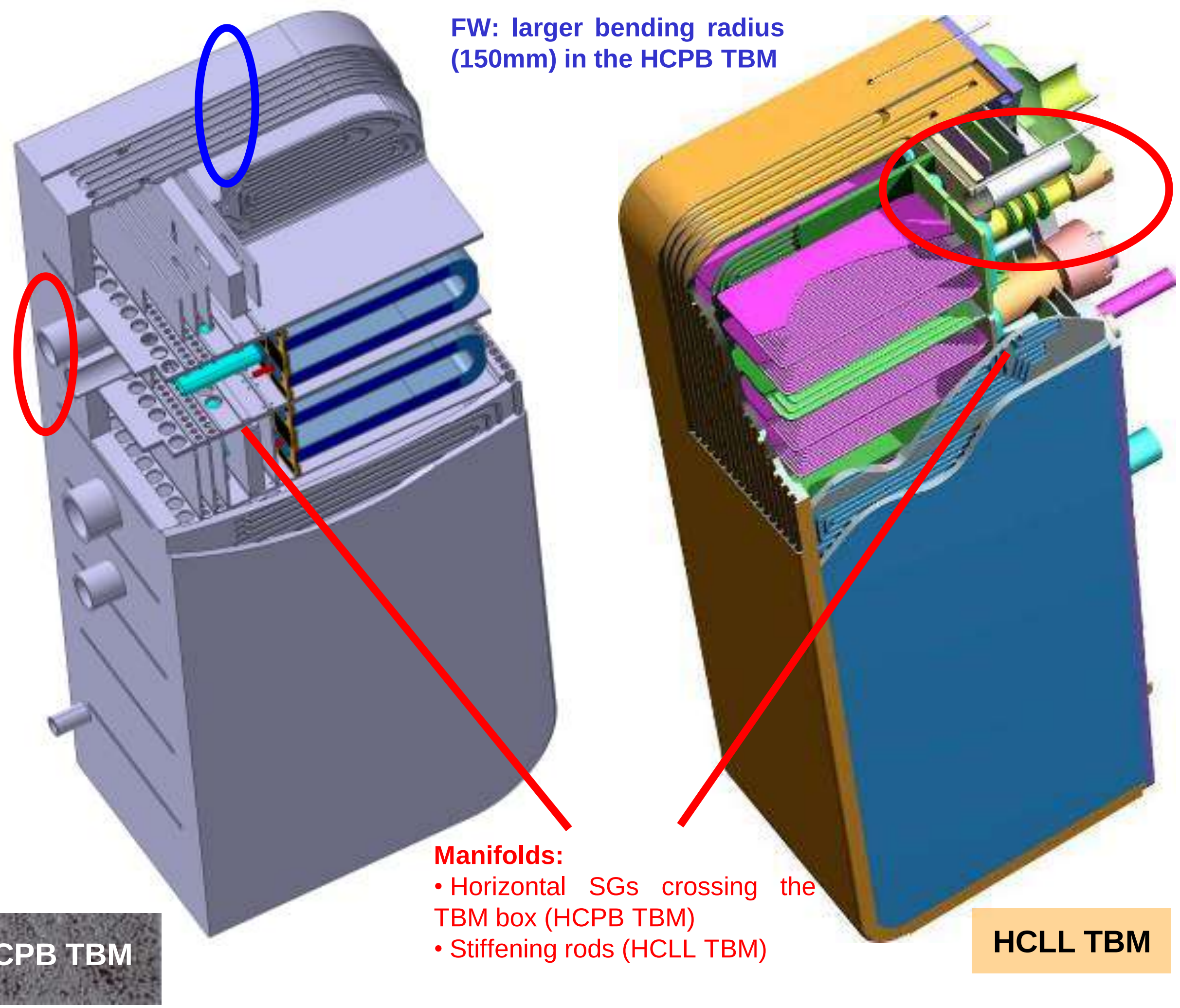
Design development strategy

Objective: develop a design of the TBM boxes maximizing the similarities.

Strategy: synergies are maximized but differences are kept in the most critical points to investigate different design options and minimize the risk.

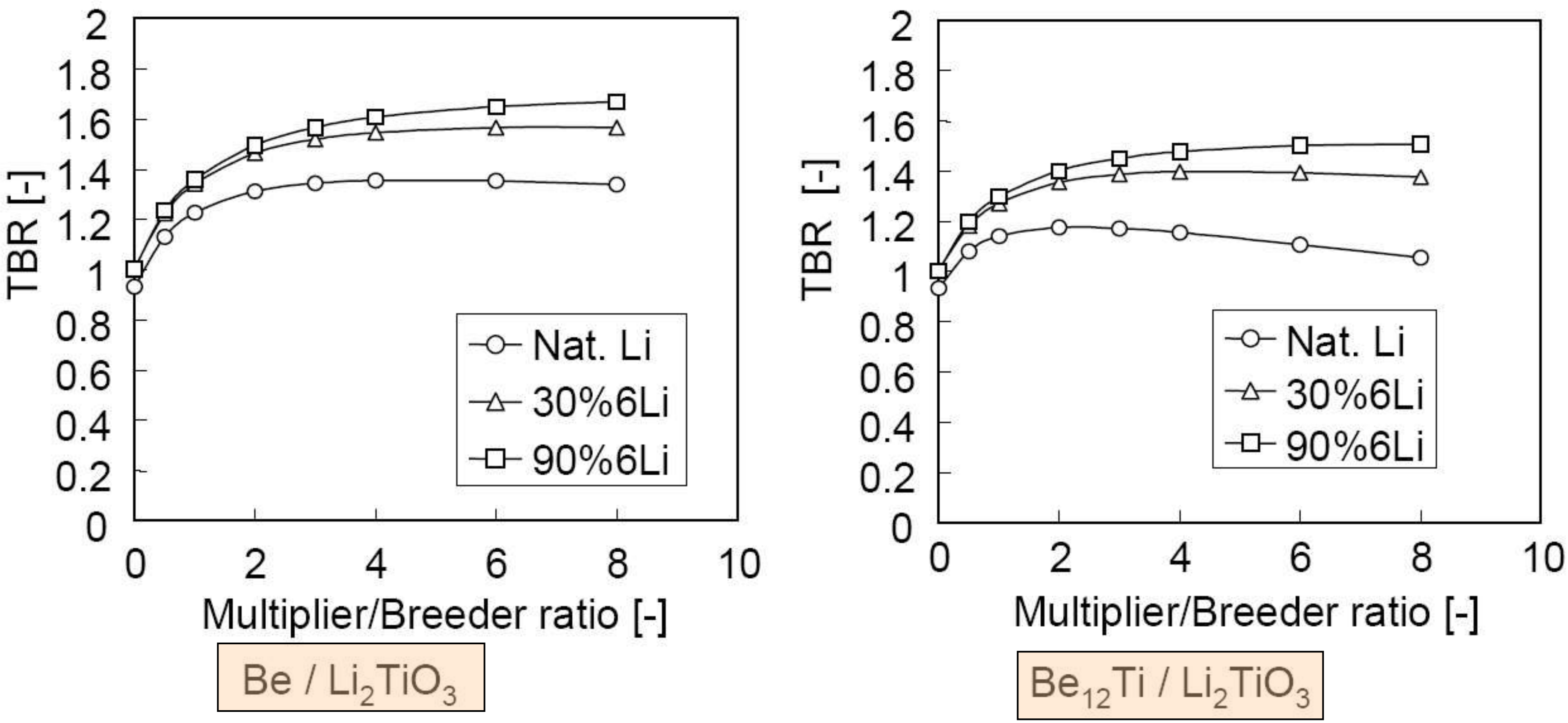
Critical points:

- FW, fabrication issues
- Manifold, design different for the different internal engineering of the 2 TBMs



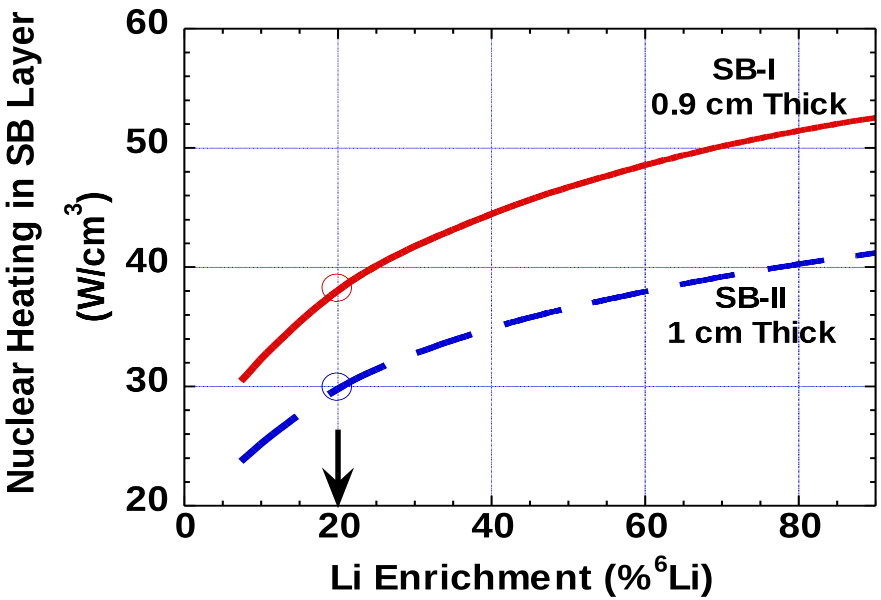
Japanese solid breeder concept

Rough survey by homogenized model of
- cooling layer (F82H + H_2O) + breeder (Li_2TiO_3) + multiplier(Be or $Be_{12}Ti$)



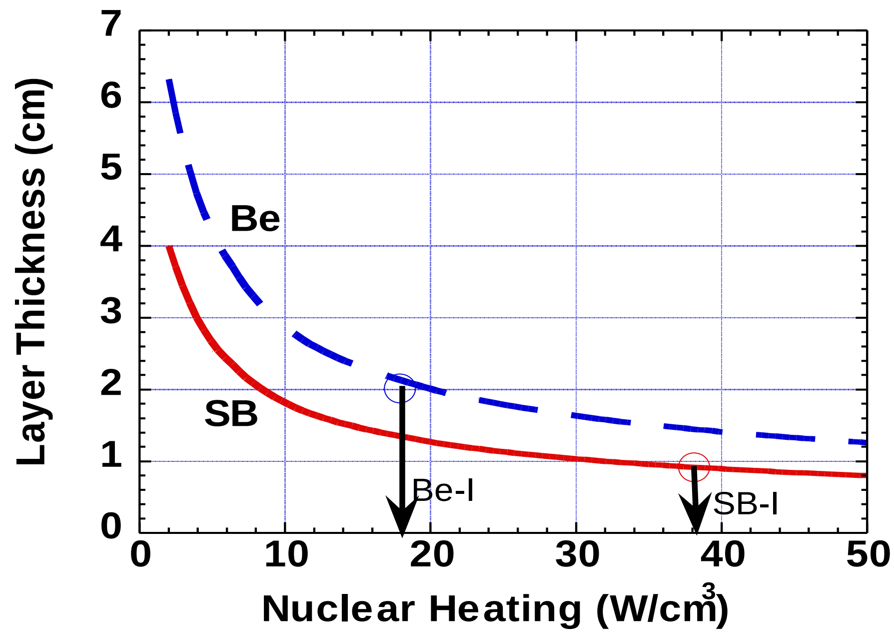
Japanese solid breeder concept

^6Li increase gives higher heat deposited in layers



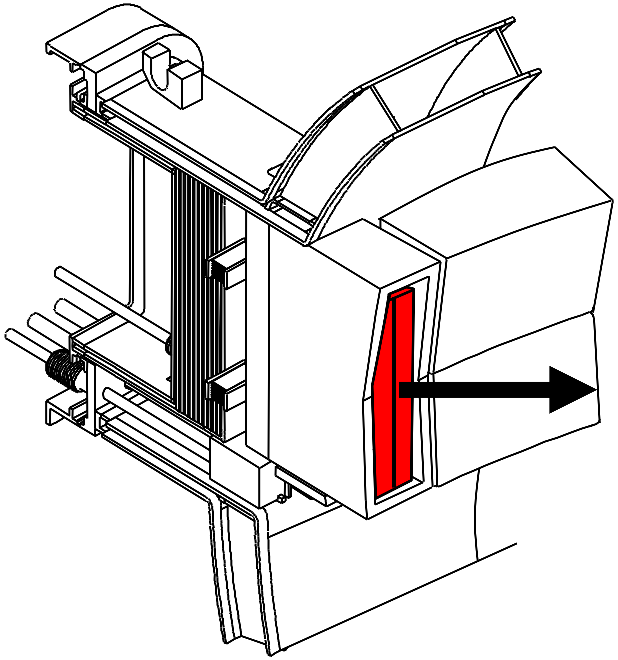
Enrichment of individual layers adjusted to keep heating and upper temperature within limits

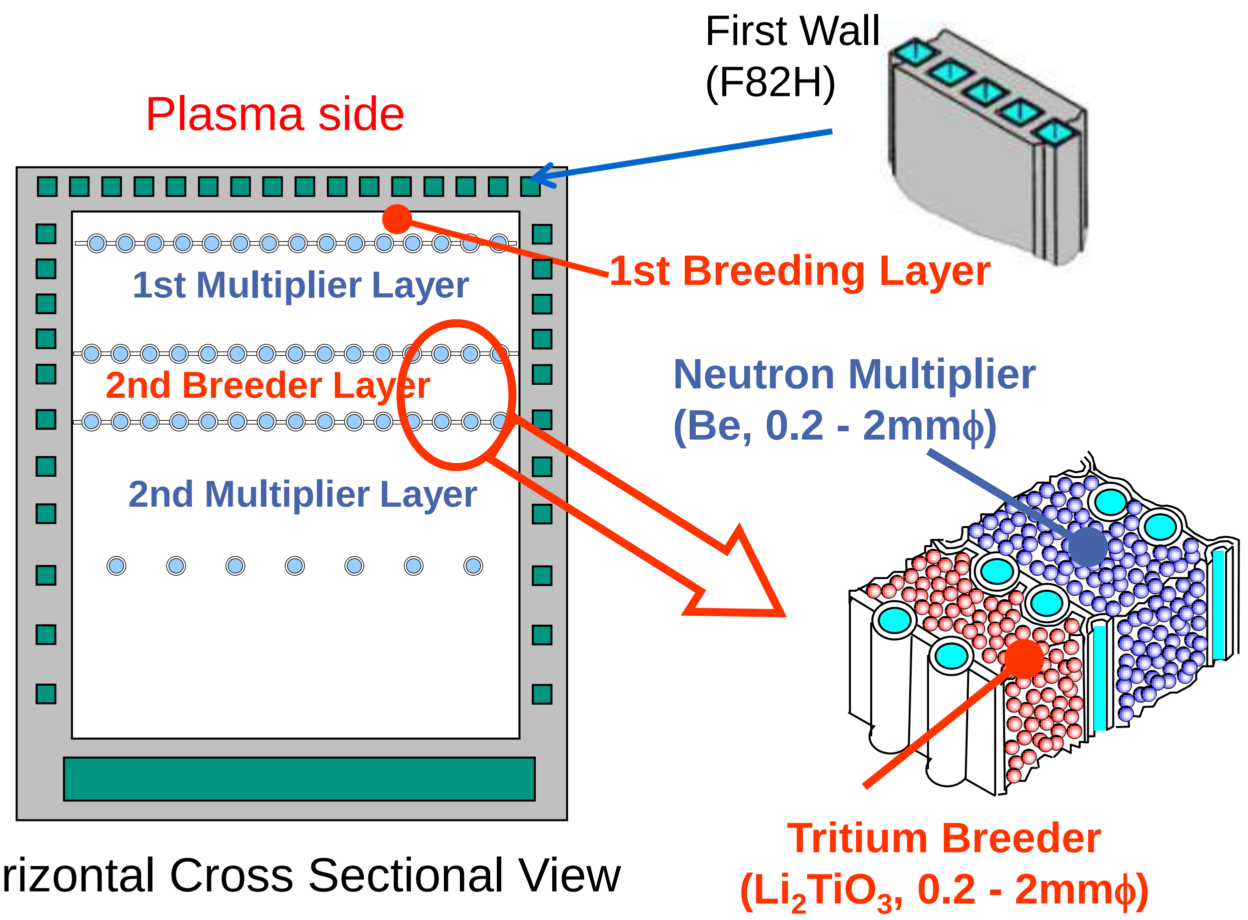
Layer thickness is limited by T_{max}



High nuclear heating at front implies thin Be and SB layers

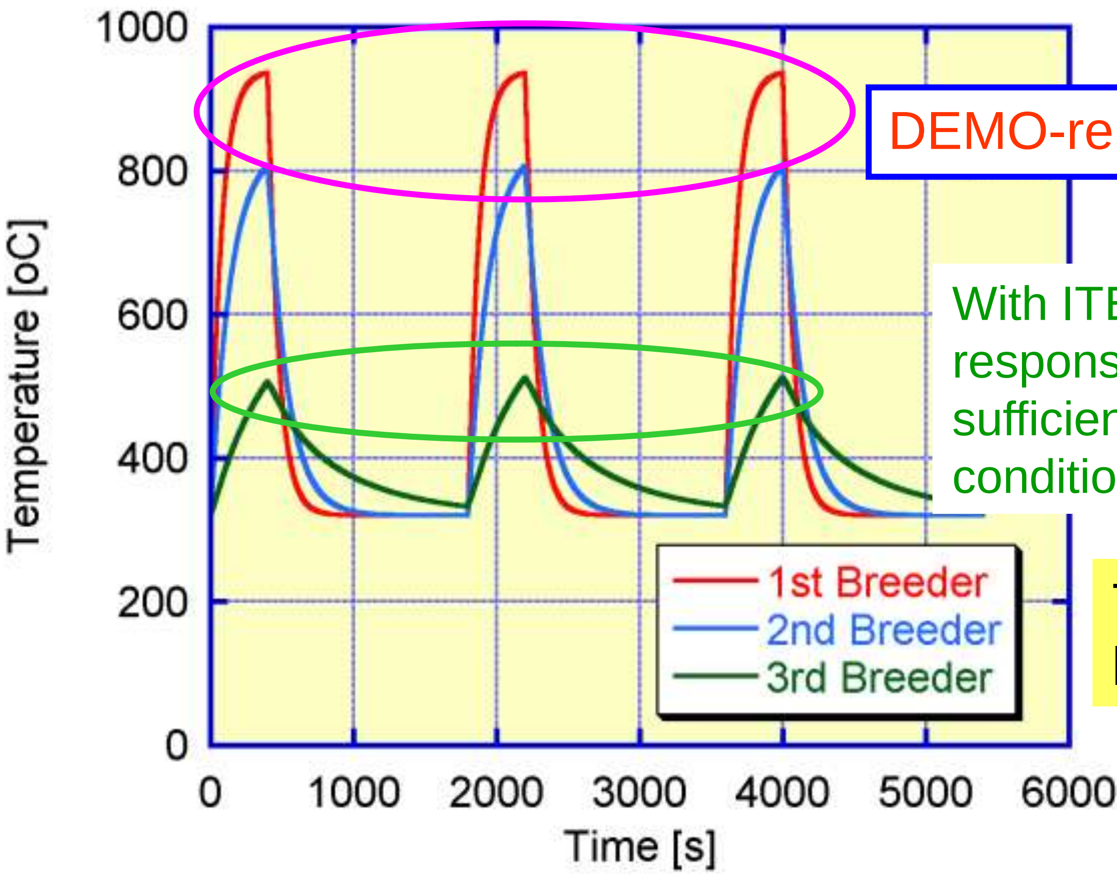
Japanese solid breeder concept





Horizontal Cross Sectional View

Japanese solid breeder concept



DEMO-relevant temperature range

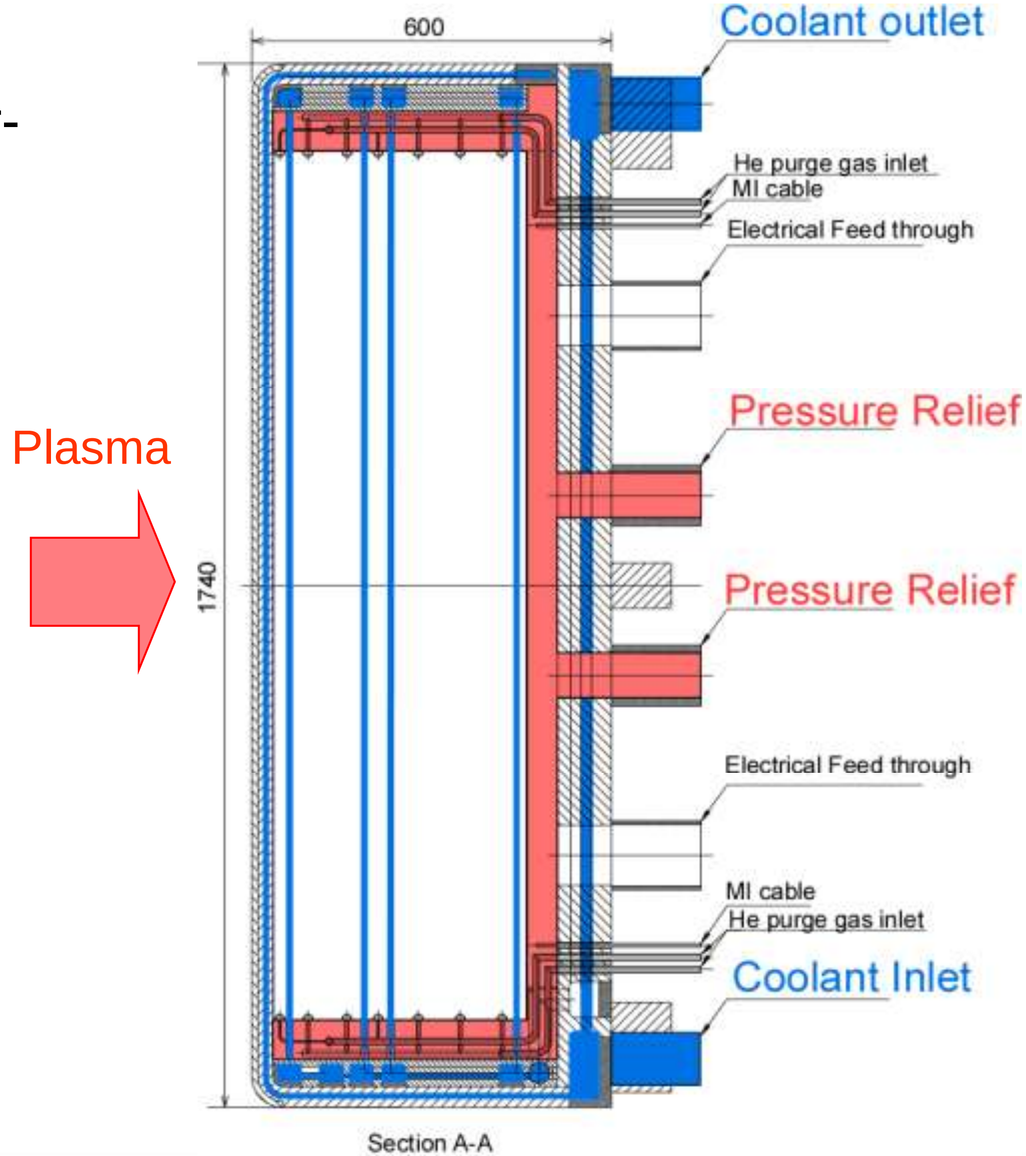
With ITER NWL, temperature response in 3rd Breeder layer is not sufficient to simulate DEMO breeder condition

The number of breeder layer in WC-TBM is two

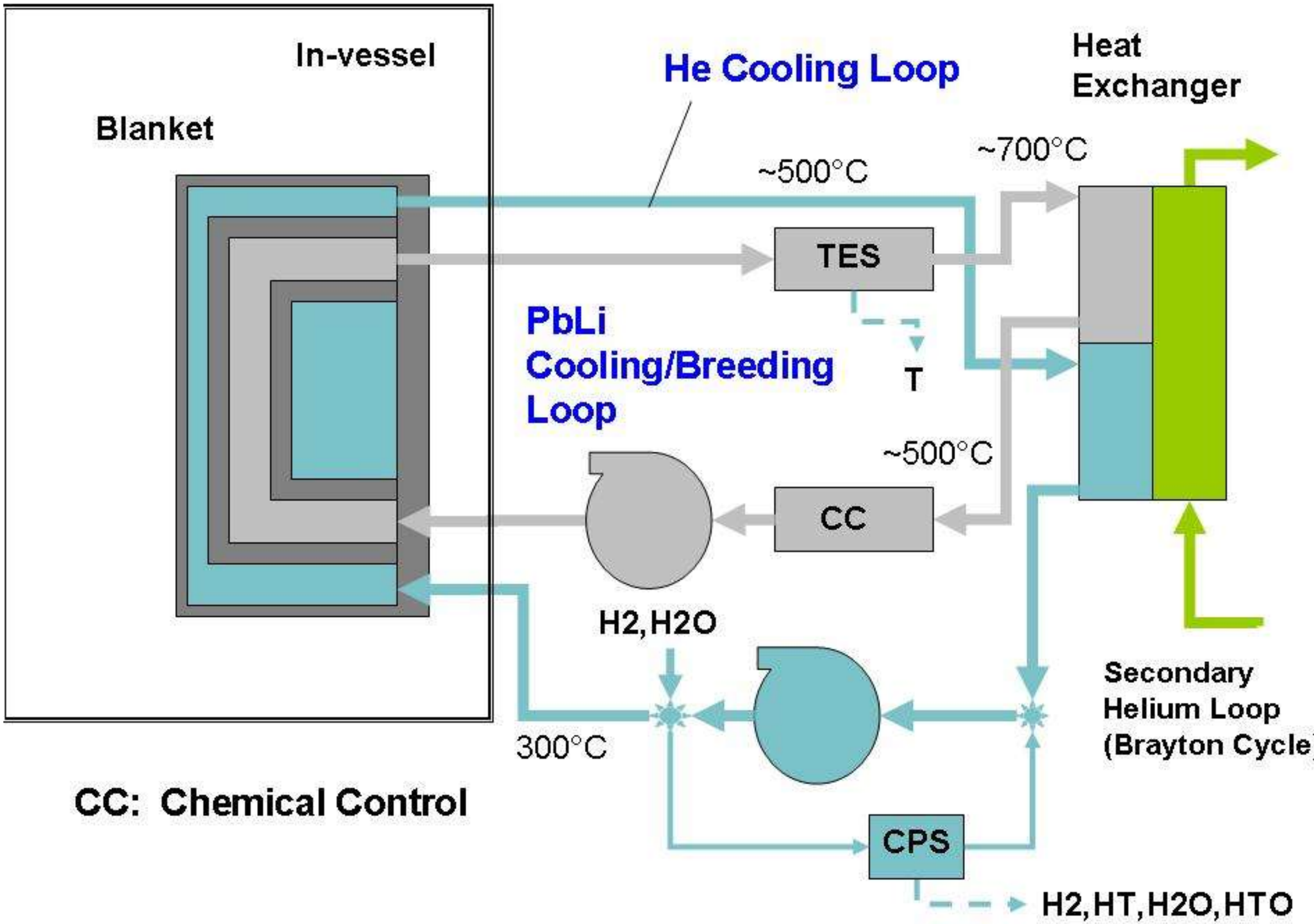
Time evolution of peak temperature of three breeder layers of water-cooled TBM with 400 sec burn/ 1400sec dwell cooled by 15MPa, 320ºC water.

Japanese solid breeder concept

Detail structure of water-cooled TBM:
2 breeding layers,
Coolant flow route.

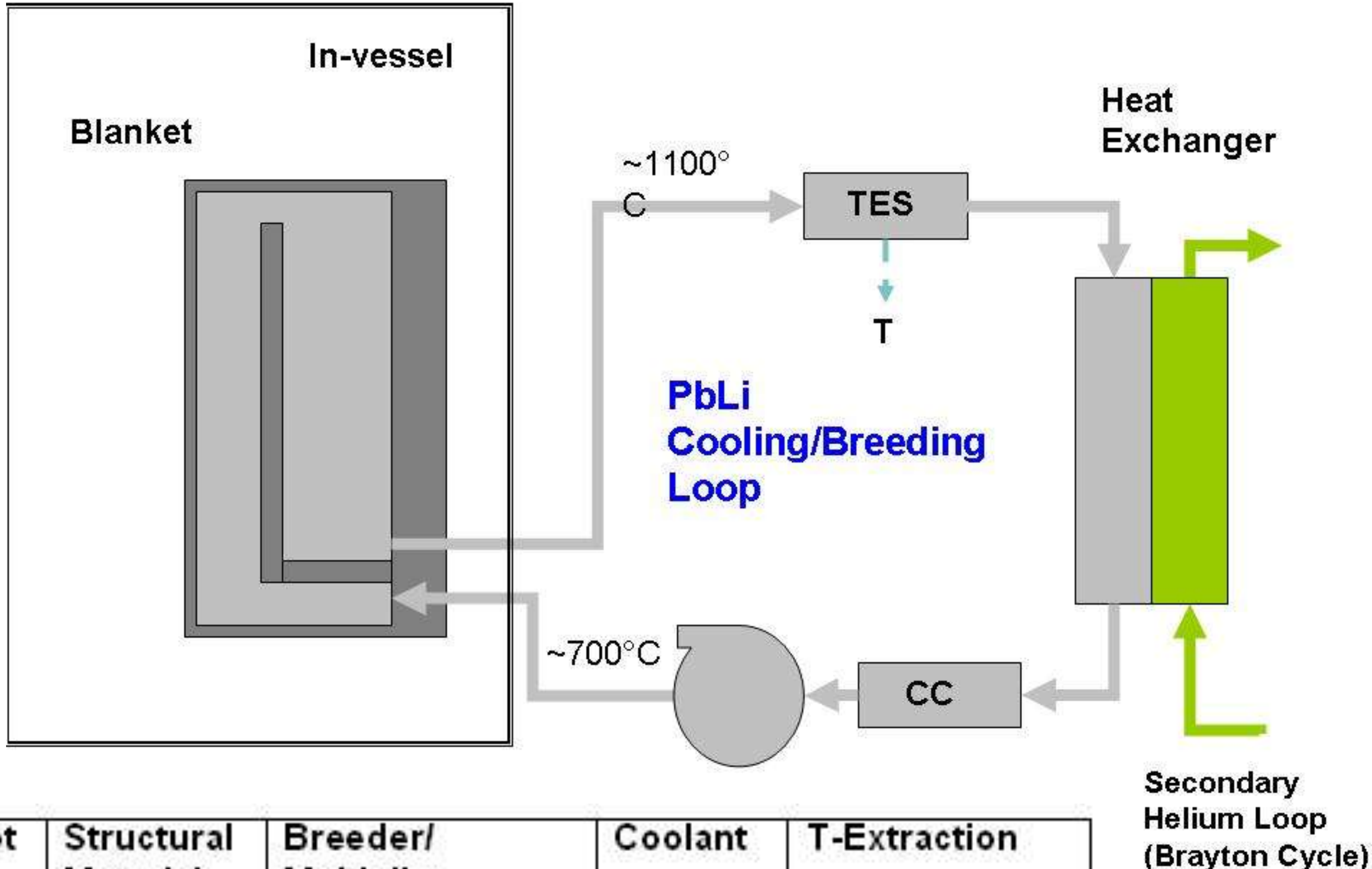


DCLL Blanket (US & FZK, 2000)



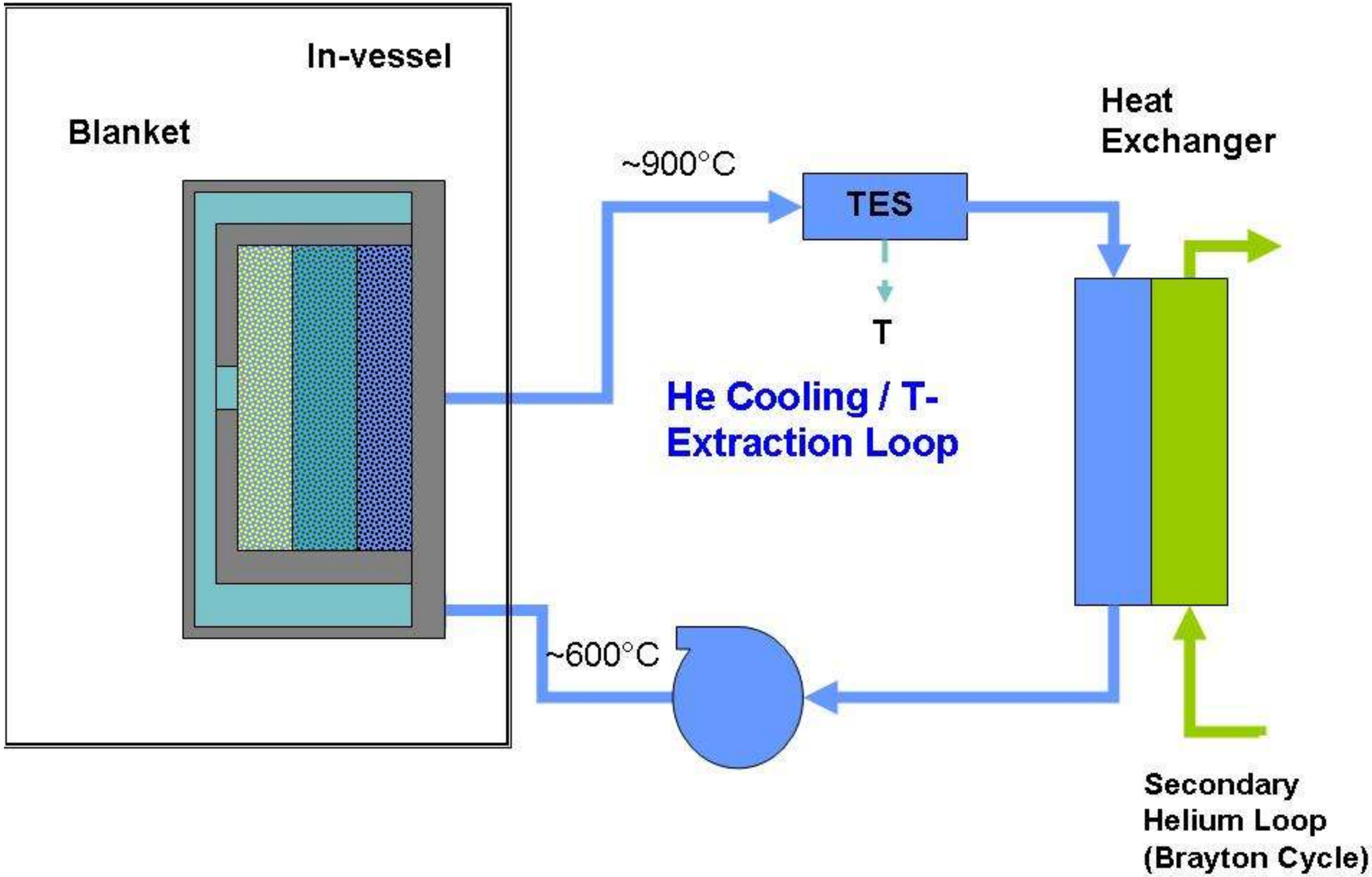
CC: Chemical Control

US ARIES Blanket system

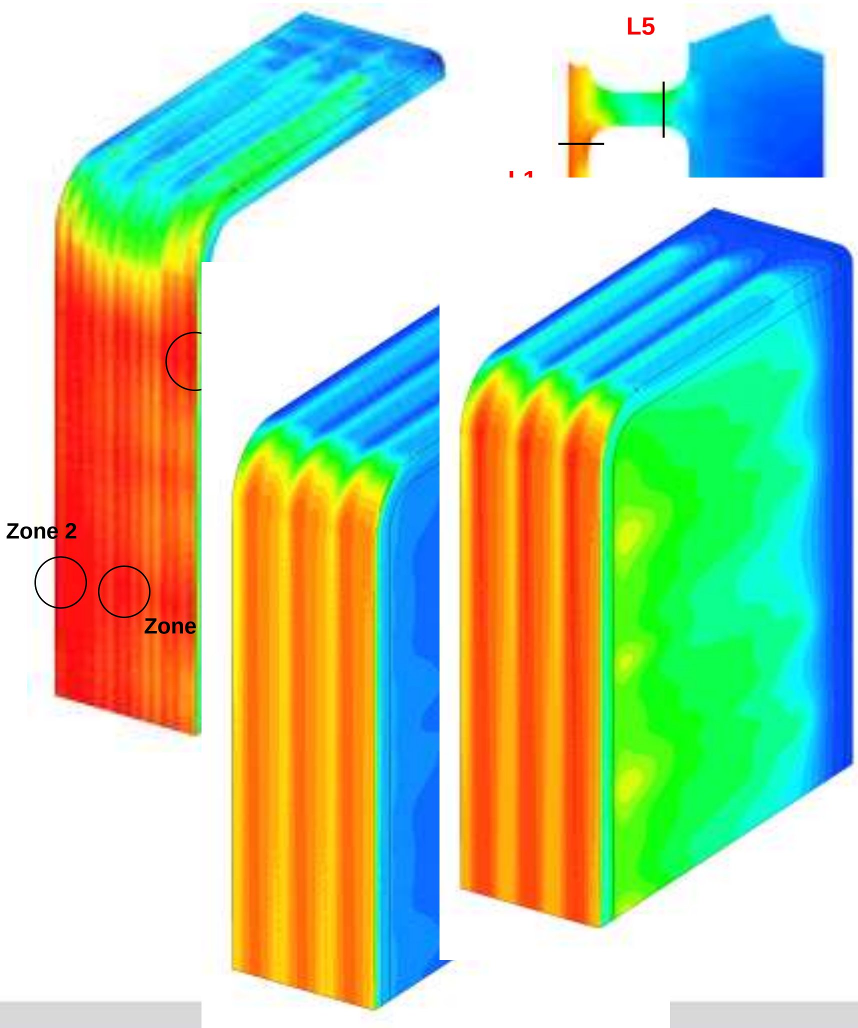


Concept	Structural Material	Breeder/ Multiplier	Coolant	T-Extraction
SCLL	Sic/Sic$_f$	PbLi	PbLi	Coolant PbLi

(Very) Advanced Solid Breeder concepts: JA Dream



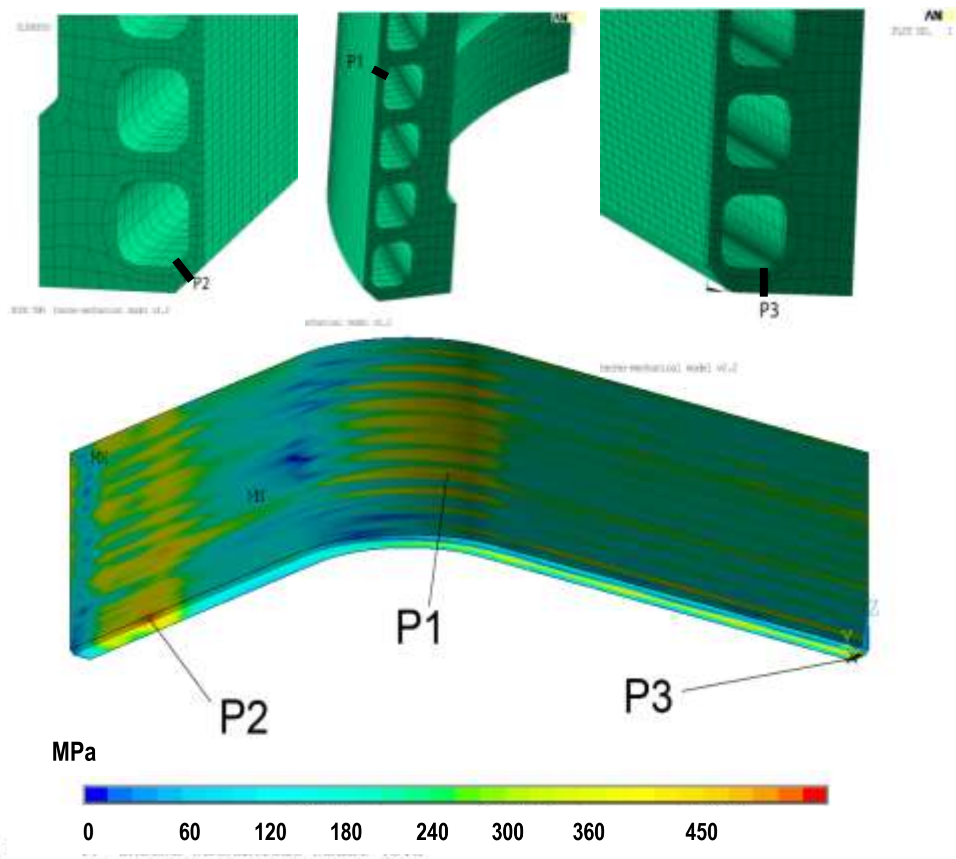
Transient thermo-mechanical analyses



Fatigue

	T (°C)	$(\Delta\overline{\sigma}_{tot})_{max}$ (MPa)	$\Delta\varepsilon_{elas.}$ (%)	K_ε	K_ν	$\Delta\varepsilon_{real}$ (%)	Allowable cycles
Line 1	471	579	0,26	1,08	1,10	0,31	**1878**
Line 2	484	619	0,28	1,15	1,14	0,36	**1062**
Line 3	488	607	0,28	1,15	1,14	0,36	**1175**
Line 4	376	504	0,22	1,00	1,03	0,23	8341
Line 5	368	295	0,13	1,00	1,00	0,13	No limit

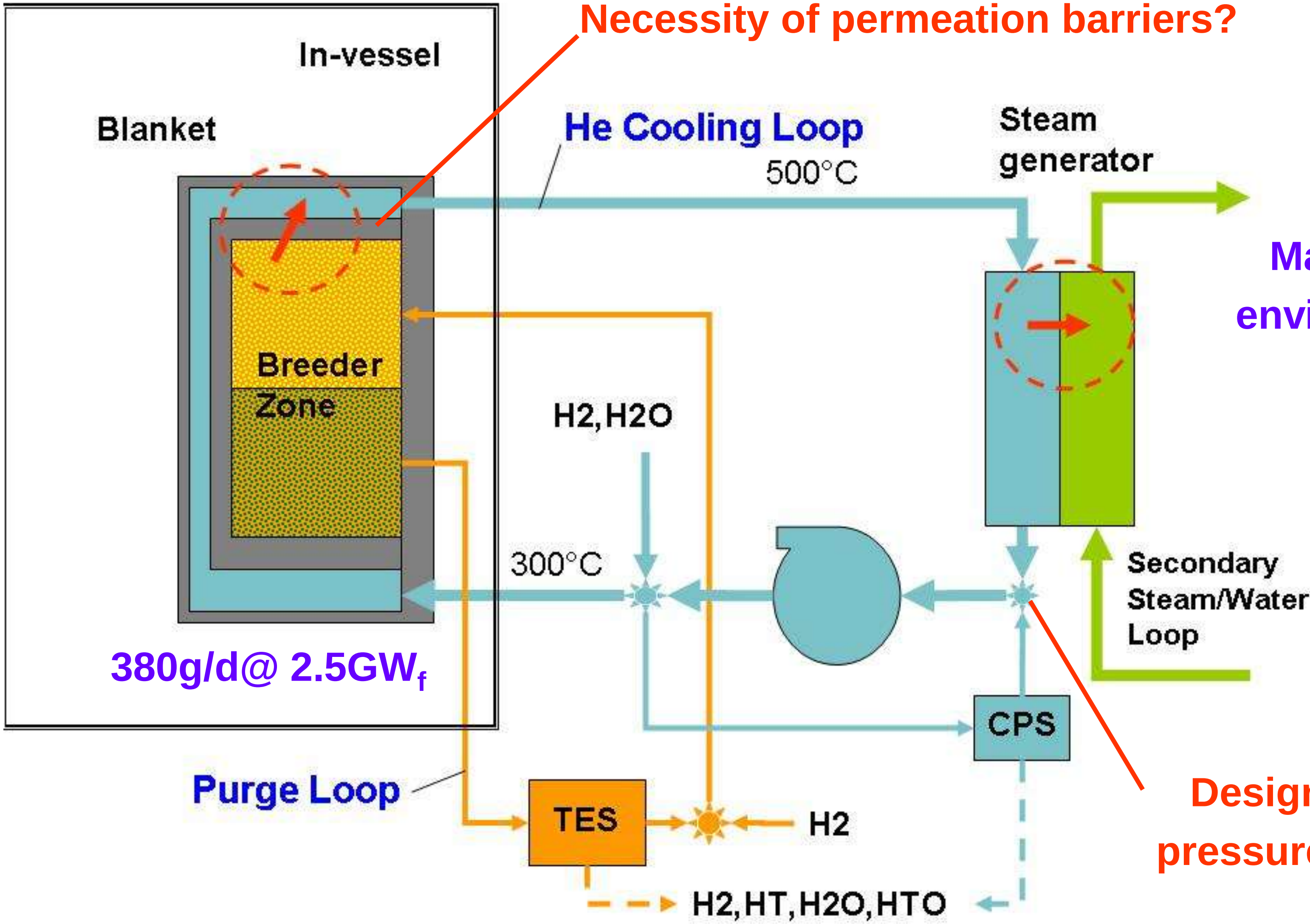
Transient thermo-mechanical analyses



Fatigue

	T (°C)	$(\overline{\Delta \sigma_{tot}})_{max}$ (MPa)	$\Delta \varepsilon_{elas.}$ (%)	K_{ε}	K_{ν}	$\Delta \varepsilon_{real}$ (%)	Allowable cycles
Line 1	434	227	0,12	1,00	1,00	0,12	No limit
Line 2	360	468	0,24	1,01	1,01	0,24	40000
Line 3	384	404	0,15	1,02	1,02	0,16	1,E+09
Line 4	307	657	0,35	1,00	1,00	0,35	10000

Necessity of permeation barriers?



380g/d@ 2.5GW$_f$

Max release to environments: 2.7 mg/day

Design HT-partial pressure in Helium ?