EU Blanket Design Activities and Neutronics Support Efforts

U. Fischer[a], P. Batistoni[b], L. V. Boccaccini[a], L. Giancarli[c], S. Hermsmeyer[a], Y. Poitevin[c]

[a]Forschungszentrum Karlsruhe, Germany
[b]ENEA Fusion Division, Frascati, Italy
[c]CEA Saclay, France

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Outline

- Introduction
- Blanket Design Description
- Neutronics Design Analyses
- Supporting Neutronics Activities
- Conclusions

Introduction

EU Fusion Technology Programme considers two development lines of a breeding blanket:

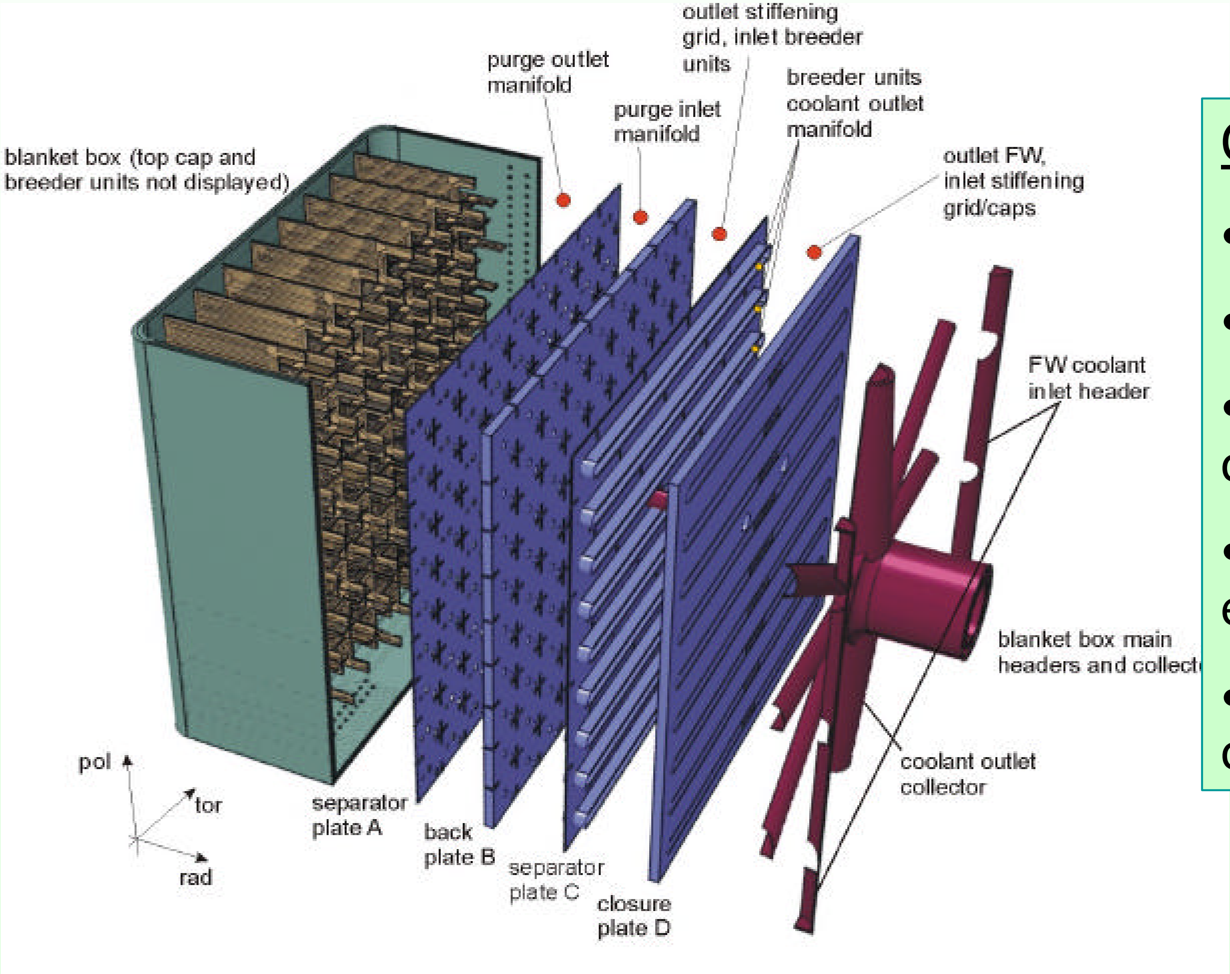
- Helium-Cooled Pebble Bed (HCPB) blanket with Lithium ceramics pebbles (Li_4SiO_4 or Li_2TiO_3) as breeder and beryllium pebbles as neutron multiplier
- Helium-Cooled Lithium-Lead (HCLL) blanket with the Pb-Li eutectic alloy as breeder and neutron multiplier

Blanket design and related R&D efforts are based on the use of the same coolant (Helium gas) and modular blanket structure to minimise the development costs as much as possible.

Design Requirements

- Tritium Breeding Ratio (TBR) ≥ 1.10 (3D-calculation)
- Modular blanket structure
  - Large Modules of 2 m x 2m (torodial x poloidal) which can be installed and removed through horizontal ports
  - Common module box that can withstand 8 Mpa (in-box LOCA)
- He (8 MPa) for cooling module box and breeder/multiplier
- ITER-like elongated single-null plasma configuration
  - Neutron wall loading of 2.0/2.4 MW/m^2 (average/ peak value)
  - Surface heat load of 0.4/0.5 MW/m^2
  - Blanket lifetime of 20,000 h full power
  - 2 mm tungsten layer as first wall protection

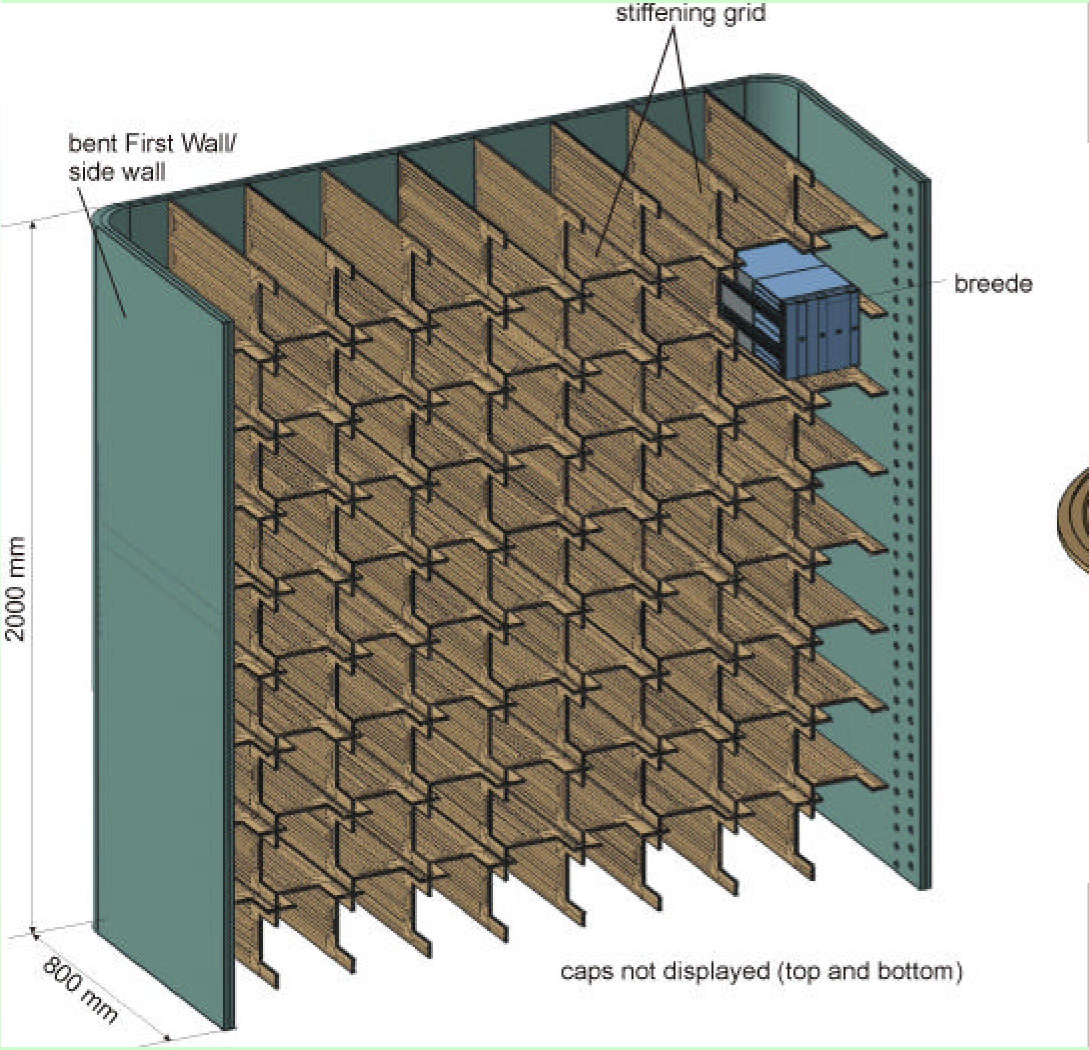
Modular Blanket Box

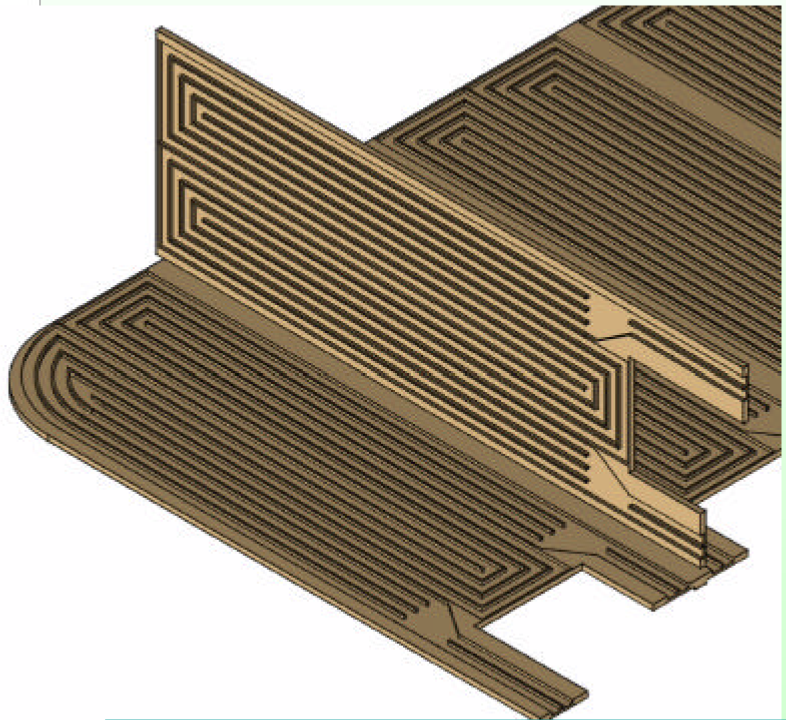


Common design features

- Module blanket box (Eurofer)
- Stiffening grid (8 mm plates)
- Rectangular cells (21 cm x 21 cm) for Breeder Units (BU)
- Cooled by He-gas (8MPa), enters an exits from the back
- Back plate acting also as He collector and distribution system

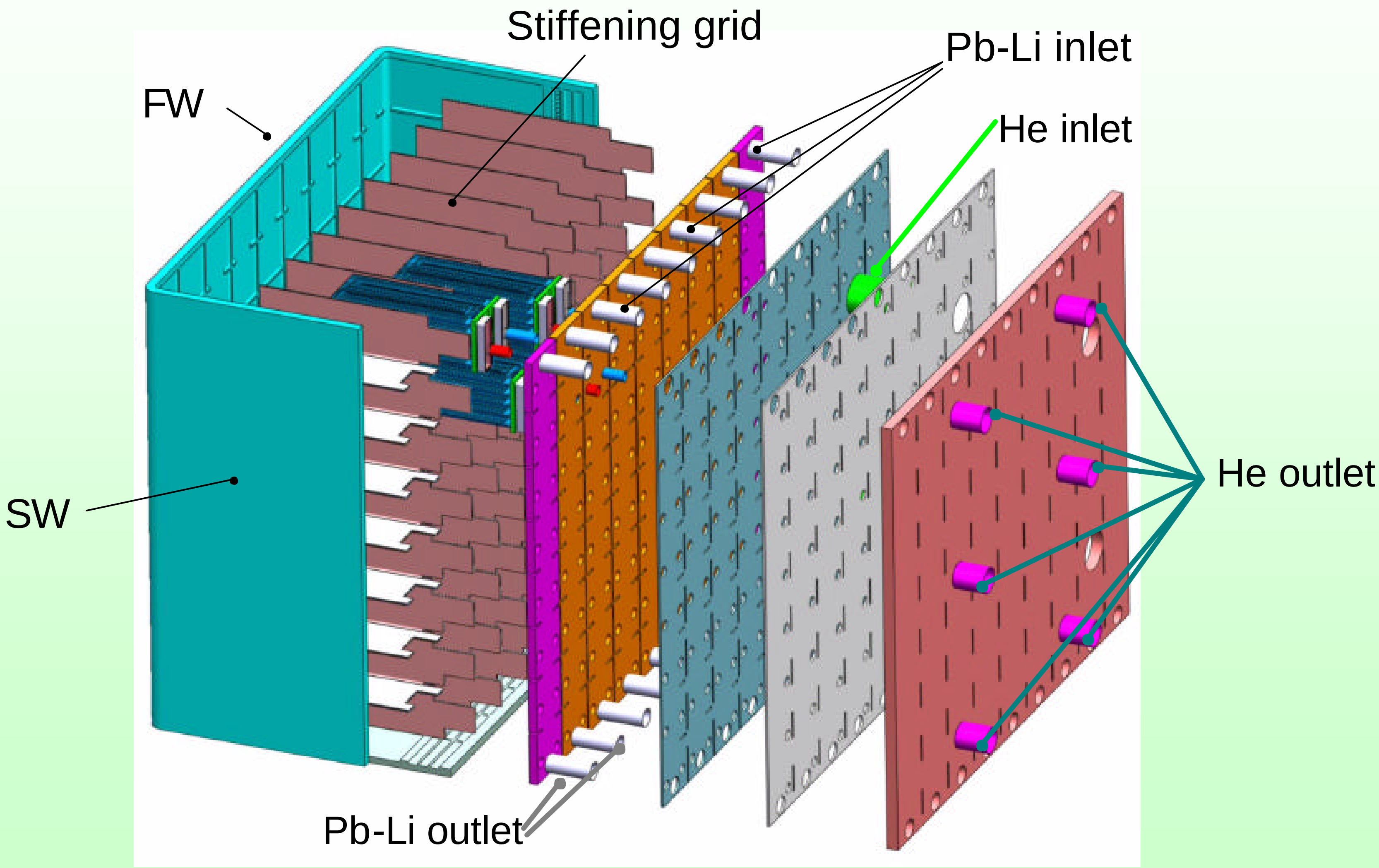
Blanket Box with HCPB Breeder Unit



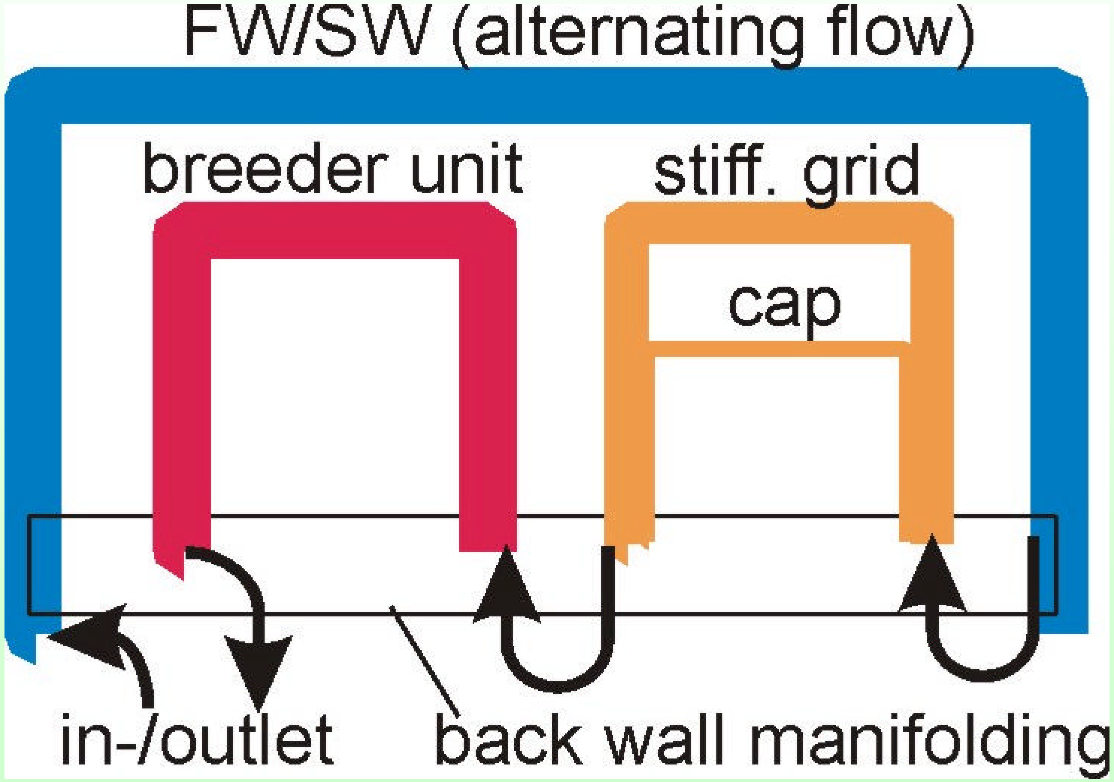


Stiffening plates with embedded cooling channels

Blanket Box with HCLL Breeder Cooling Unit



He coolant flow scheme



- First pass: First Wall and side walls
- Collection in back wall
- Second pass: stiffening grid (75%) and caps (25%)
- Collection in back wall
- Third pass: breeder units
- Collection and exit

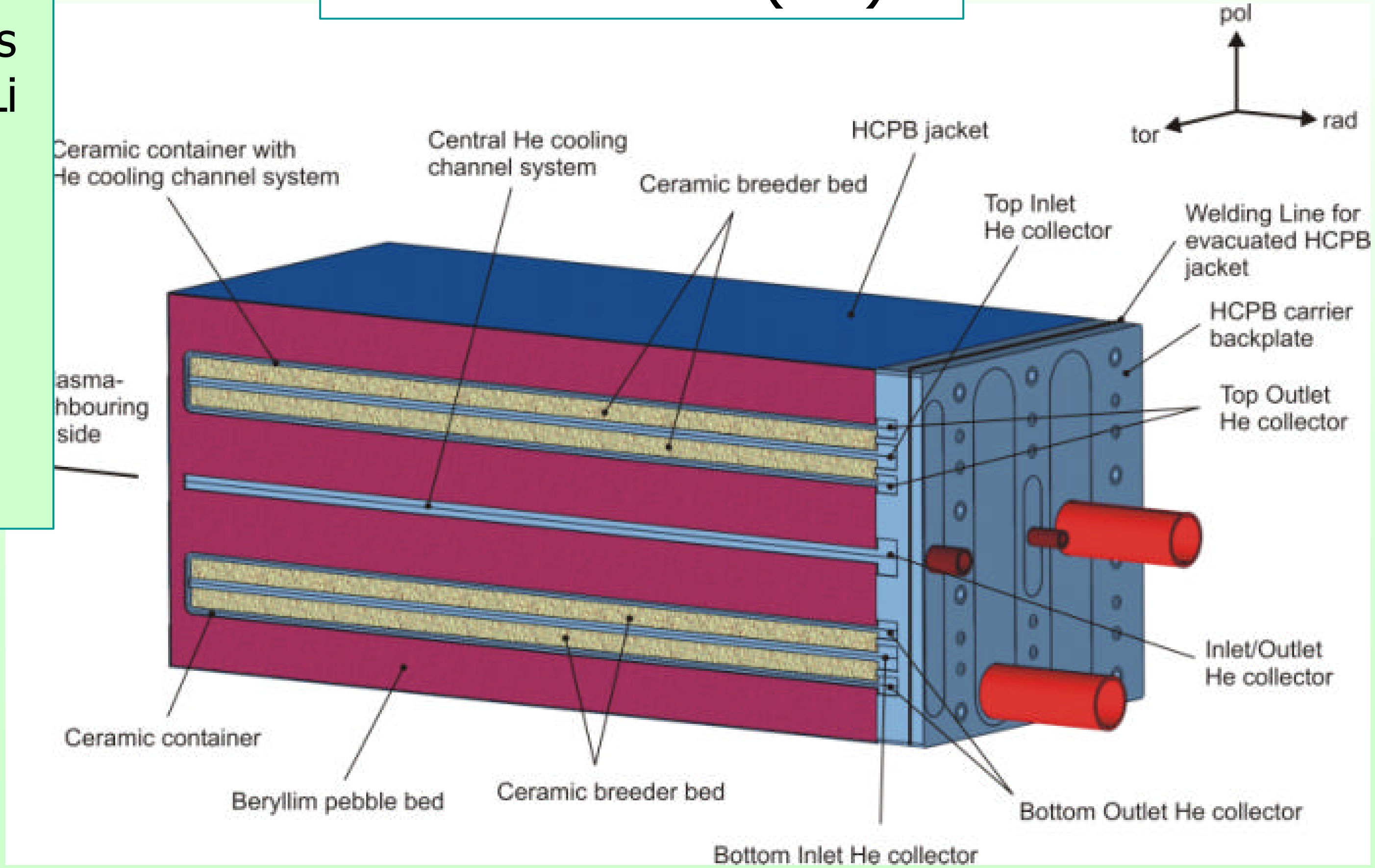
p_{Hw} = 8 Mpa, $T_{He,in}$ = 300°C, $T_{He,\ out}$=500°C

HCPB Blanket Concept

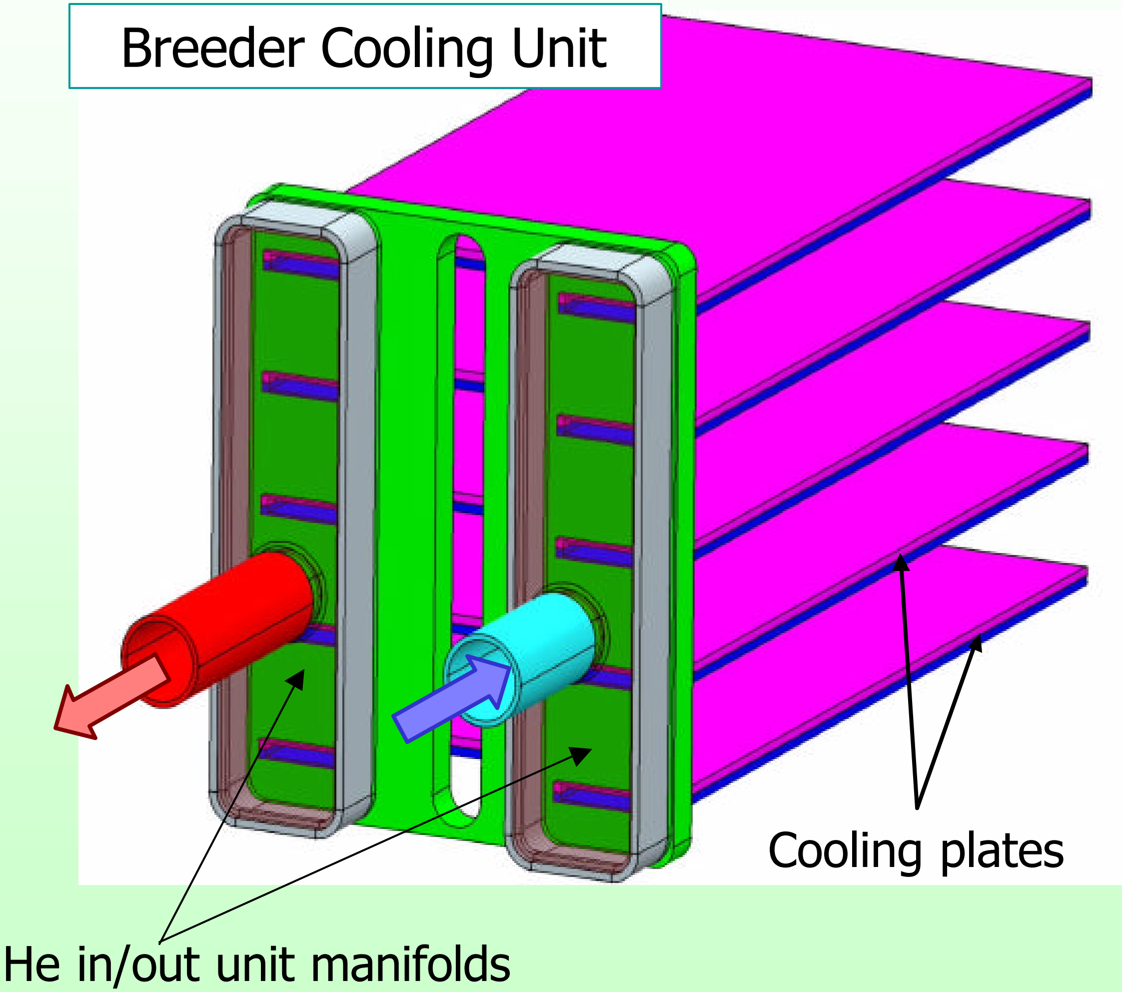
Main blanket features

- Li_4SiO_4 breeder pebbles (0.2-0.6 mm), 40 at% ^{6}Li
- Be pebbles (1 mm) for neutron multiplication
- He-gas coolant (8MPa)
- RAFM steel Eurofer

Breeder Unit (BU)



HCLL Breeder Blanket Concept



Main blanket features

- Pb-Li (90 at% ^{6}Li) for T-breeding and neutron multiplication
- He-gas (8MPa) for cooling structure and Pb-Li breeder
- RAFM steel Eurofer
- Pb-Li slowly circulating (15 mm/s) for T-extraction (30 recycles/day)

HCPB/HCLL Main Design Parameters

	HCLL	HCPB
Heat Flux on FW	0.5 MW/m^2	0.5 MW/m^2
Neutron Wall Loading	2.4 MW/m^2	2.4 MW/m^2
He inlet/outlet temperature	300/500 °C	300/500°C
He coolant operating pressure	8 MPa	8 MPa
He flow velocity in FW/SP/CP	85/22/35 m/s	85/40/40 m/s
Maximum temperatures • FW (steel) • CP (steel) • Breeder/multiplier	 563°C 537°C 544°C (at PbLi/steel interface)	 548°C 544°C 917°C (breeder) 655°C (Be)

Neutronic Design Analyses

- Based entirely on 3D Monte Carlo calculations (MCNP)
  - Detailed 3D torus sector models (based on PPCS, model B)
  - Blanket modules, shields, vacuum vessel, divertor, TF-coil etc.
  - Neutron source spatial distribution
  - FENDL-2 cross-section data

- MCNP calculation runs
  - MCNP4C on Linux cluster under PVM
  - Up to 20 parallel processors per run

Neutron Source Modelling in MCNP

Source density distribution

$$s(a) = \left[1 - \left(\frac{a}{A}\right)^2\right]^P$$

$0 \leq a \leq A$,
A = minor plasma radius

Plasma contour lines

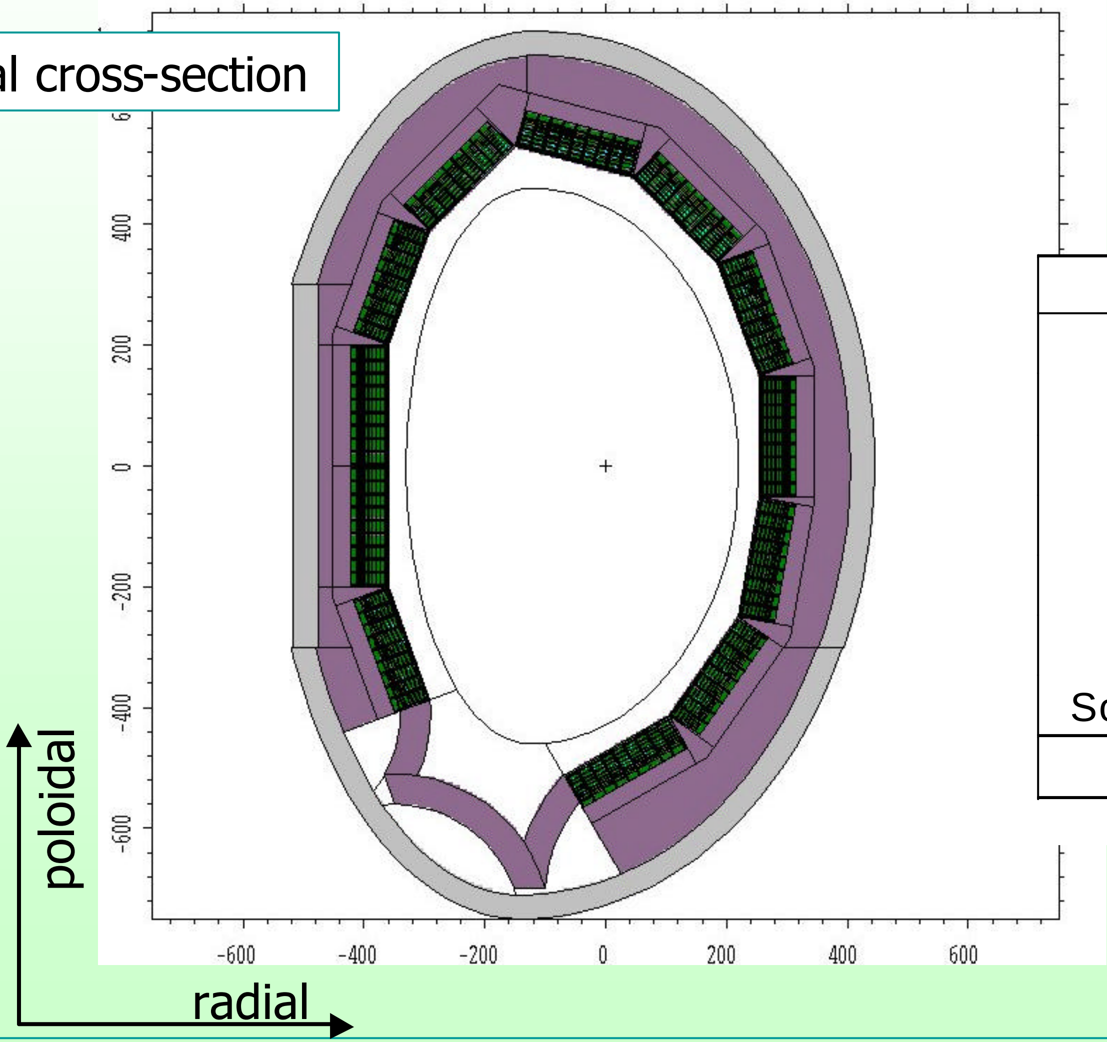
$$R = R_0 + a \cdot \cos(t + d \cdot \sin t) + e \cdot \left[1 - \left(\frac{a}{A}\right)^2\right]$$

$$z = E \cdot a \cdot \sin t$$

$$d = d_0 \cdot \frac{a}{A}, \qquad 0 \leq a \leq A, \quad 0 \leq t \leq 2 \cdot \Pi$$

MCNP Power Reactor Model (HCPB)

Vertical cross-section

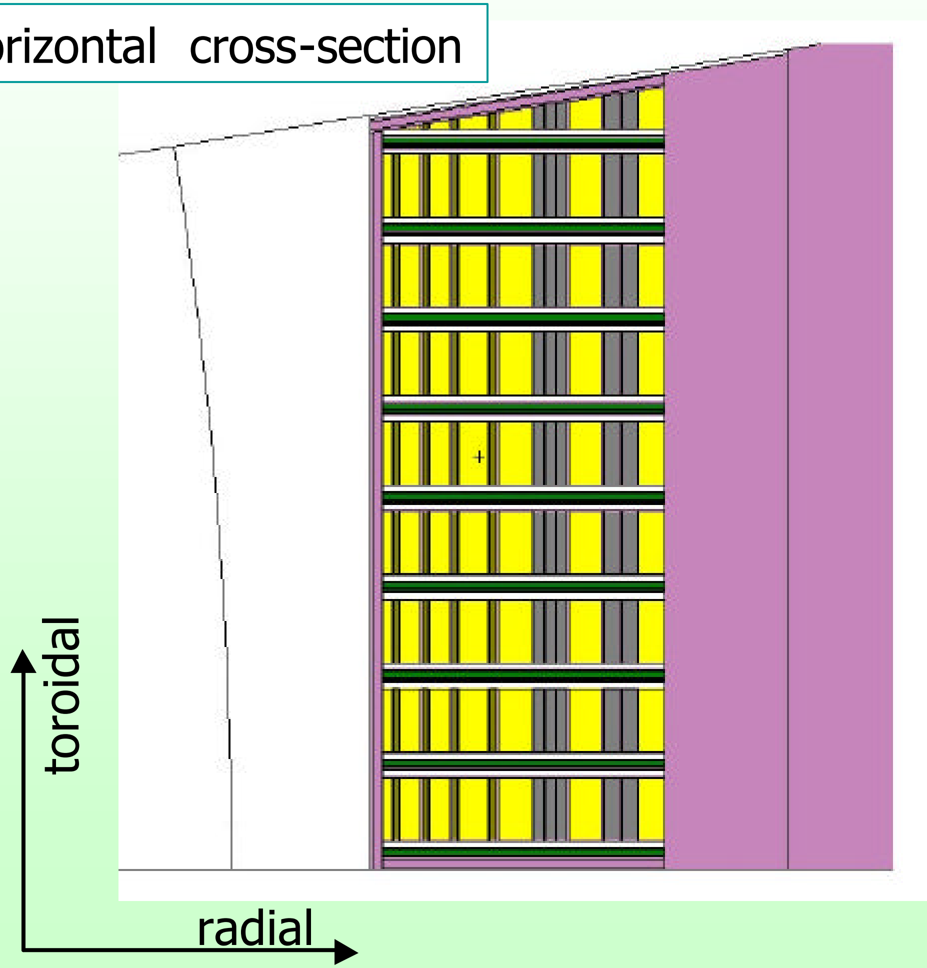


9 ° torus sector model based on parameters of PPCS model B (HCPB)

Parameter	HCPB
Major radius [m]	8.6
Minor radius [m]	2.8
Elongation	1.7
Triangularity	0.27
Radial shift [m]	0
Vertical shift [m]	0
Source Peaking Factor	1.7
Fusion power [MW]	3300

HCPB Blanket Concept
- Breeder Pebble Beds Parallel to the First Wall -

Horizontal cross-section



Concept offers high flexibility for neutronics design optimisation

Radial build: number of breeder pebble beds, thickness , distances, ^{6}Li-enrichment can be optimised

Major drawback:

Large amount of space consumed by radially running Helium feeding pipes running at the lateral sides of the BU towards the first wall

HCPB Blanket Concept

Optimised radial build of design variant with pebble beds parallel to First Wall

Material	Be	breeder	Be	breeder	Be	breeder	Be	breeder	Be	breeder	Be	breeder	Be
thickness [mm]	20	11	50	11	50	12	70	15	80	3x24	80	2x38	50
Li-6 [at%]		60		60		60		60		90		90	

TBR=1.15

Note: Bed heights limited due to low heat conductivity of breeder pebble bed

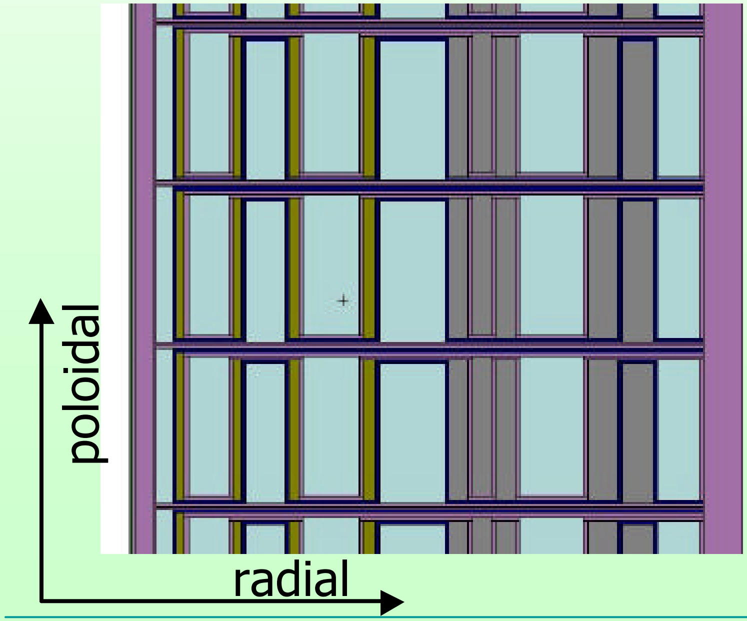
TBR sufficient to cover losses & uncertainties, but:

- High Li-6 enrichment required
- Large blanket thickness required ≅ 70 cm
- High Be mass inventory ≅ 440 tons (PPCS-type FPR)

HCPB Blanket Concept

Variant with beds parallel to FW and meander-type cooling plates

Material	Be	breeder	Be	breeder	Be	breeder	Be	breeder	Be	breeder	Be	breeder	Be
thickness [mm]	20	11	50	11	50	12	70	15	80	3x24	80	2x38	50
Li-6 [at%]		60		60		60		60		90		90	
TBR		0.28		0.26		0.24		0.18		0.19		0.06	
Li-6 [at%]		40		40		40		40		60		60	
TBR		0.25		0.24		0.23		0.18		0.19		0.06	

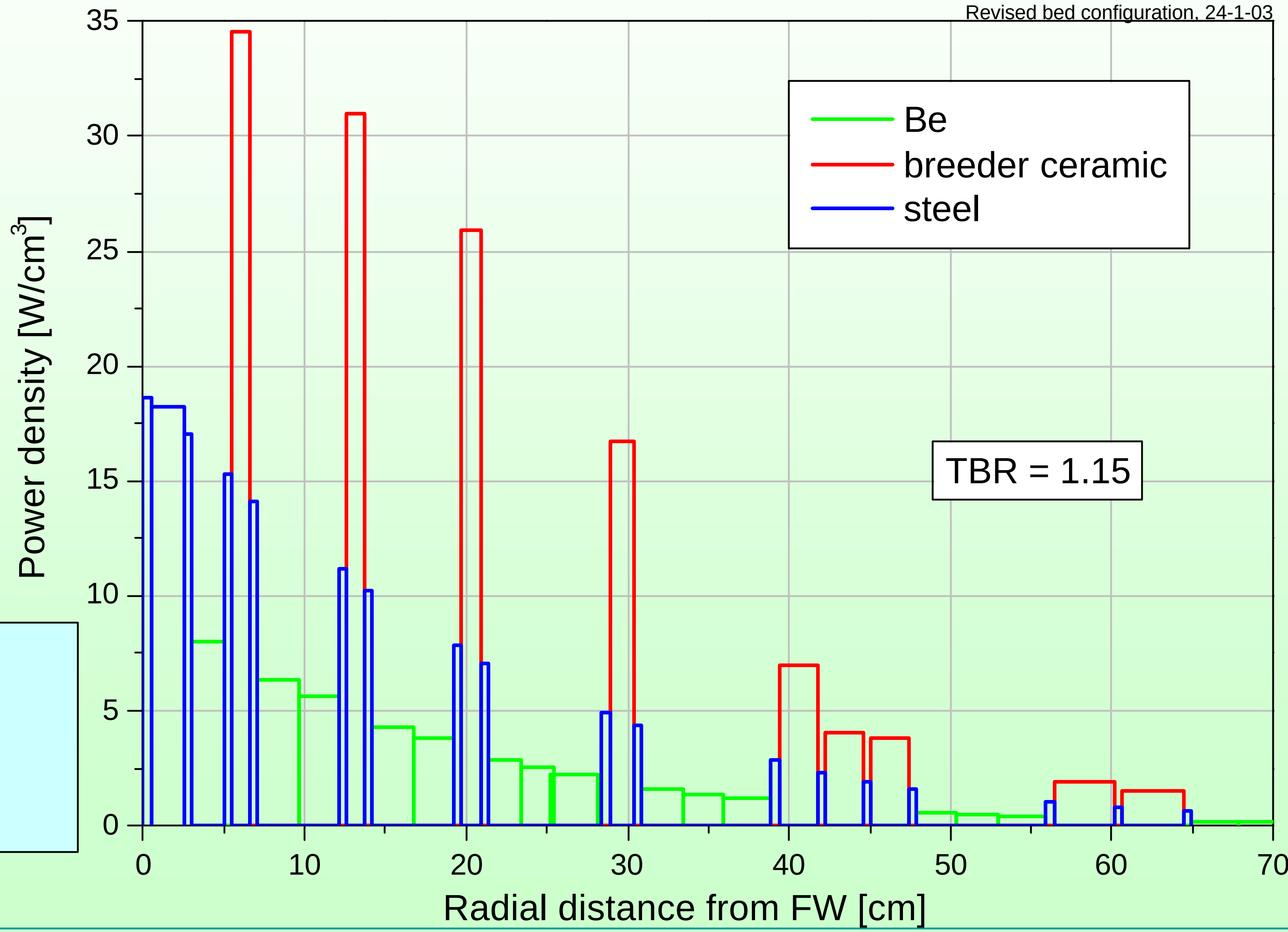


- TBR = 1.21 (Li-6: 4x60 + 2x90 at%)
- TBR = 1.15 (Li-6 : 4x40 + 2x60 at%)

Still disadvantage of

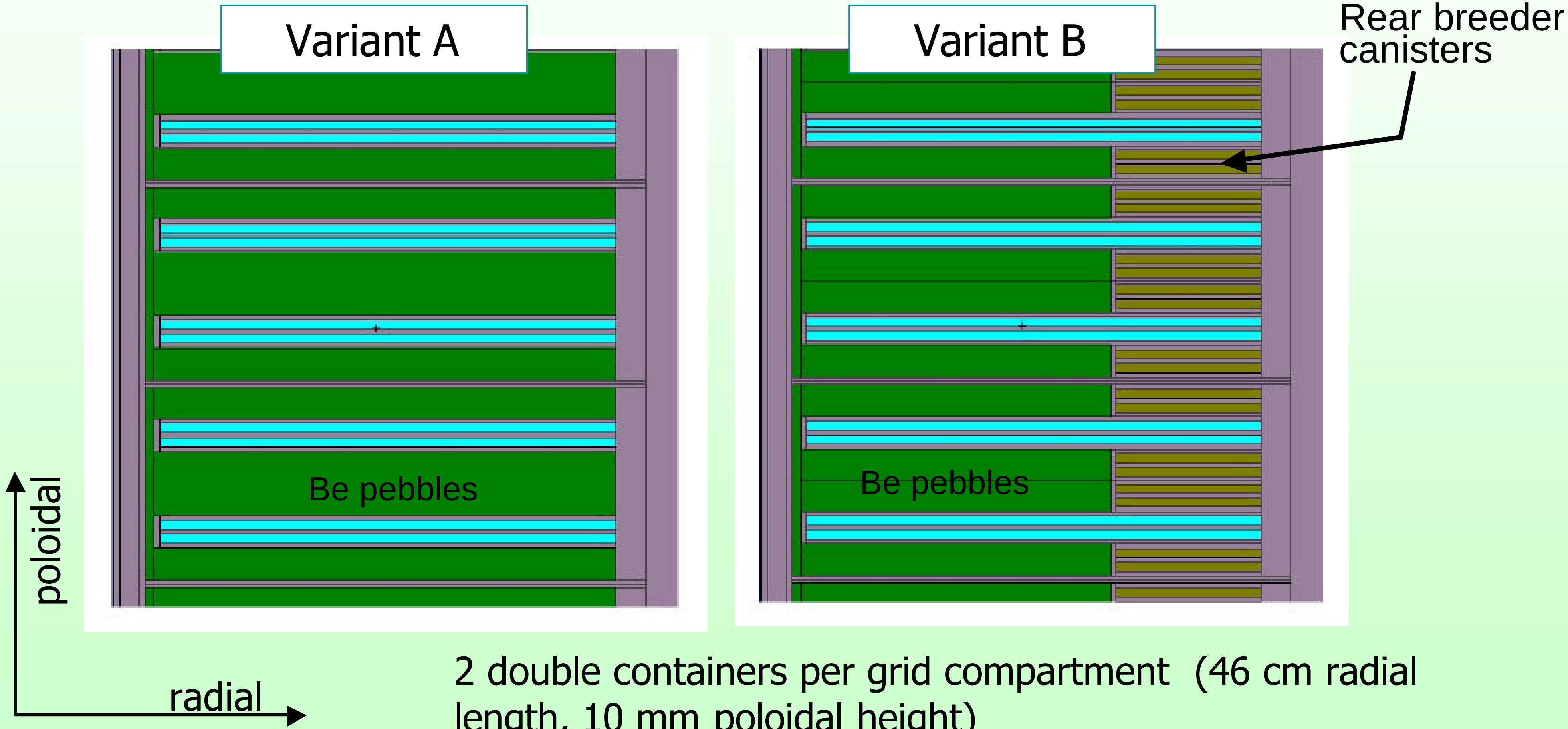
- Large blanket thickness ≅ 70 cm
- High Be mass inventory ≅ 483 tons

HCPB Blanket Concept
- Breeder Pebble Beds Parallel to First Wall -



Power density profiles in central outboard blanket module

HCPB Blanket Concept
- Breeder Pebble Beds Perpendicular to First Wall -



2 double containers per grid compartment (46 cm radial length, 10 mm poloidal height)

HCPB Blanket Concept
- Breeder Pebble Beds Perpendicular to First Wall -

Variant A

Advantage variant A : Low Be mass inventory

^{6}Li - enrichment	neutron multiplication	TBR	Beryllium mass inventory [tons]	Li_4SiO_4 mass inventory [tons]
30	1.70	1.10	412	147
35	"	1.12	"	"
40	"	1.14	"	"

Variant B

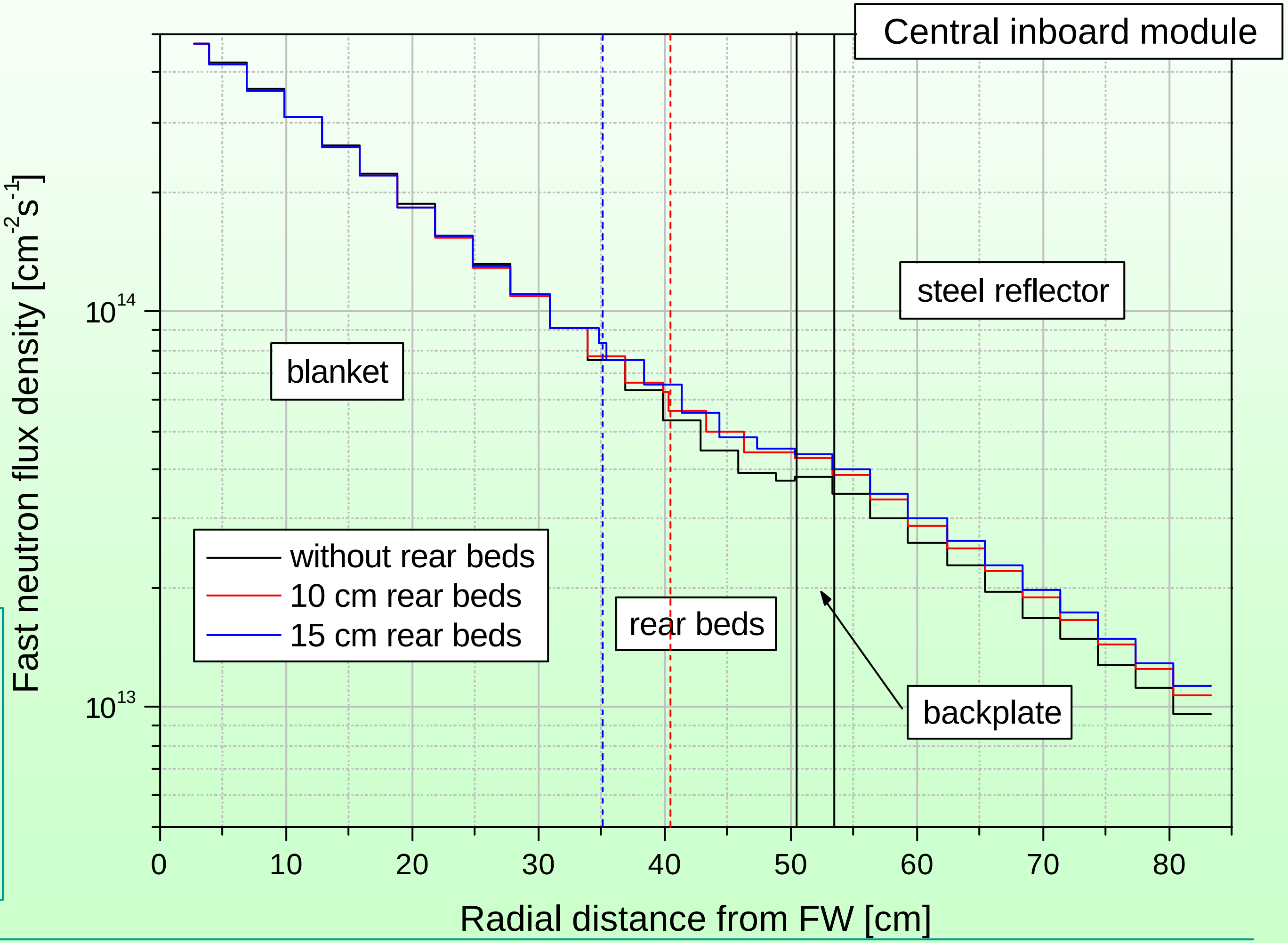
Advantage variant B: Less complex configuration

Rad. length of rear beds [cm]	^{6}Li-enrichment [at%]		neutron multiplication	TBR		mass inventory [tons]	
	rear beds	main beds		total	rear beds	Be	Li_4SiO_4
10	30	30	1.68	1.10			
10	60	30	1.68	1.11			
10	60	40	1.68	1.15	0.10		
5	60	40	1.69	1.15	0.06		
15	60	40	1.66	1.14	0.15	284	242
20	60	40	1.64	1.12	0.22		

HCPB Blanket Concept

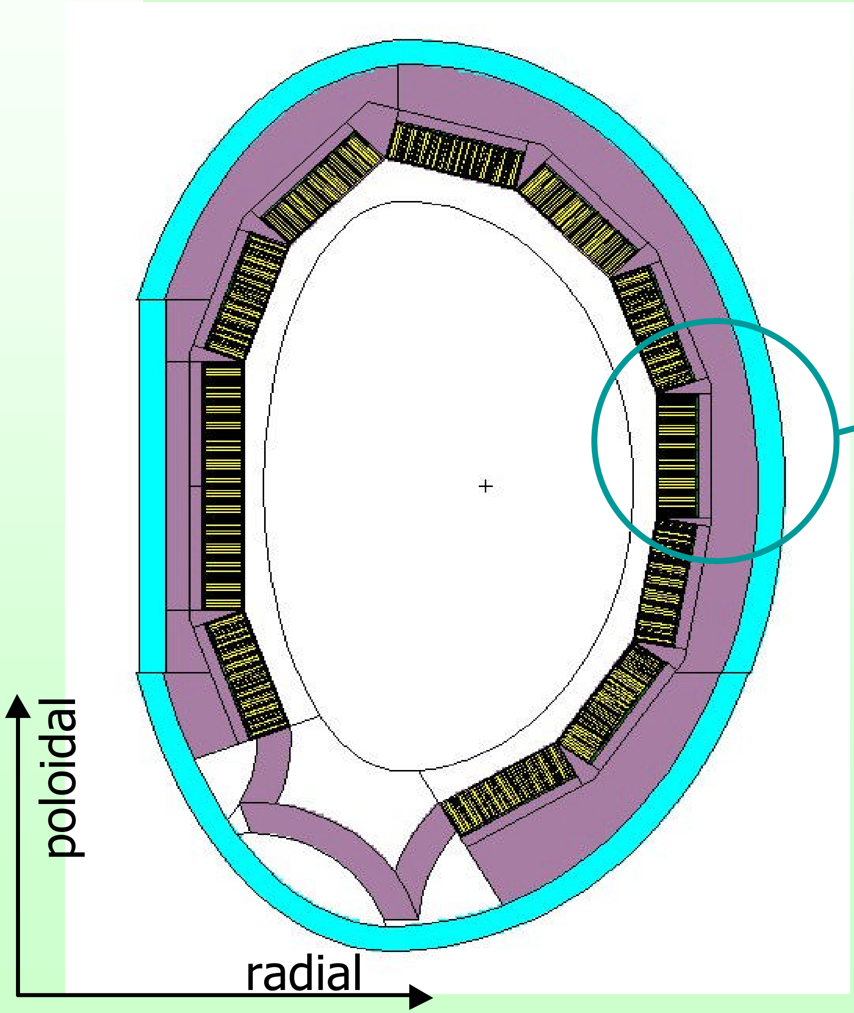
- Shielding Performance of Variants With Pebble Beds Perpendicular to FW-

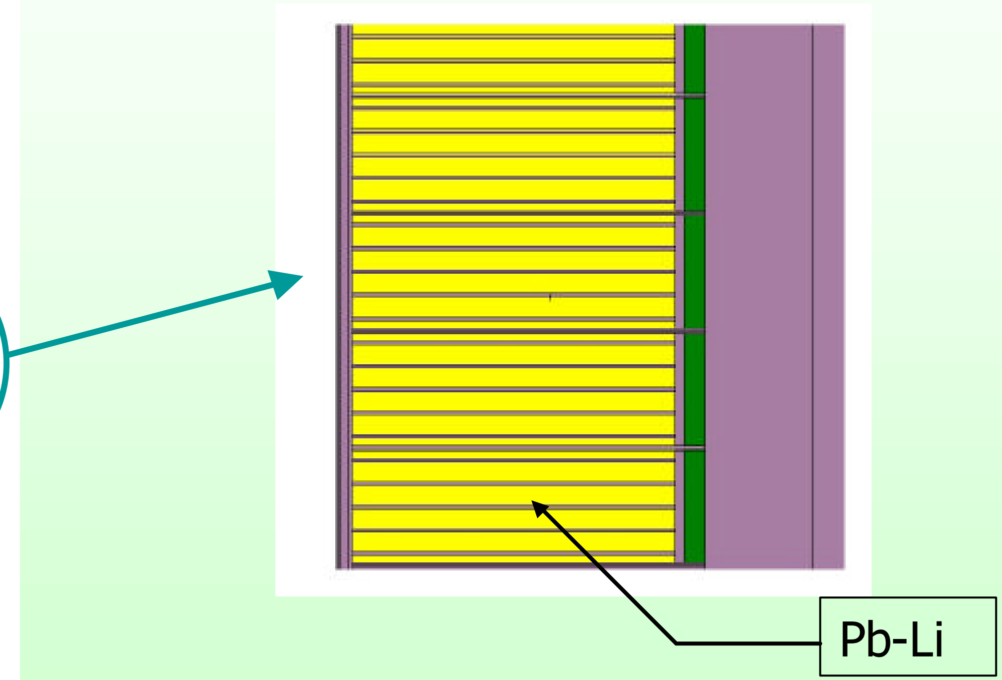
Fast (E>0.1MeV) flux radial profiles in central inboard blanket modules



Variant A performs better due to due high neutron moderating efficiency of Be neutron multiplier

HCLL Blanket Concept
- MCNP torus sector model -





Adapted from HCPB reactor model
⇒ replacing HCPB by HCLL modules

HCLL Blanket Concept

Tritium Breeding Ratio

Radial thickness of breeder zone [cm]	TBR	Neutron multiplication	Comments
75	1.22	1.58	Reference case
60	1.17	1.58	
55	1.15	1.58	

2 mm W first wall armour taken into account

- Modular HCLL blanket concept viable solution for fusion power reactor
- Optimisation mainly subject to thermal hydraulics considerations

⇒ HCLL considered as near term option in PPCS study replacing the WCLL plant model (study underway)

Supporting Neutronics Activities Effort

EU is conducting a continuous effort on fusion neutronics and nuclear data as part of the integrated fusion materials and technology programme

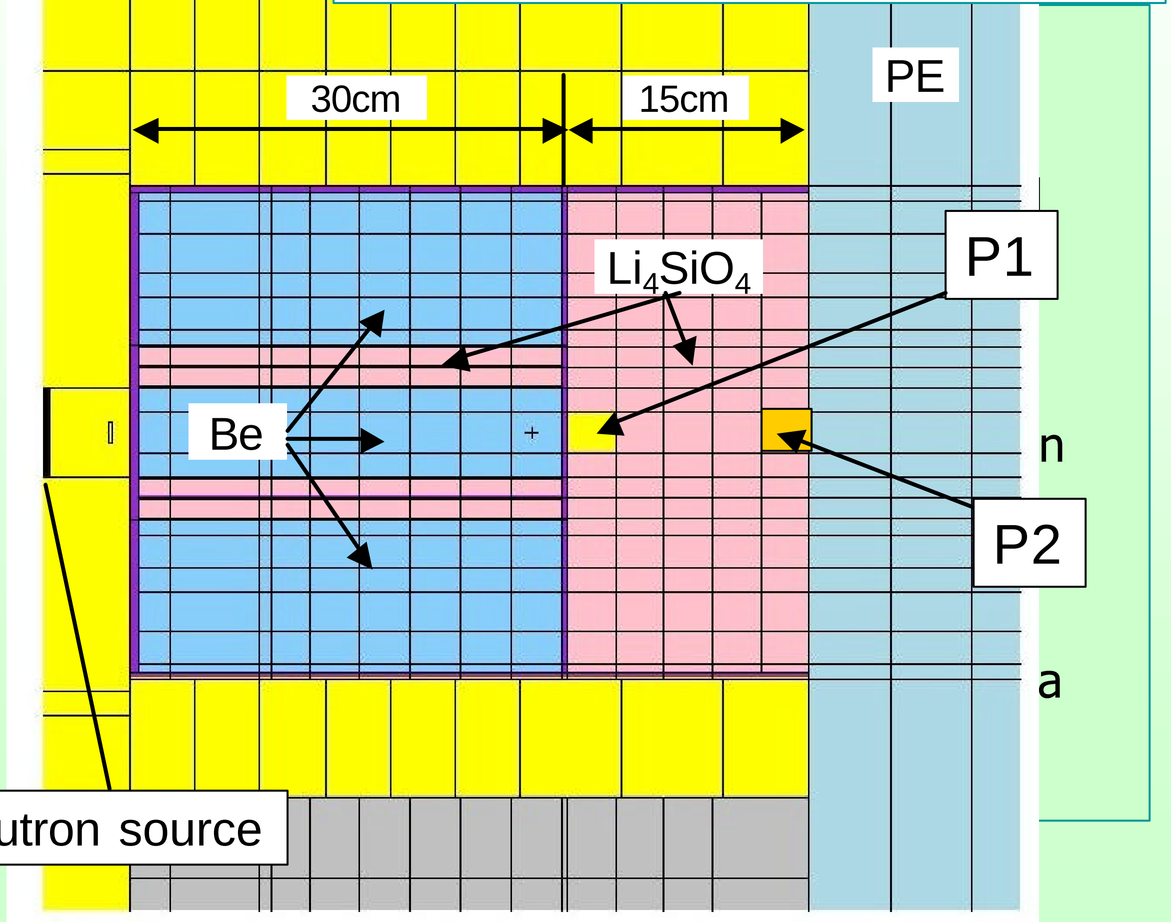
- Theoretical programme part
  - Evaluation and qualification of nuclear data for neutron transport and activation calculations
    - Þ European Fusion File (EFF-3), European Activation File (EAF-2003)
  - Monte Carlo based technique for uncertainty assessments
- Experimental programme part
  - Major effort on activation experiments for validating activation cross-section data: SS-316, MANET, F82H, Eurofer, V/V-alloy, pure elements (Al, V, Ni, Cu, Cr, Fe, Hf, Nb, Y, W), CuCrZr, SiC, Li_4SiO_4
  - Current focus on neutronics TBM mock-up experiments
    - ⇒HCPB blanket mock-up in preparation at FNG; measurements in 2005
    - ⇒Follow-up experiment on HCLL mock-up staring in 2006

HCPB Breeder Blanket Mock-up Experiment

at Frascati Neutron Generator (FNG)

<u>Objectives:</u>

- Benchmark experiment to validate codes and data and check breeding performance prior to TBM testing in ITER
- Preparation of measuring techniques for TBM testing in ITER Þ Tritium production
- Development of required computational tools and data Þ uncertainty assessments



Conclusions & Outlook

- EU fusion programme well on track to develop DEMO relevant breeding blankets which can be tested in ITER.
- HCPB and HCLL Helium-cooled blankets have been elaborated.
- Key R&D issues (e. g. manufacturing technologies, Tritium control, Helium coolant flow) are being investigated.
- Mock-up test programme for TBM planned to be conducted prior to TBM installation in ITER.
- EU is conducting continuous effort on neutronics and nuclear data to support nuclear design activities.
- Neutronics mock-up experiments will be conducted for HCPB and HCLL blanket concepts to validate TBR performance.