Blankets - key element of a fusion reactor - functions, design and present state of development

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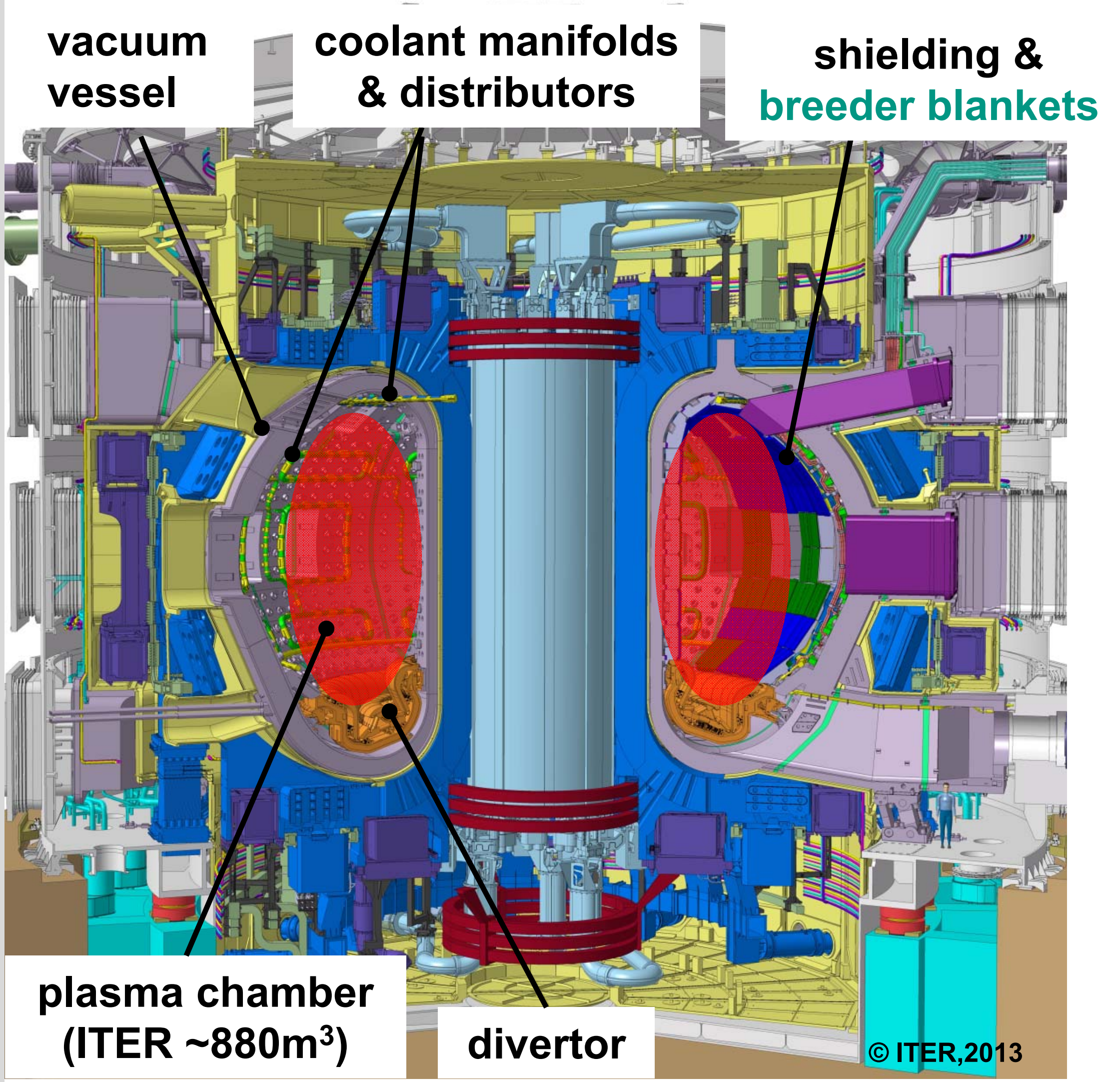
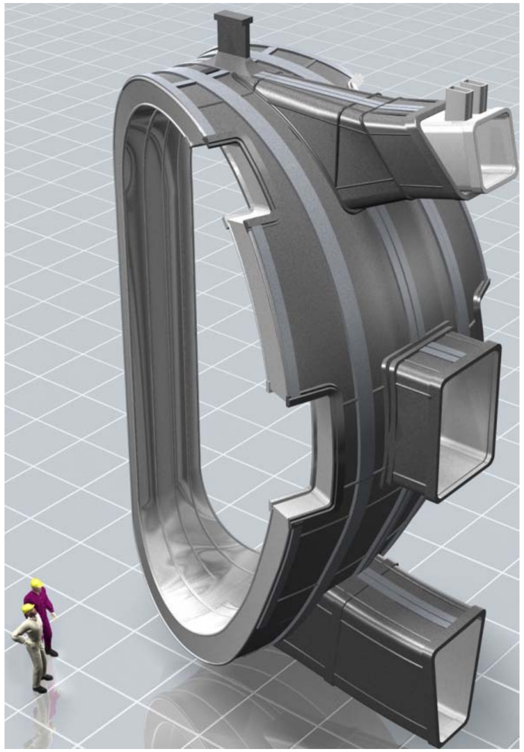
- **Fundamental functions** ➡ **functionality**
- **Operational frame** ➡ **basic design**
- **Reliability, Efficiency** ➡ **engineering design**
- **Maintenance, safety** ➡ **final design & design integration**
- **Blanket development** ➡ **validation**
- **Fusion power plant safety** ➡ **safety approach, status**
- **ITER Testblankets, DEMO Blankets**
- **Summary**

Fusion Reactor – Thermo-nuclear core -ITER



Top level blanket functions

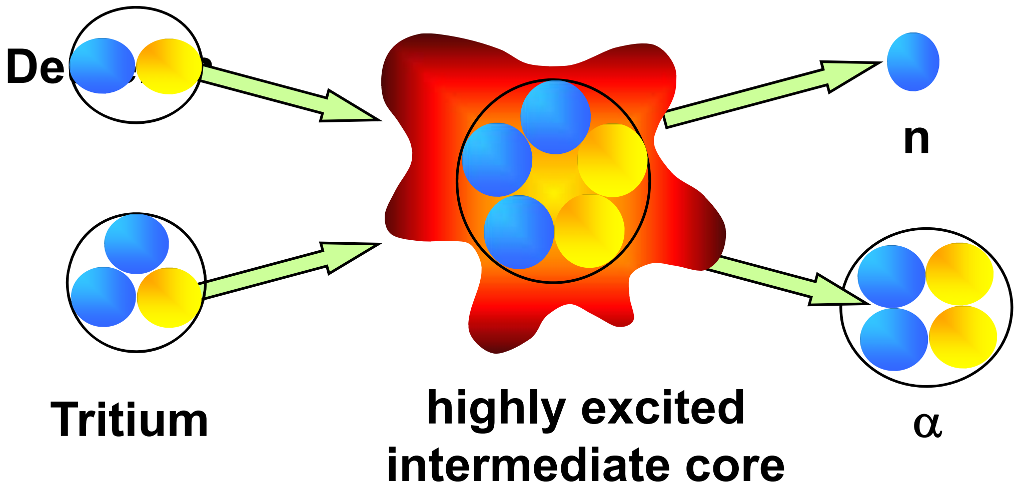
- tritium breeding
- heat removal
- contribution nuclear shielding



Blanket - Fundamental function- „Breeding“

How to breed Tritium ?

- **Fusion – reaction**



neutron (14.1MeV)
(no magnetic confinement)
- ➡ fuel generation „breeding“
- ➡ nuclear heating
- ➡ material activation

He-nucleus (α) (3.5MeV)
(magnetic confinement !!)
- ➡ plasma „self-heating“
- ➡ heat radiation to blanket

$^{2}\mathrm{D} + {}^{3}\mathrm{T} \longrightarrow {}^{4}\mathrm{He}\ (\alpha) + \mathrm{n} + 17.6\ \mathrm{MeV}$

Capture neutron in nuclear reaction producing tritium

- (n,T)-reaction on (suitable) naturally abundant nuclide

Blanket - Fundamental function- „Breeding“

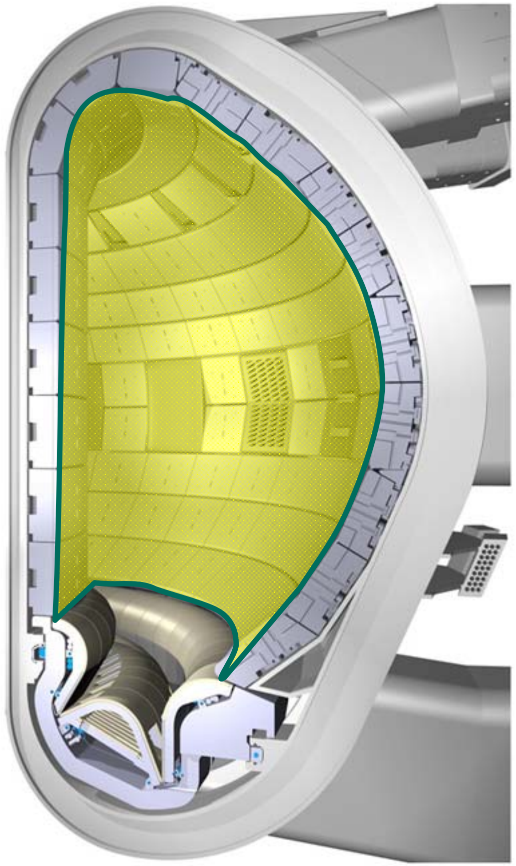
- **Which nuclide / element / material ?**

  $^{6}Li + n = T + ^{4}He +$ 4.8 MeV or $^{6}Li(n,\alpha)T$ + 4.8 MeV

  $^{7}Li + n = T + ^{4}He + n$ - 2.5 MeV or $^{7}Li(n,n'\alpha)T$ - 2.5 MeV

  (other potential reactions $^{3}He(n,p)T$ + 0.8 MeV, $^{2}H(n,\gamma)T$+6.3 MeV)

- **Which configuration ?**
  - Breeder arrangement in ***Blanket*** around plasma chamber so that neutron absorbed in breeder
  - Reactor constraints
    - Plasma chamber (80% for Blanket -coolant, structure material- 20% divertor & plasma heating devices)
    - Parasitic neutron absorptions (non breeding materials)
    - Neutron leakage (ports, diagnostics)
    - ➡ **Need for neutron multiplication**



- **How to prove tritium breeding capability?**
  - neutronic calculation (➡ method/data/geometry !)
  - calculation validation against experiment(s)

Blanket - Fundamental function- „Breeding"

Production of Tritium from Li ?

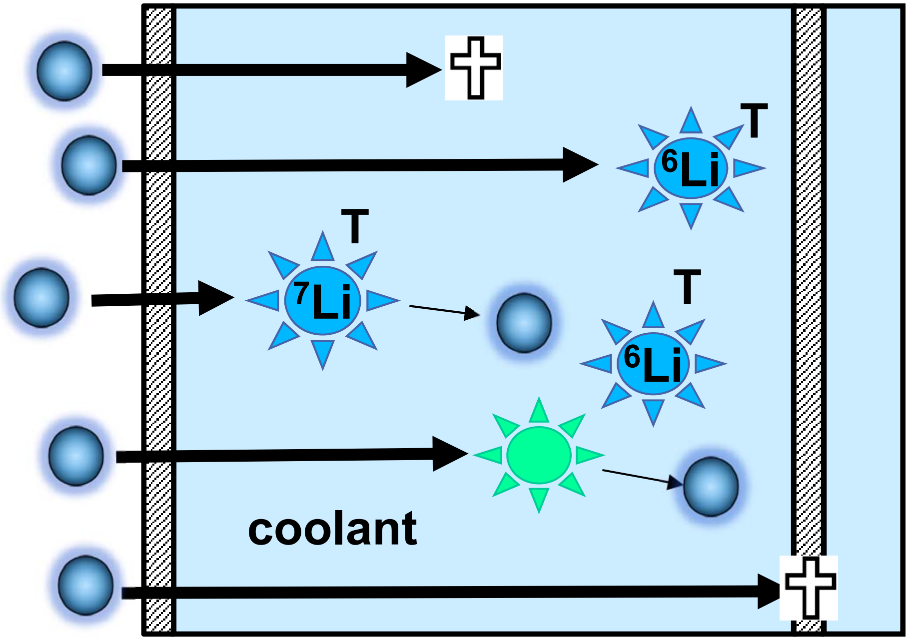
reactor requires

$$TBR = \frac{\text{number of tritons produced per second in blanket}}{\text{number of fusion neutrons produced per second in plasma}} > 1$$

(TBR=Tritium Breeding Ratio ➡Tritium self-sufficency criterion)

Constraints

- only neutron per fusion reaction
- plasma chamber not solely covered by blankets
- structure & functional materials „eat" (absorb) precious neutrons
- some neutrons escape (leakage)
- ➡ **neutron multipliers mandatory**



E_n=14 Mev

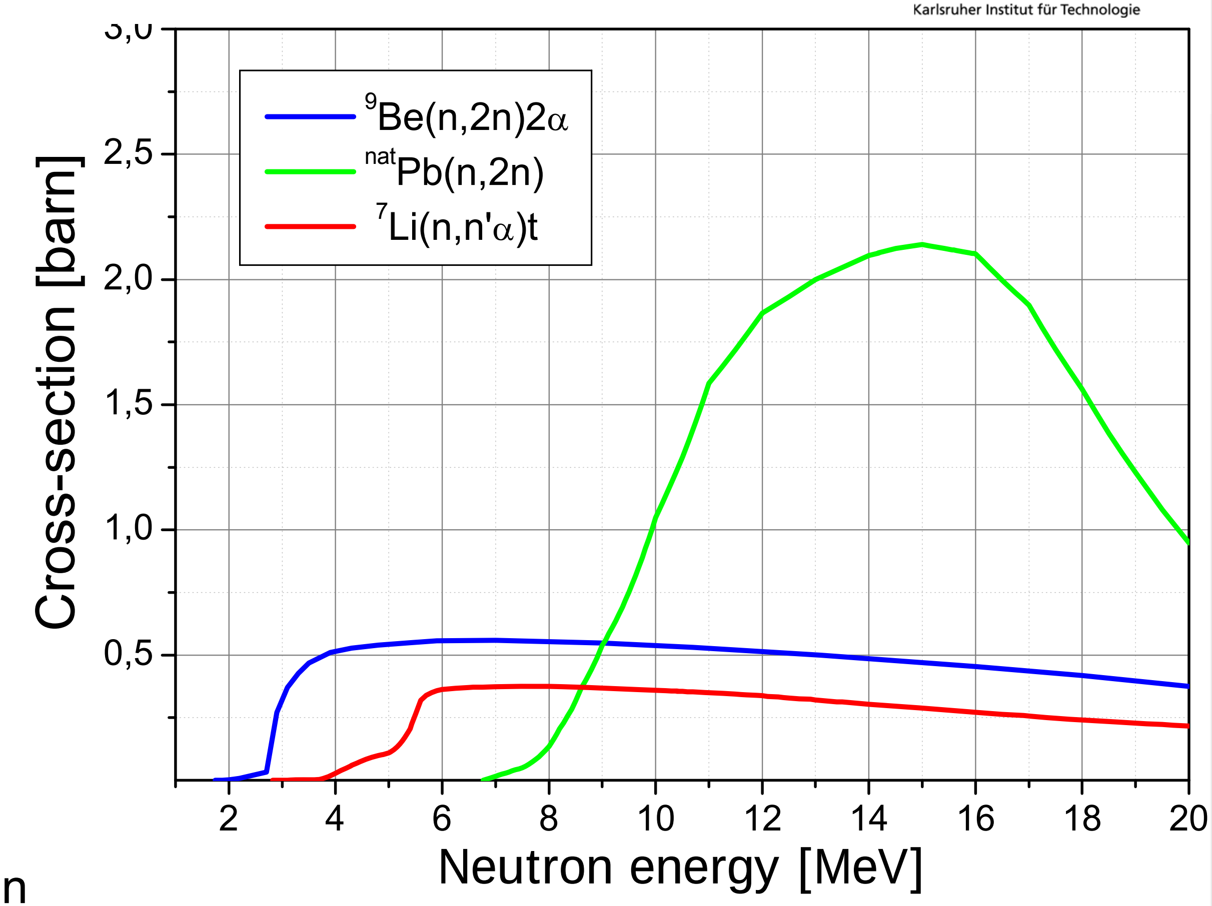
Blanket - Fundamental function- „Breeding“

Neutron multiplication ?

Required (n,2n) reactions
with high σ in
Energy range up to 14MeV

Beryllium (Be)
- low E for (n,2n)
- good moderator (shielding)
- small world ressources
- Be dust toxic

Lead (Pb)
- simultaneous use as coolant
- high availability, low cost
- corrosion with material
- weight
- activation through Po formation



➡ 2 technical blanket options

- Homogeneous - liquid multiplier Pb mixed with Li as eutectic(acting also as coolant !)
- Heterogeneous- solid multiplier and solid breeder

Blanket - Fundamental function- „Cooling“

Power flow in a DEMO

- Fusion Power P_{fus}=3GW
- External heating and current drive
  $P_{H\&CD}$= 50MW(200MW)

Power loads for PFC

(PFC=Plasma-facing components)

- P_n =2.4 GW
- P_{rad}=500MW
- P_{part}=150MW

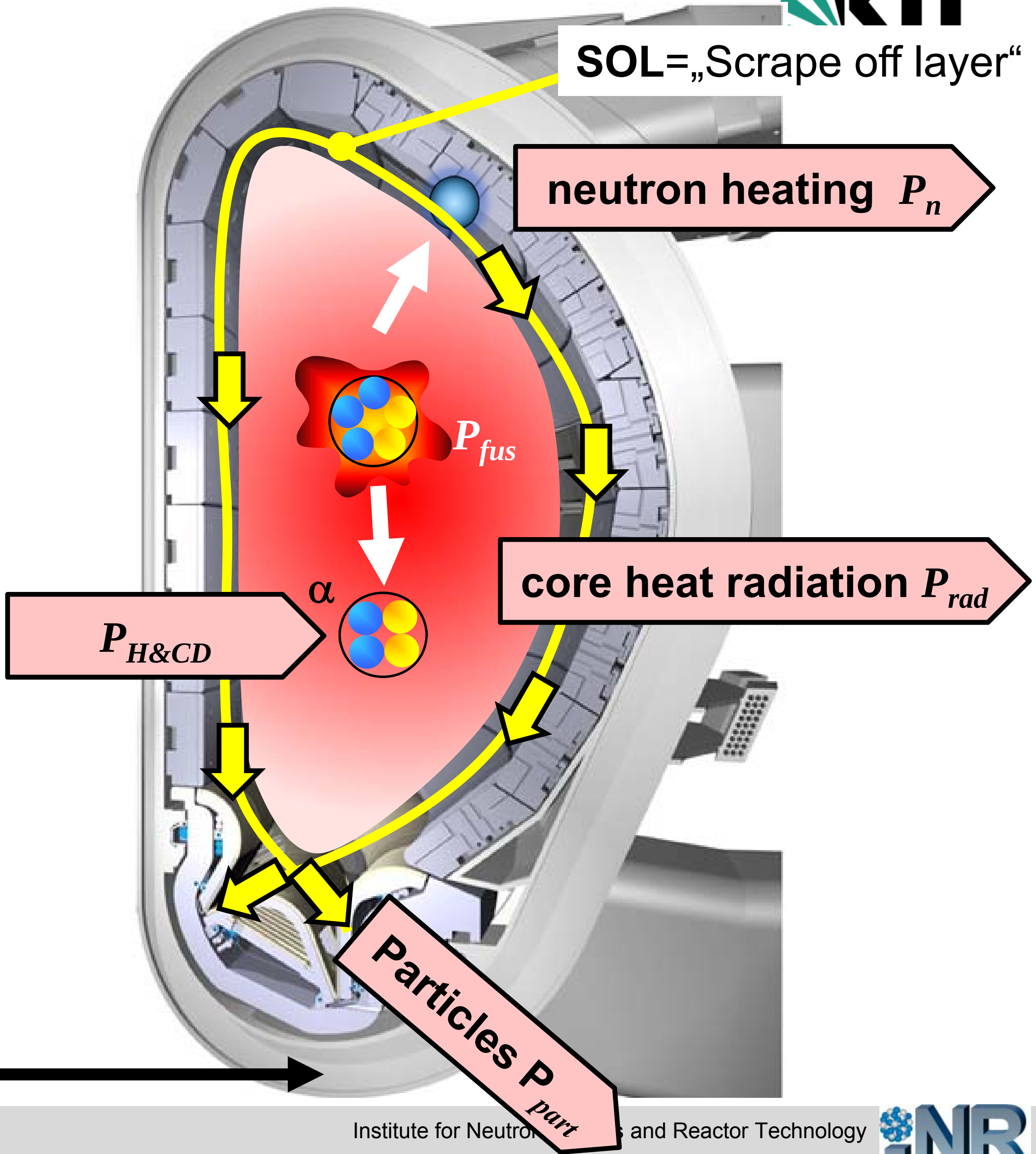
DEMO with R=9m

Blanket Area A=1000m²

- q_n =2.4 MW/m² (mean)
  2.9 MW/m² (max.)
- q_{rad}=0.5MW/m² (mean)

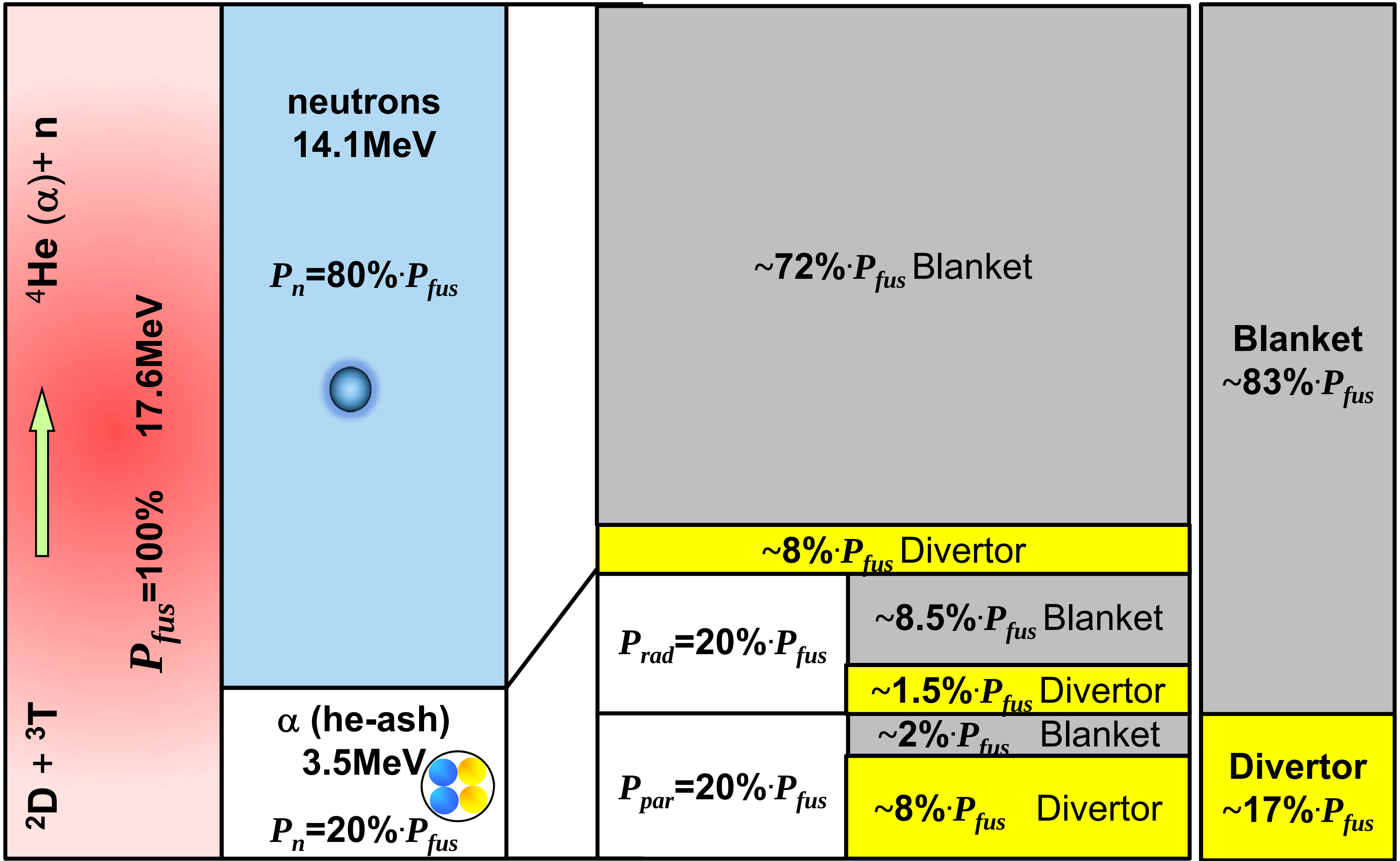
Divertor

- q_{part}=10-(20)MW/m²



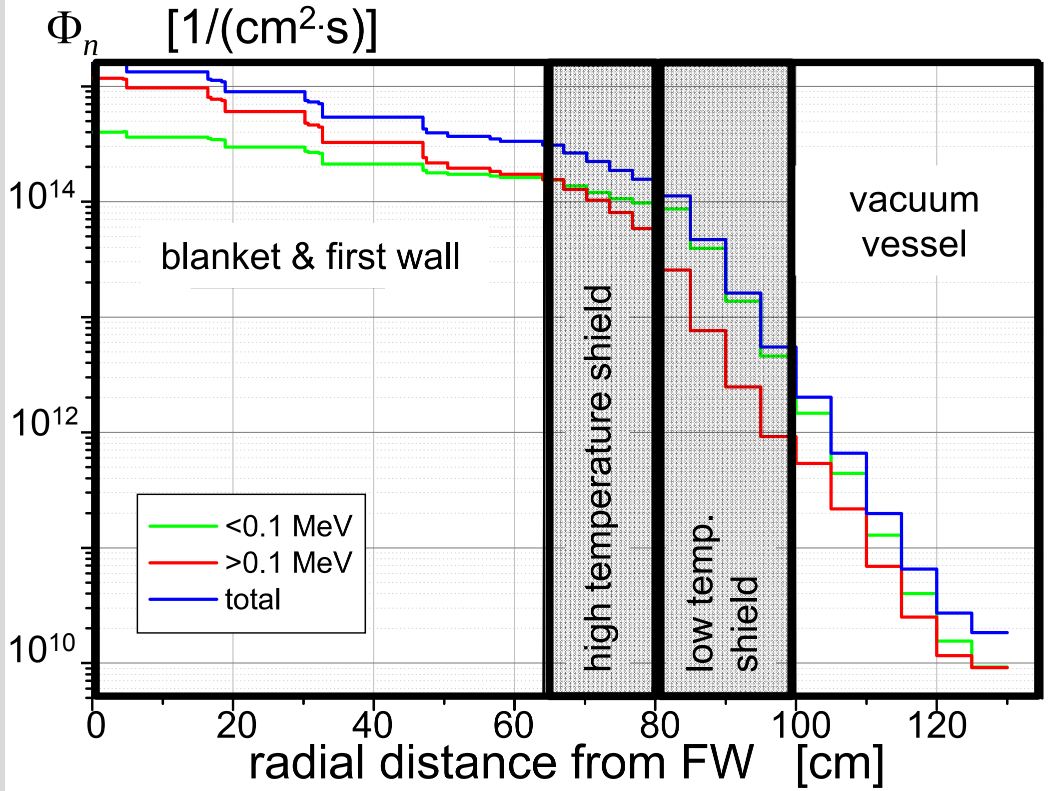
Blanket - Fundamental function- „Cooling“

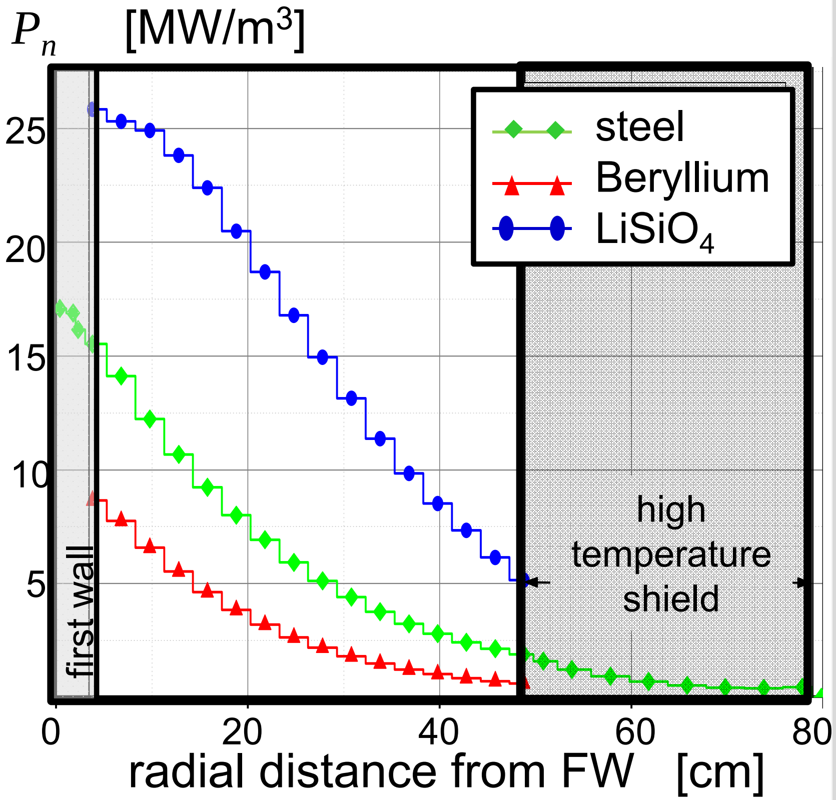
- **Power flow distribution**



Blanket - Fundamental function- „Cooling“

Given Fusion reaction P_{fus} ➡ Φ_n ➡ volumetric heat release





Magnitude Example:

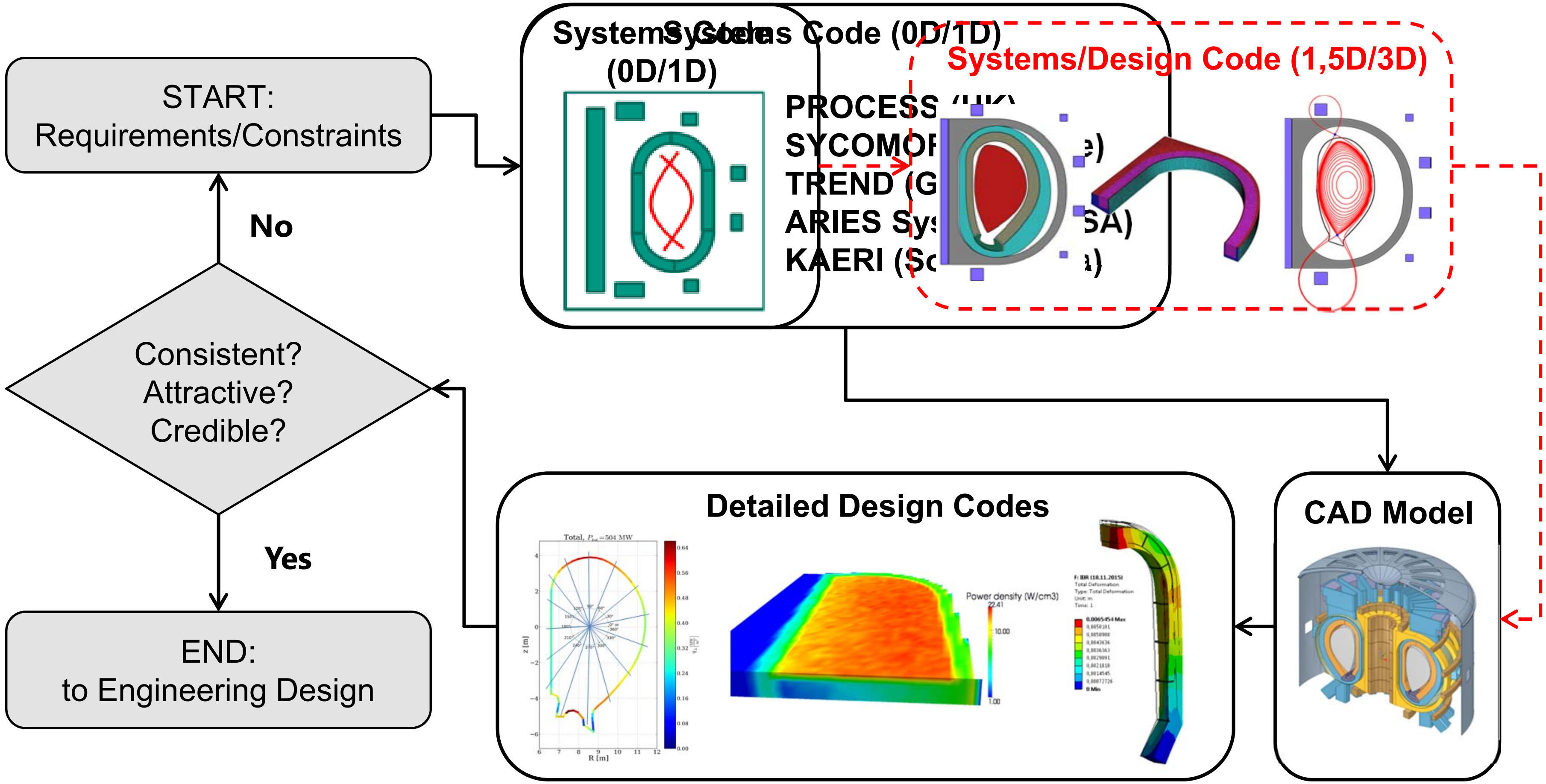
- FW neutron wall load q_n≈2.5 MW/m² ➡ $q_{n,max}$ ≈ 25 MW/m³
  assuming FW wall thickness t=5 mm ➡ $q_{n,max}$ ≈ 0.125 MW/m²
- FW neutron wall load q_n≈2.9 MW/m²:
  assuming blanket radial built of 1m ➡ $q_{n,max}$ ≈ 2.9 MW/m³

$< q_{rad} = 0.5$ [MW/m²]

<100MW/m³ LWR

Blanket – How to design a blanket ?

- General approach: (as done for ITER)



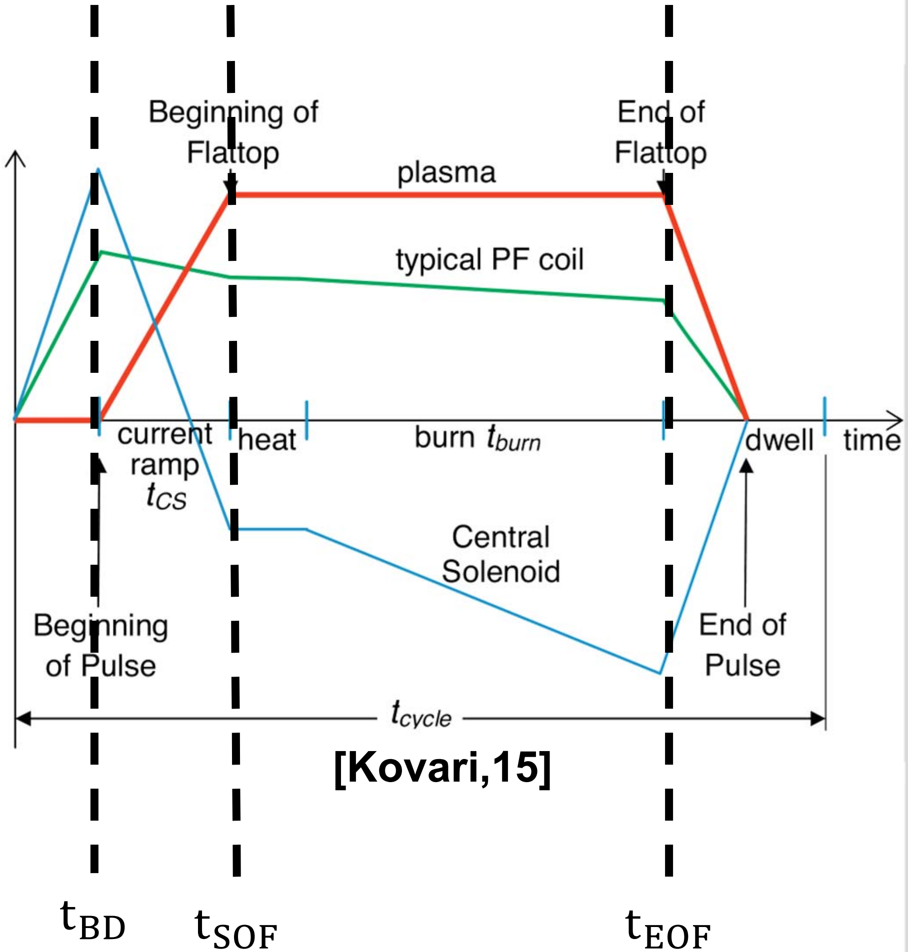
- KIT approach: modular system code (lowest level 1,5D-3D)
- ➡ capability to provide data for safety analysis code

Blanket – How to design a blanket ?

Tokamak major operat. parameters are time dependent

Magnetic Equilibrium and Confinement

- Loop voltage in plasma confining region
  - $U_{loop} = I_p R_p = \frac{\partial \psi_b}{\partial t} \approx \frac{\Psi_{b,SOF} - \Psi_{b,EOF}}{\tau_f}$
- Pre-magnetization phase (t_{BD})
  - $I_p = 0$
  - $\Psi_b = \Psi(t_{BD})$
  - to maximize wrt. limits in coils
- Start of flat-top (t_{SOF})
  - $I_p =$ 100% of nominal current
  - $\Psi_b = \Psi(t_{BD}) - L_i I_p - \Delta\Psi_{res}$
- End of flat-top (t_{EOF})
  - $I_p =$ 100% of nominal current
  - $\Psi_b = \Psi(t_{EOF})$
  - to minimize wrt. limits in coils



➡ **system code capability must exploit enveloping time regime**

Blanket – How to design a blanket ?

- KIT system code logics (EUROFUSION)

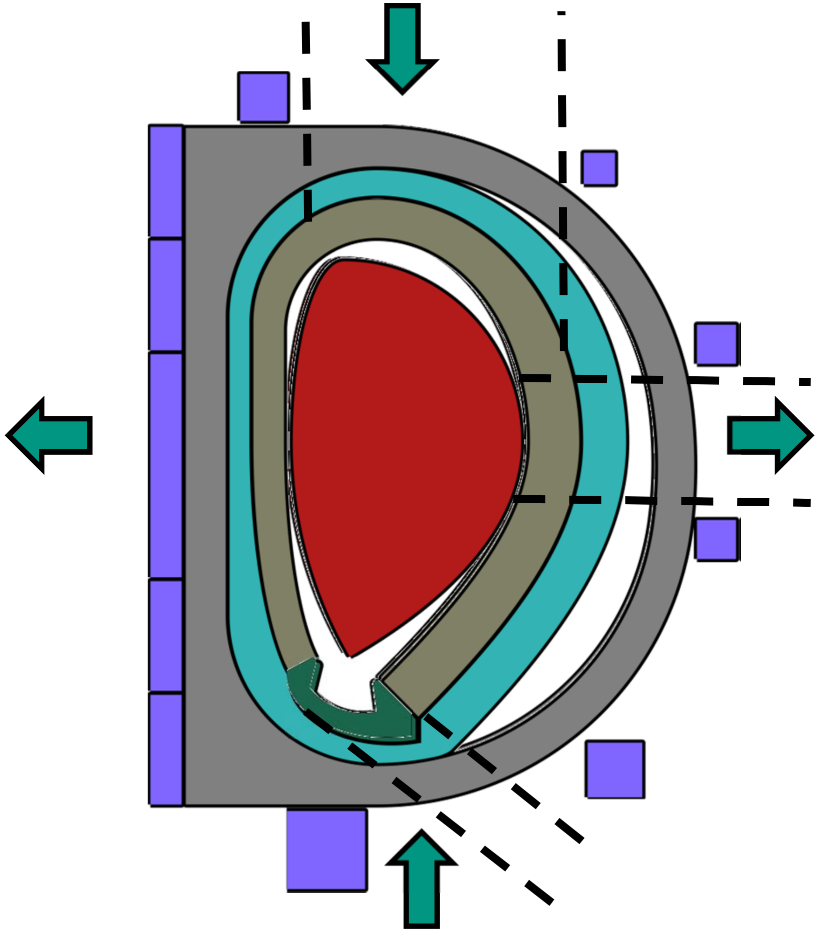
© Franza, 2017

Physics

- Plasma
- Blanket
- Divertor
- Vacuum Vessel
- TF Coil
- PF Coils/CS

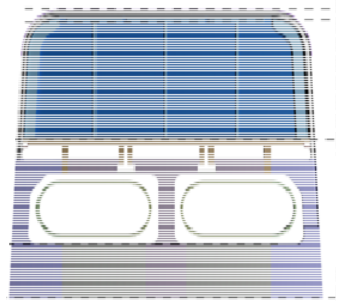
r (cm)

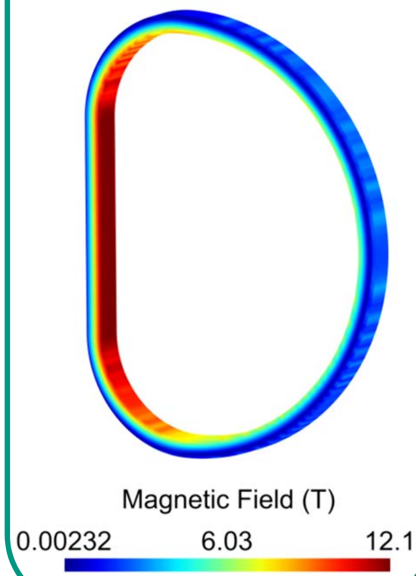
Requirements



Constraints

Technology

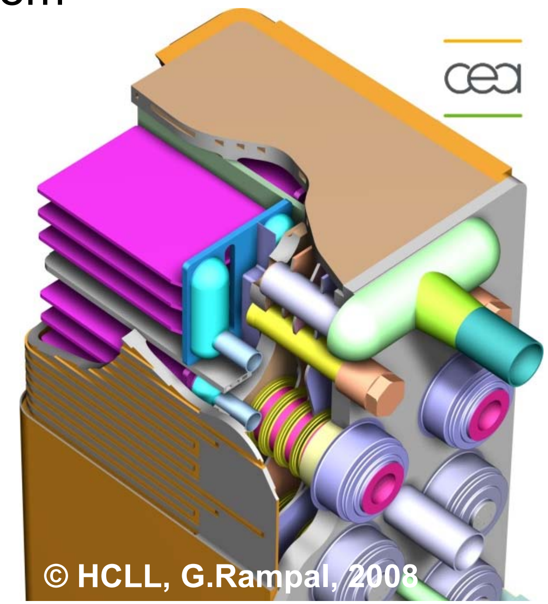




Blanket – Basic functions- „Interfaces“

Interface-functions

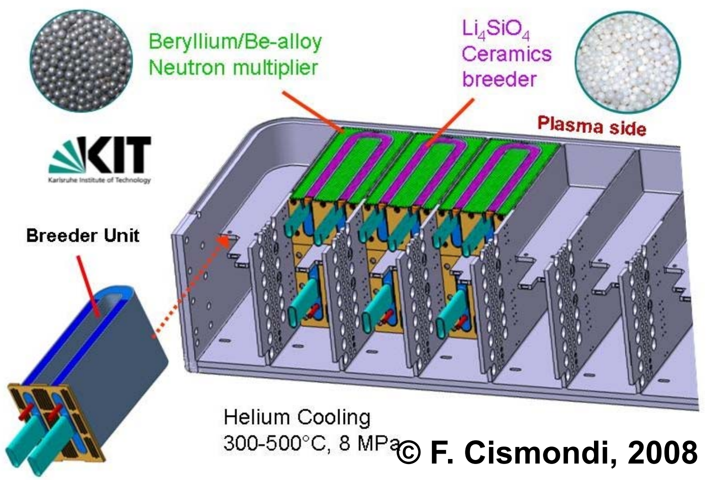
- coolant temp. to operate efficiently Power Conversion System (PCS)
- Fuel extraction (Tritium) from coolant/breeder
- ISI&R and maintenance/(dis-)assembling



Mainly two blanket lines existent

- ***Liquid Metal Blanket (homogeneous blanket)***
  - Lithium metal (with or without ^{6}Li-enrichment)
  - Pb-Li eutectic alloy (high ^{6}Li-enrichment required)
  - self-cooled/cooled by He or water (or combination)
  - large blanket thickness (≈ 60 – 80 cm)
  - ➡ Helium Cooled Lithium Lead (HCLL)
- *Solid breeder blanket with neutron multiplier*

- Beryllium neutron multiplier
- beramic breeder materials: Li_4SiO_4, Li_2TiO_3 , Li_2O
- only small blanket thickness needed (≈30–50 cm)
- Be/breeder configuration subject to optimisation
- ➡ Helium Cooled Pebble Bed (HCPB) blanket



Blanket – Basic functions- „Interface➡PCS"

Requirement: sufficient PCS coolant temperature for high efficiency η_{th}

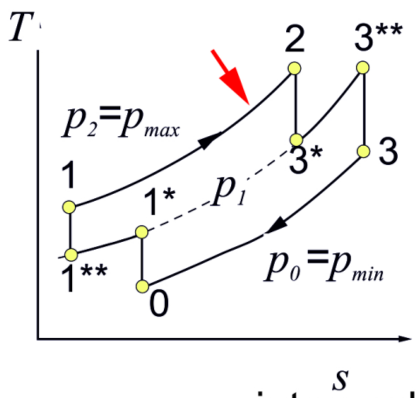
PCS Types

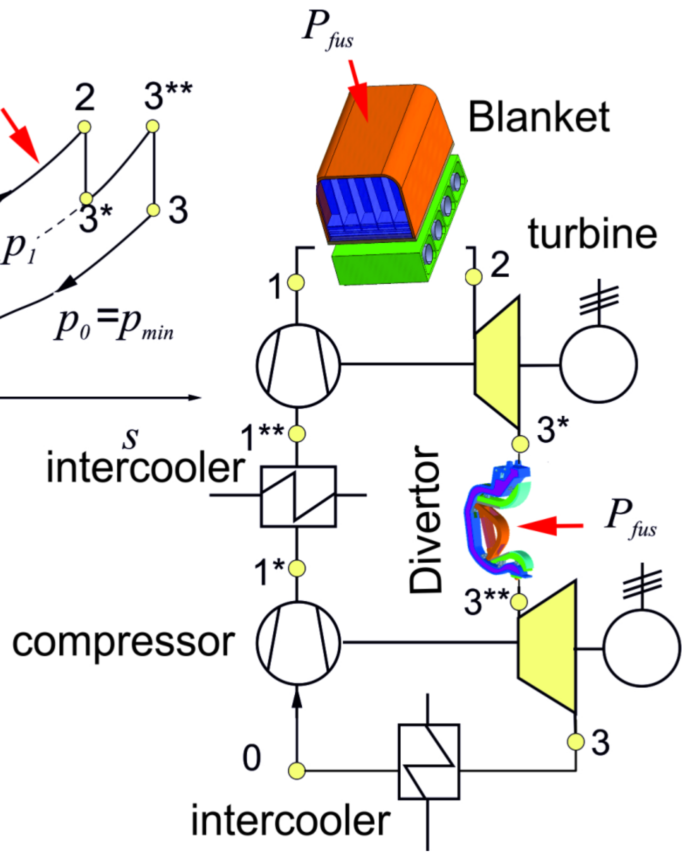
- Joule-Brayton (Gas turbine cycle)
- Clausius-Rankine (steam turbine)

Joule-Brayton -Process

- use of inert He
- demand for high η_{th} temperatures >700°C
- ➡ high material challenges
- ➡ high pumping power ≈8-10%· P_{fus}

- For efficiencies η_{th} >40% staggered heating required to maintain in acceptable stress and performance limits of components
  - Stage 1 300-480°C
  - Stage 2 480-620°C
  - Stage 3 480-700°C
  - Stage 4 700-800°C





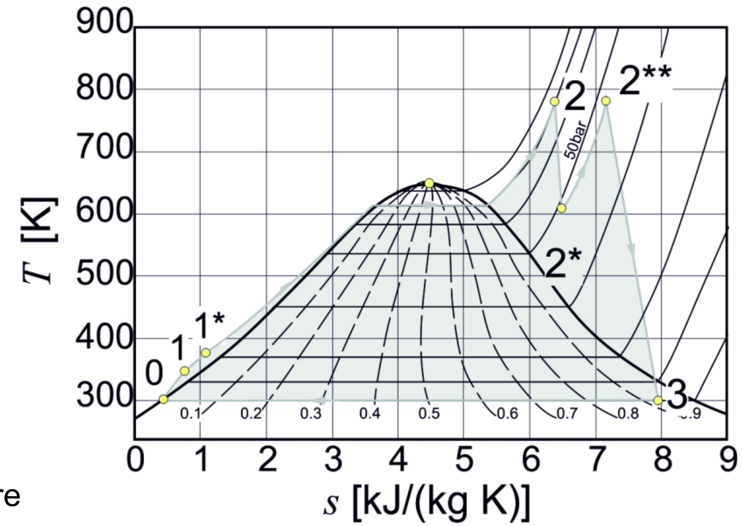
1432MW Blanket (He)
335MW Divertor
1976MW Blanket (PbLi)
248MW Divertor
HCLL Blanket, DEMO
*G. DuBois, Belgatom 2002

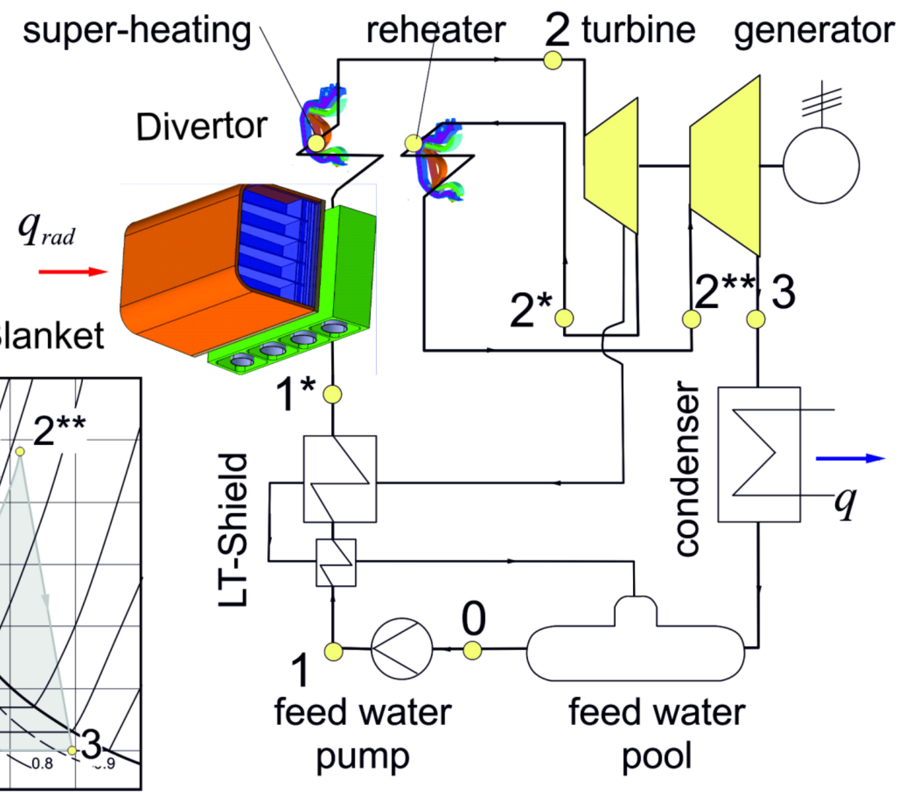
Blanket – Basic functions- „Interface➡PCS“

Clausius- Rankine Process

- lower mean average temperature
- but multi-stage required
- operation threshold higher than advanced PWR

P_{fus} DEMO*	4050 MW
$P_{el,net}$	1500 MW
Plant efficiency, $P_{el,net} / P_{fus}$	37 %
P_{pumps}	40 MW
η_{th}	42 %

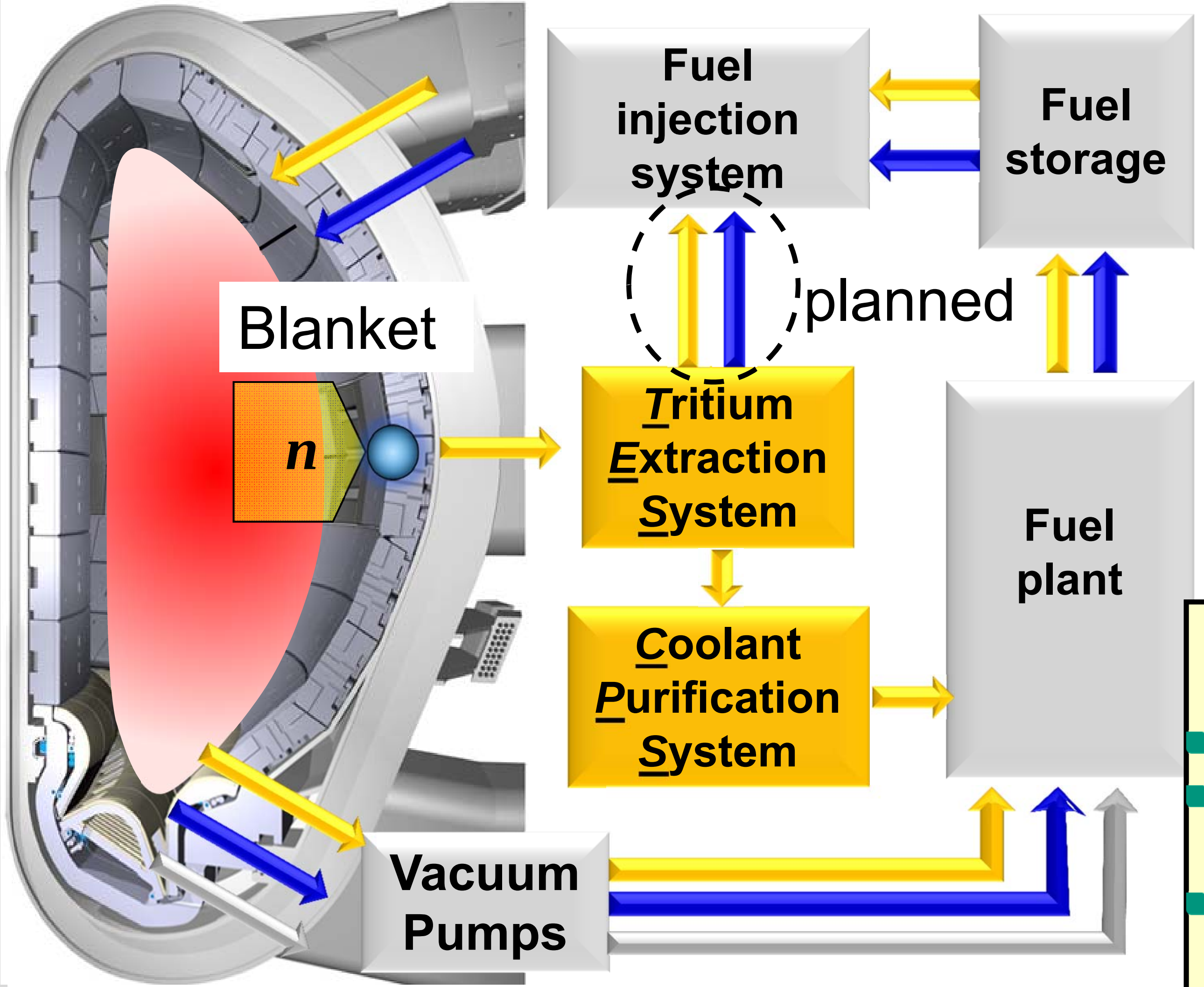




* Boccaccini, 2012, lecture

Blanket – Basic functions- Interface➡tritium plant"

- Blanket= central tritium source for reactor fuel cycle



Required for DEMO
(1GW$_{el}$)-self-sustainability
- T =380-410 g/day
- D = 270g/day

Radiation protection limit
- T =270mg/day losses to environment

Blanket - Basic functions- „Interface➡tritium plant“

- **Tritium management = coolant dependent ***

Potential coolants

- Water
- Helium
- Liquid metal (PbLi, Li)
- Molten salt (FLiBe)
- ➡ all pose engineering challenges (R&D)

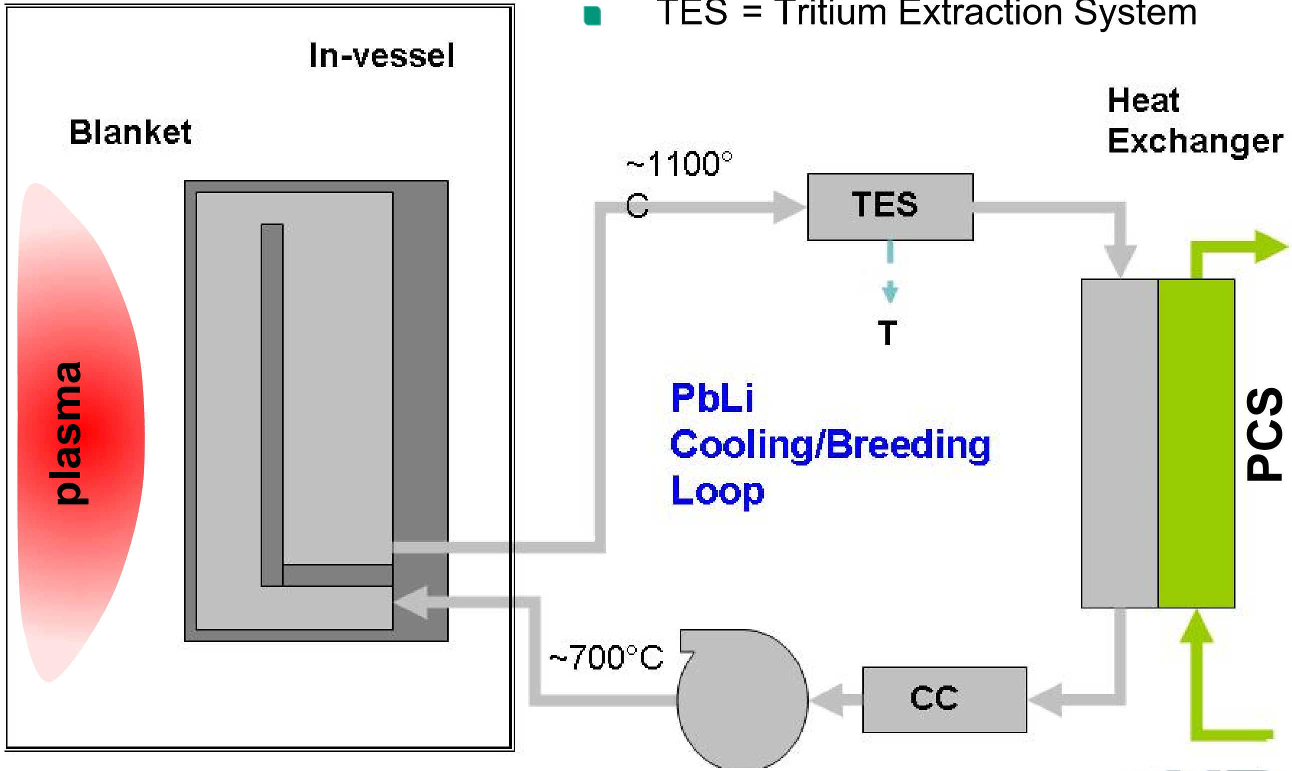
- **Self-cooled-Blanket (ARIES-AT)**

(homogeneous blanket)

„the simplest case“

structure material	SiC/SiC_f
coolant	PbLi
multiplier	Pb
breeder	Li
T-extraction	PbLi

- PCS = Power conversion System
- CC = Coolant Chemistry Control
- TES = Tritium Extraction System



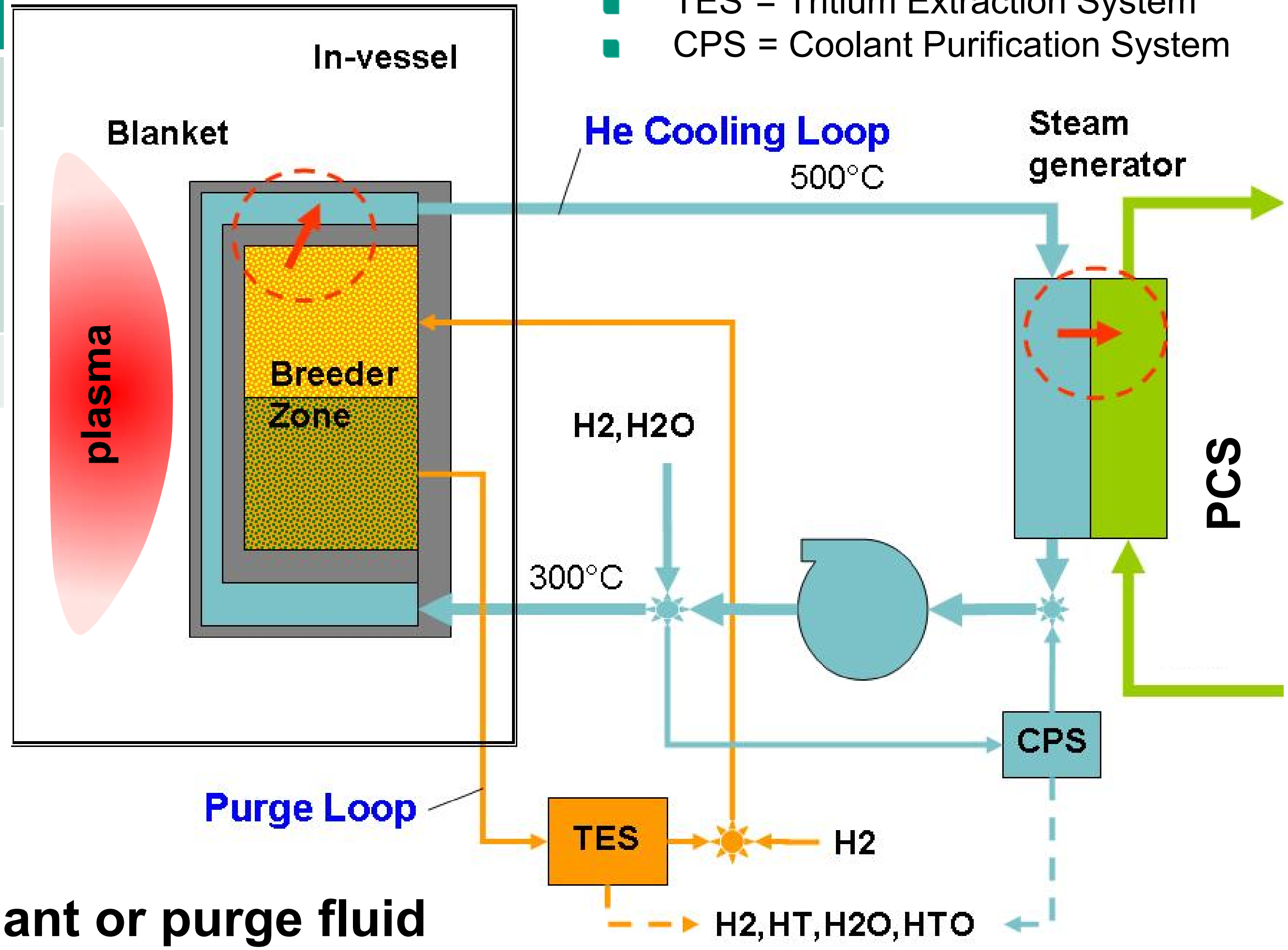
Institute for Neutron Physics and Reactor Technology

Blanket - Basic functions- „Interface➡tritium plant“

- **Helium Cooled Pebble Bed Blanket (HCPB) (heterogeneous blanket)**

structure material	EUROFER
coolant	He
multiplier	Be
breeder	Li_2SiO_4, Li_2TiO_3
T-extraction	He

- PCS = Power conversion System
- CC = Coolant Chemistry Control
- TES = Tritium Extraction System
- CPS = Coolant Purification System

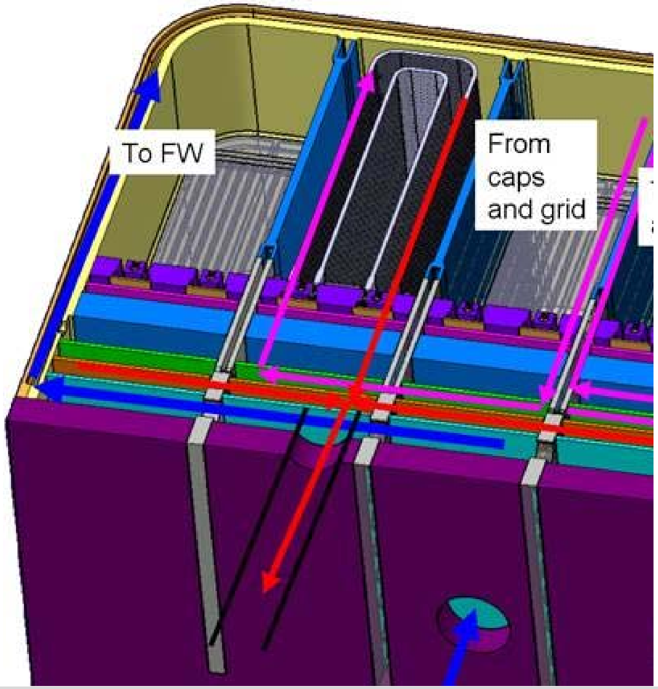


➡ **T-transfer by coolant or purge fluid**

Blanket – Basic design - „Structures“

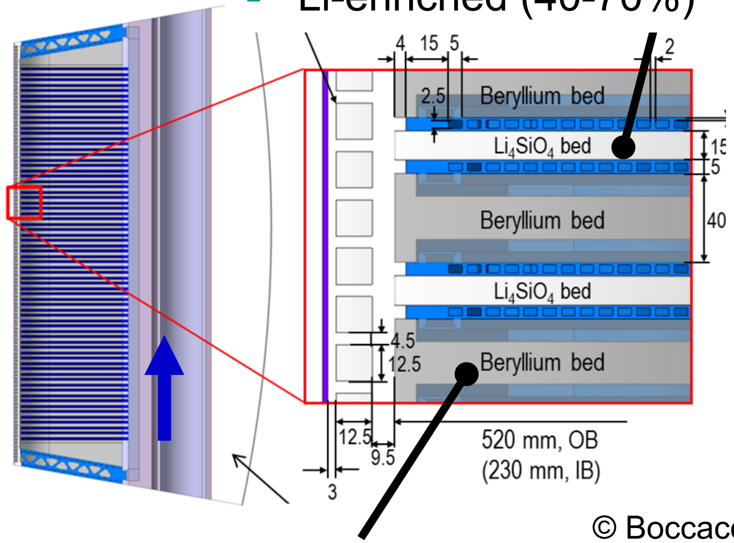
Fundamental design – HCPB blanket

- coolant/breeder/multiplier arrangement
- in structural material,
- which can be mounted/disassembled
- at given nominal boundary and sustaining design extension conditions
- and finally reasonable reliable fabricated



Ceramic breeder

- pebble bed 64% packing factor
- d=0.2-0.6mm
- ^{6}Li-enriched (40-70%)



Be-multiplier

- pebble bed 64% packing factor
- d=1mm

Design aspects

- modular breeder units ➡mass fabrication
- robust simple modules ➡pressure resistant
- central feeder /collector units reduced replacements efforts

HCPB

Blanket – Basic design - „Verification“

HCPB

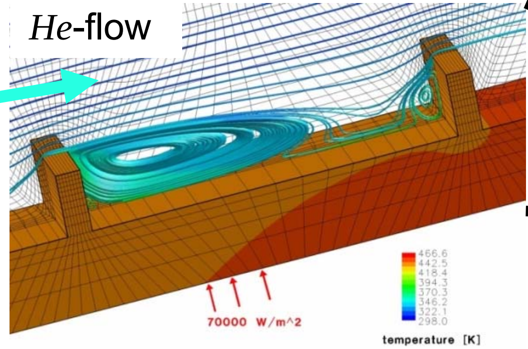
Now computations may start

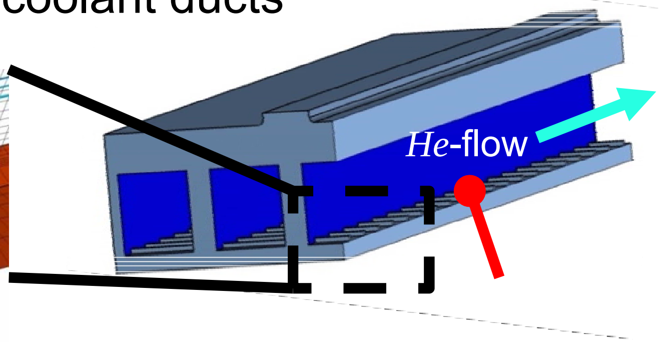
- Thermal-hydraulics
- Thermo-mechanics
- Transient behavior

Example HCPB blanket

improved FW-Cooling

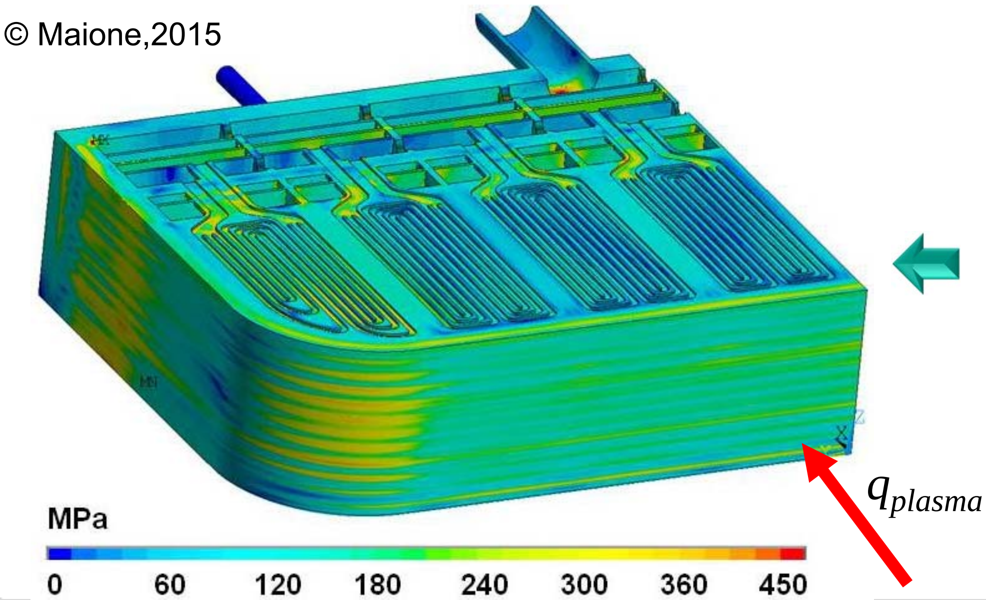
- structuring of coolant ducts



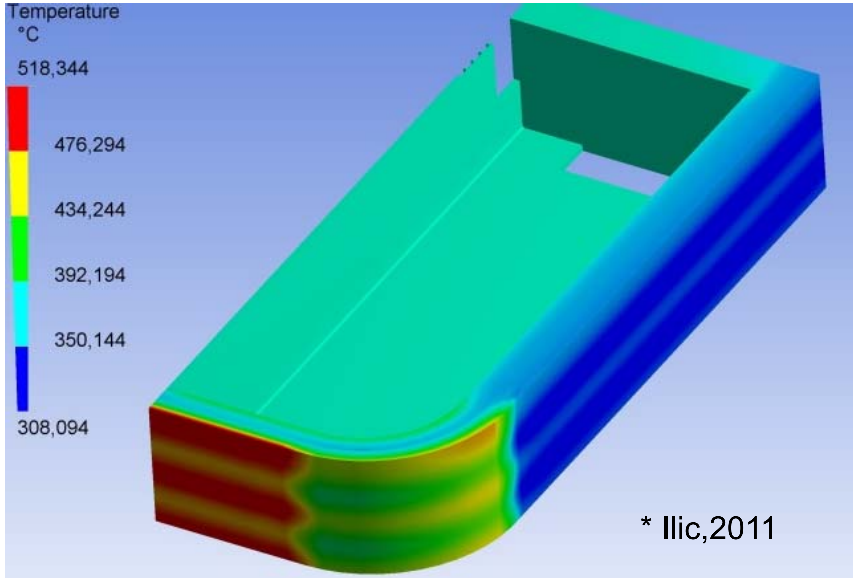


stress distribution

© Maione,2015



temperature distribution

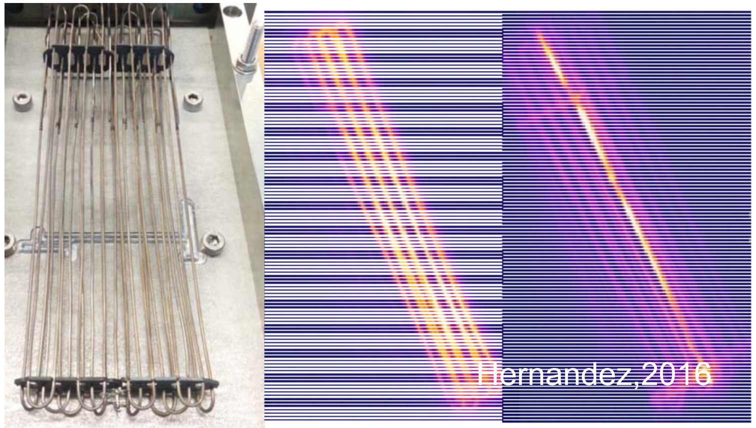


* Ilic,2011

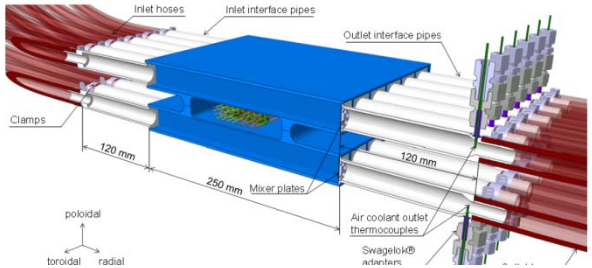
Blanket – Basic design - „Validation“

Heat transfer validation in pebble beds
@ prototypical conds

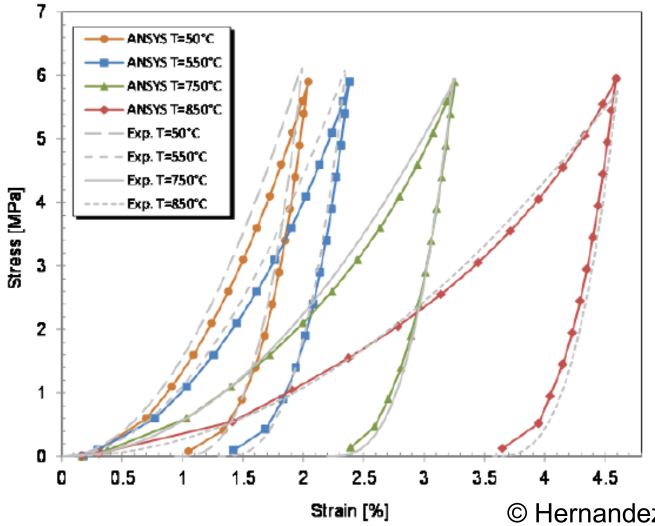
- mimicing different volumetric heat sources (independent heaters, TC instrumentation)



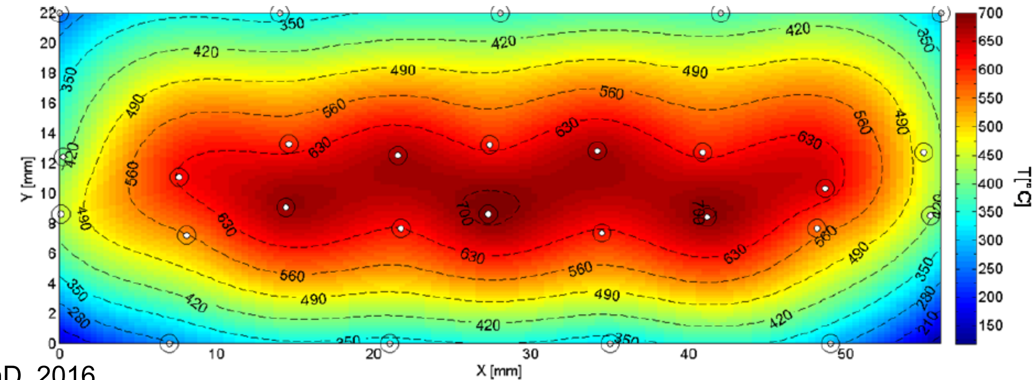
- flexible coolant provision (start-up/shut down, accidental conds., nominal operation)



- accountance for temperature dependence of stress/strain behaviour of pebble beds



➡ **validated computational model for steady state**



© Hernandez, PhD, 2016

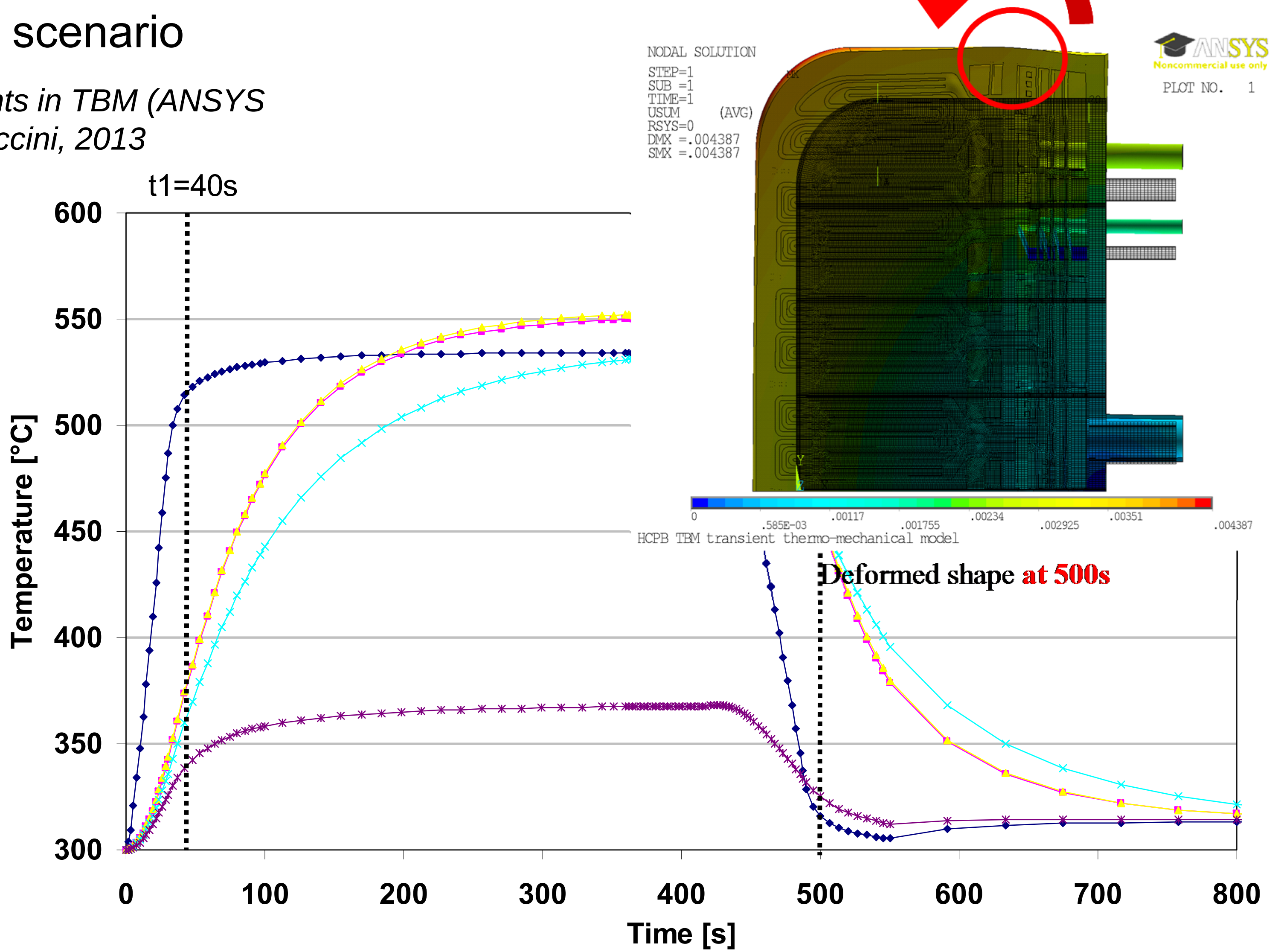
Blanket – Basic design - „Verification“

HCPB

Transients

- ITER typical scenario

Temperature transients in TBM (ANSYS Calculations), Boccaccini, 2013



Blanket – Basic design - „Fabrication “

HCPB

Karlsruher Institut für Technologie

How to fabricate modules ?

- First wall
- coolant ducts,
- breeder units and
- multiplier pebble beds

Example HCPB blanket

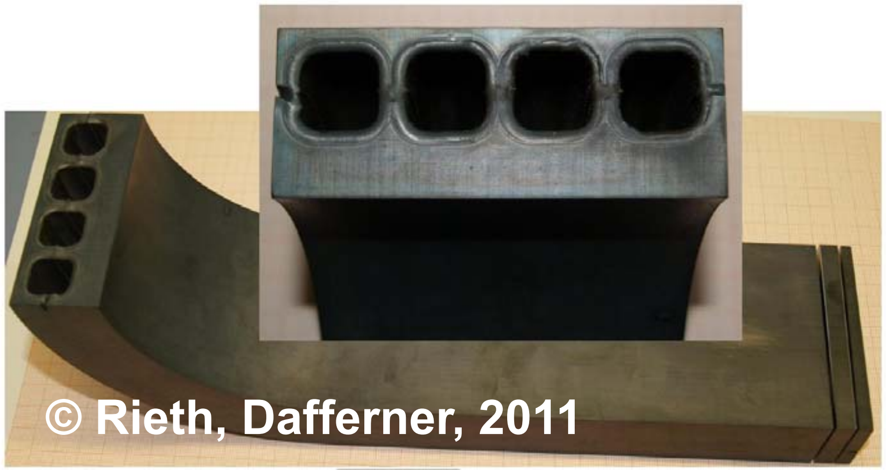
First wall coolant ducts

- prefabricated
- hot isostatic presses and
- bend

© Rey, 2012, half plate FW

Alternative route FW coolant ducts

- prefabricated hipped sandwich
- square channel
- EB to seal



© Rieth, Dafferner, 2011

© Full scale FW- mock-up

Blanket – Basic design - „Fabrication “

HCPB

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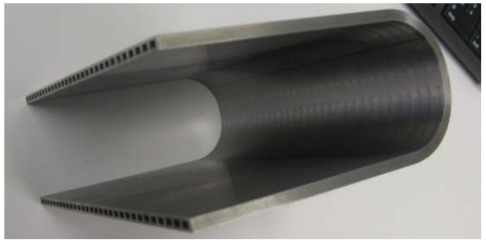
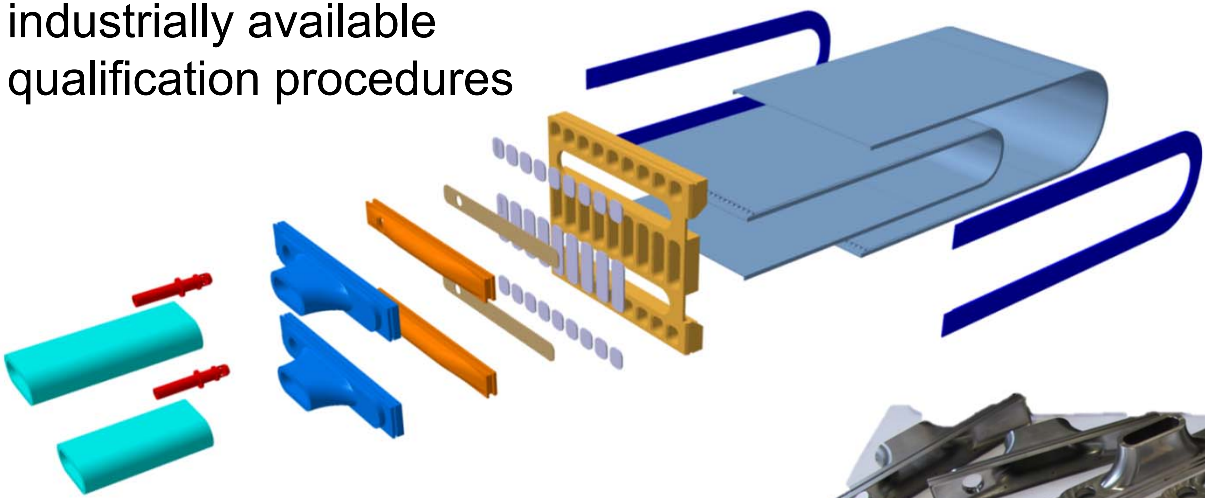
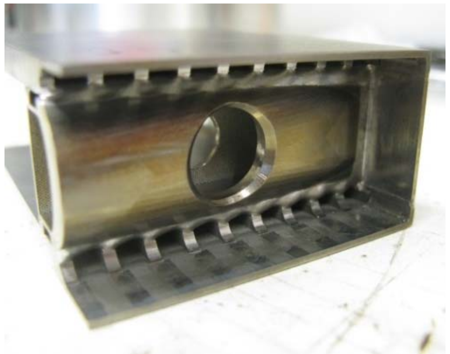
Breeder units

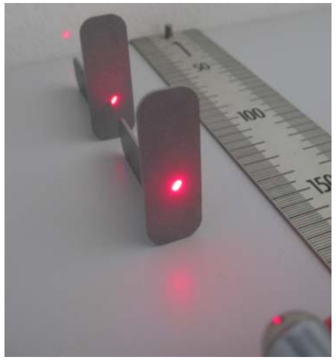
- simple parts
- automatized fabrication and joining processes
- industrially available qualification procedures



Boccaccini, Rey , 2012



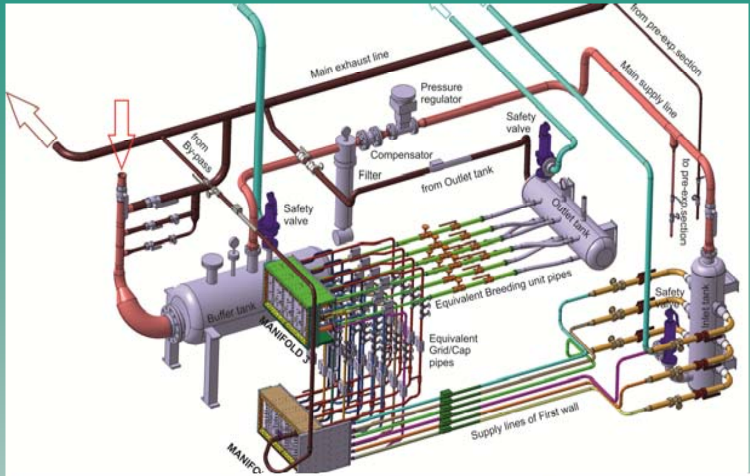


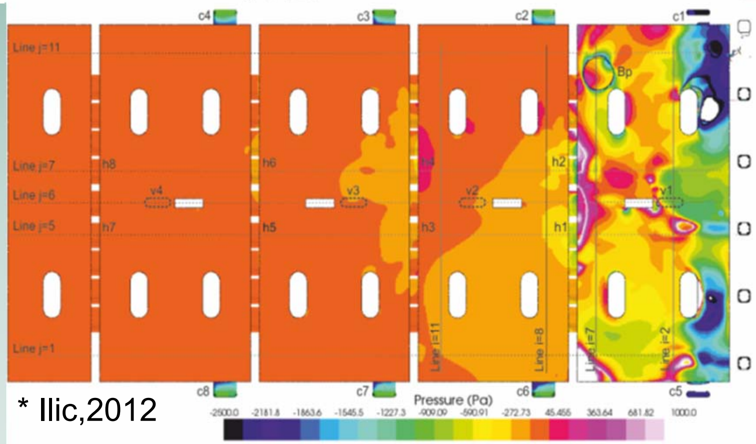


Blanket –Design - „Validation“

HCPB

Blanket hydraulics manifold/distributor (GRICAMAN)

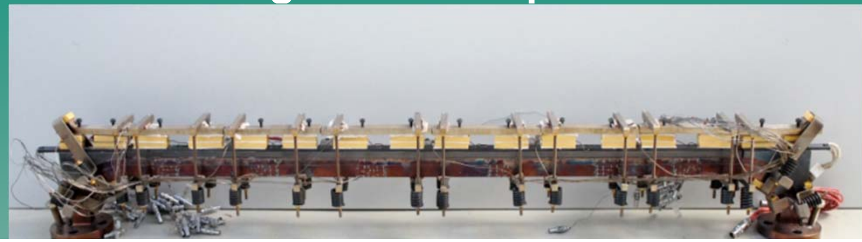


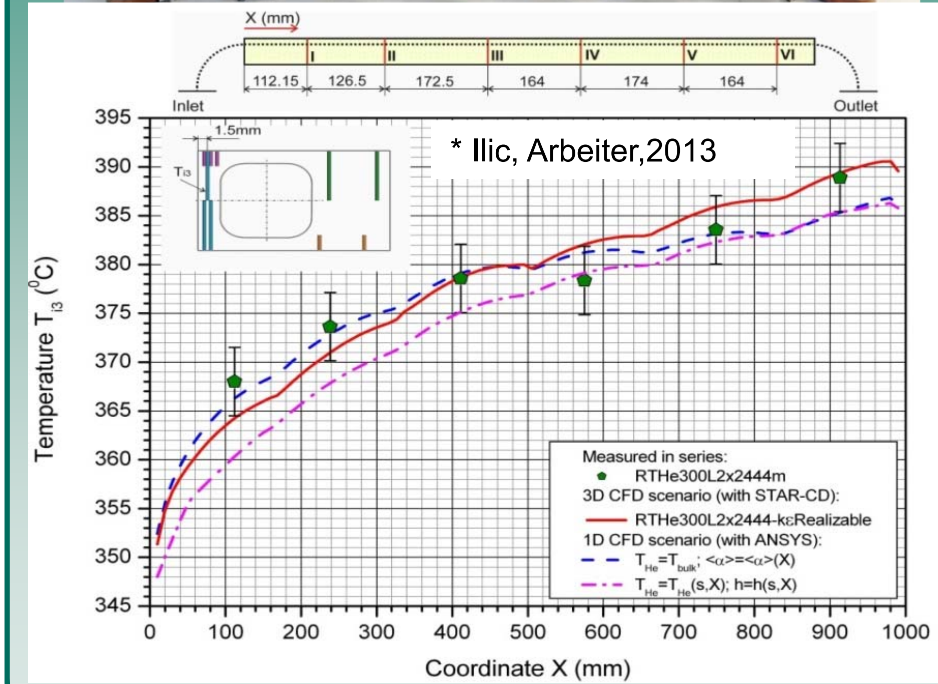


* Ilic,2012

Flow distribution of TBM manifold system simulated and verified against experiment in 1:1 fabricated mock-ups

Heat transfer of the first wall cooling: HETRA experiment





Heat transfer in first wall channel tested in 80bar helium loop at 270kW/m². CFD models validated against experiments.

Blanket –Design - „Validation“

HCPB

He- infrastructures to allow for prototypical scale testing

- HELOKA-HP (KIT, figures below), p=10MPa, m=2.4kg/s, T≈500°C
- HEFUS(ENEA) p=8MPa, m=0.35kg/s, T≈530°C
- KATHELO (KIT), p=10MPa, m=0.25kg/s, T≈850°C

- TBM FW experiments
- 30m³ vacuum chamber
- IR radiation heaters (➡W/m²)

- 1:1 TBM exp., divertor exp. (10-20MW/m²)
- 30m³ vacuum chamber
- electron Beam Gun 800kW

Blanket – Final design - „Integration“

Requirements for a FPP

- Life-time 40-60years
- Reliability >80%

\+ decommisioning, repository, …

Limiting component factors:

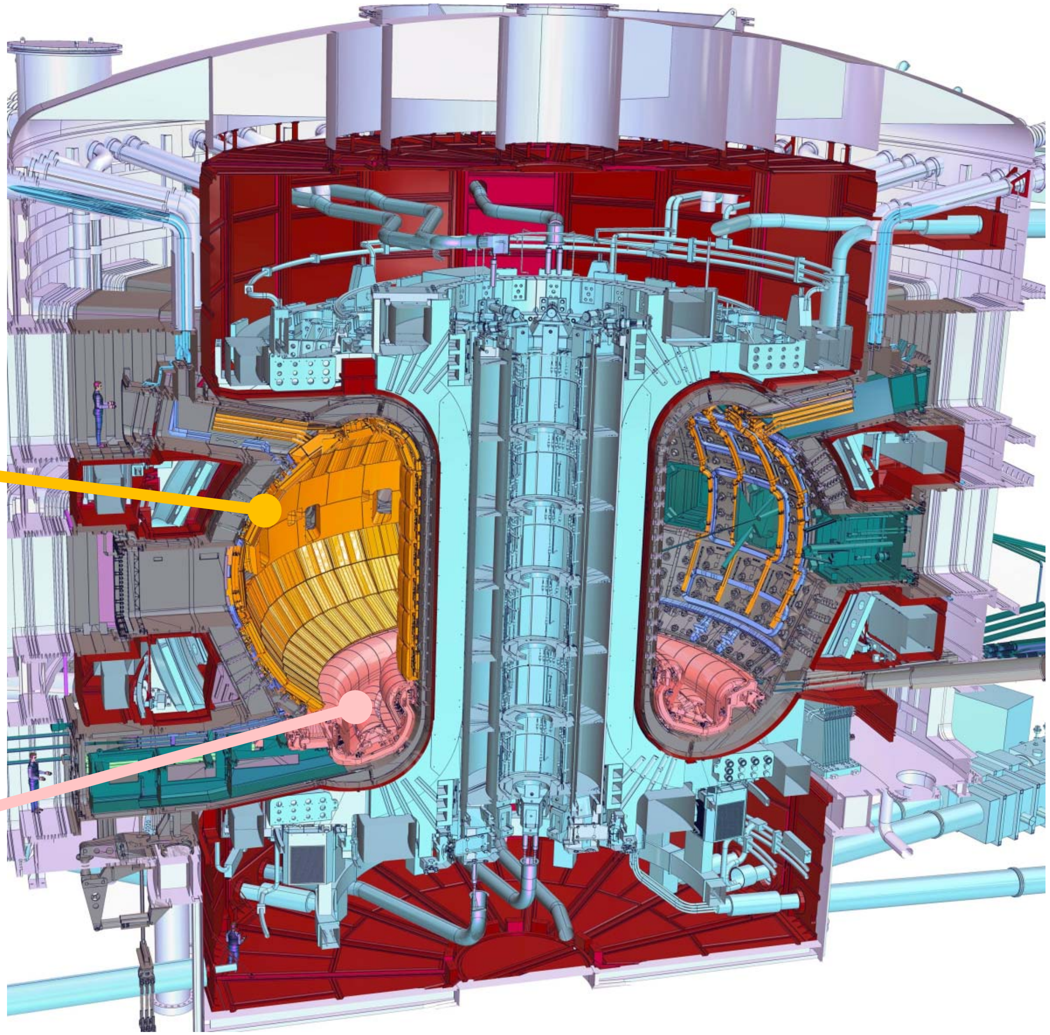
- Plasma facing components
- accumulated dose
- fatigue, creep,…..

Blanket

- mat. damage 100-150dpa
- 400appm/y He in mat
- activation limits
- ➡ remote handling, transfer
- ➡ life-time 3-5years

Divertor

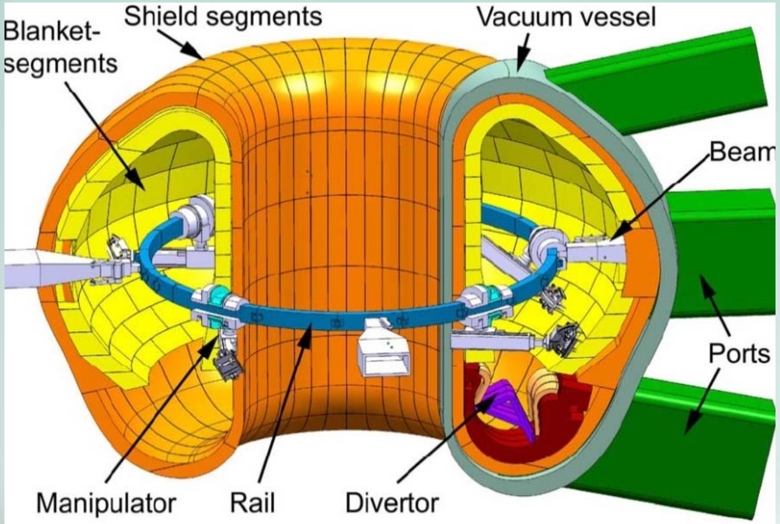
- mat. damage 15-30dpa
- fatigue 10-20MW/m^2
- ➡ remote extraction
- ➡ life-time 1.5-2.5years



Blanket – Final design - „Integration“

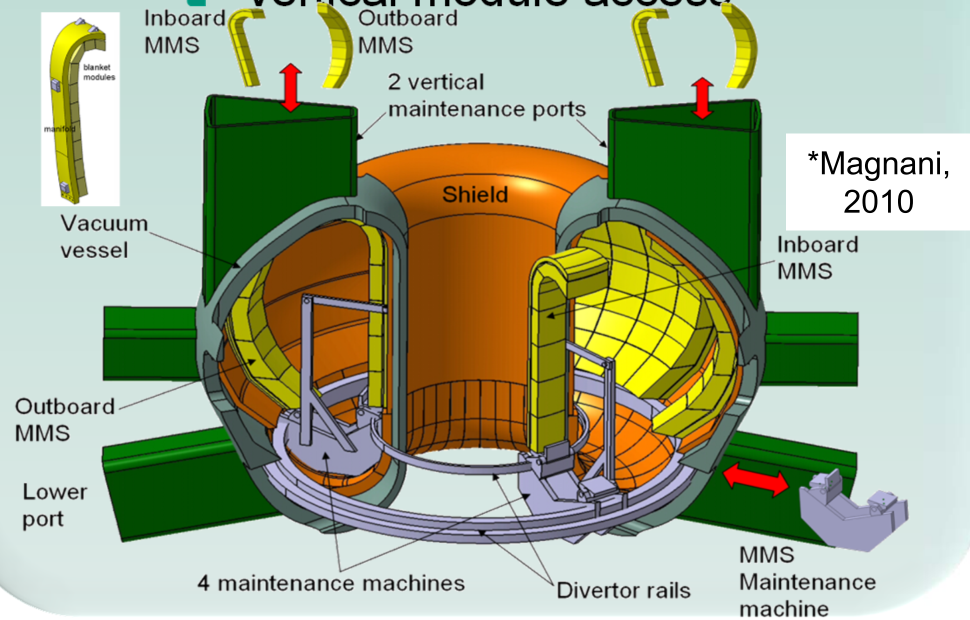
ITER configuration

- water-cooled main structure
- 6 test blankets @ three ports



DEMO Multi-Module-Segment

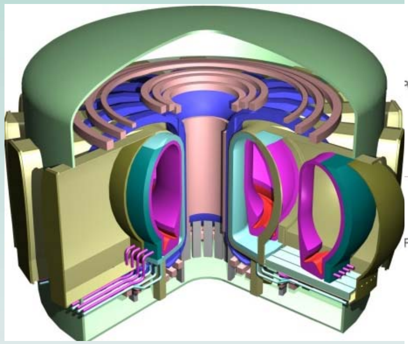
- rail based maintenance
- vertical module access

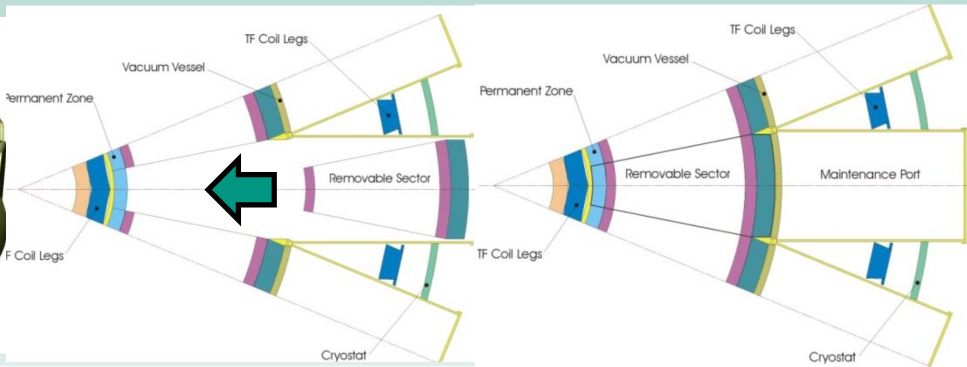


DEMO: Large sector concept

- horizontal access
- horizontal seeming
- vacuum vessel no static containment

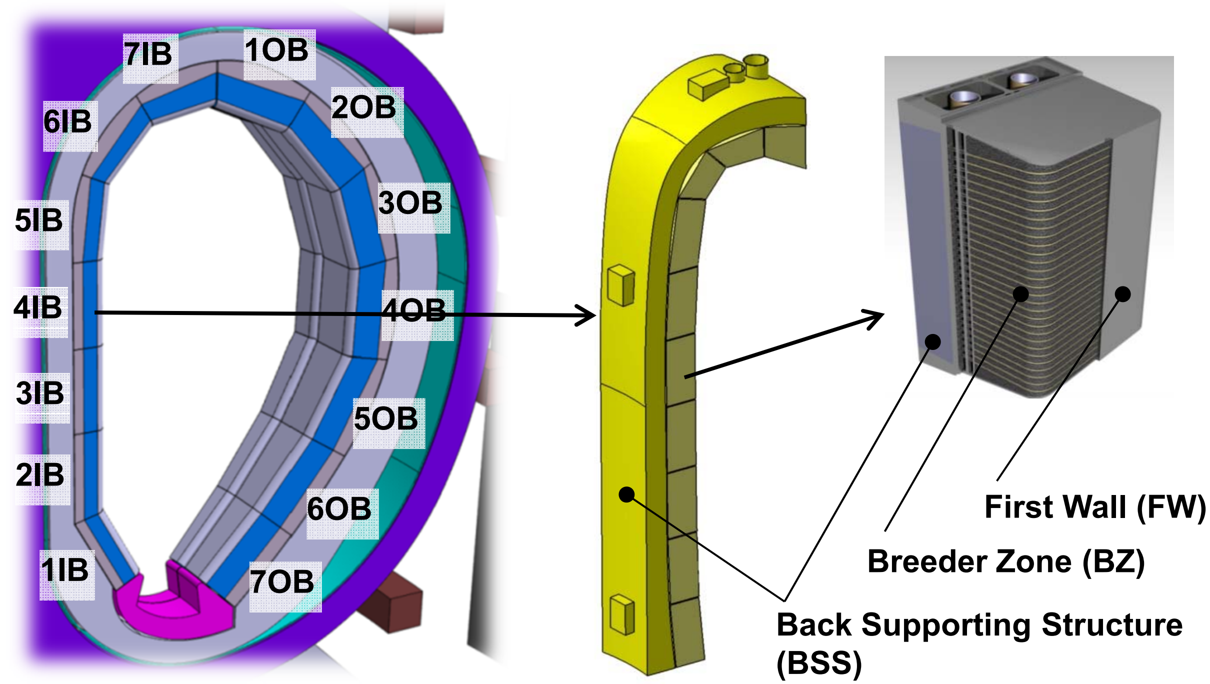
ARIES, US-study



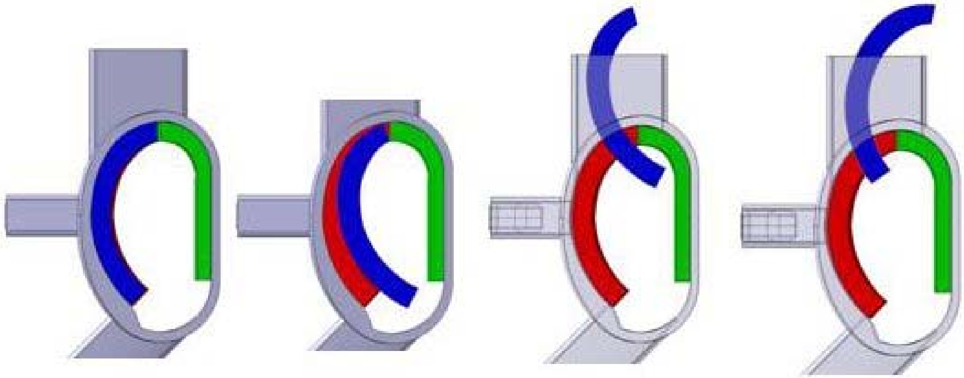


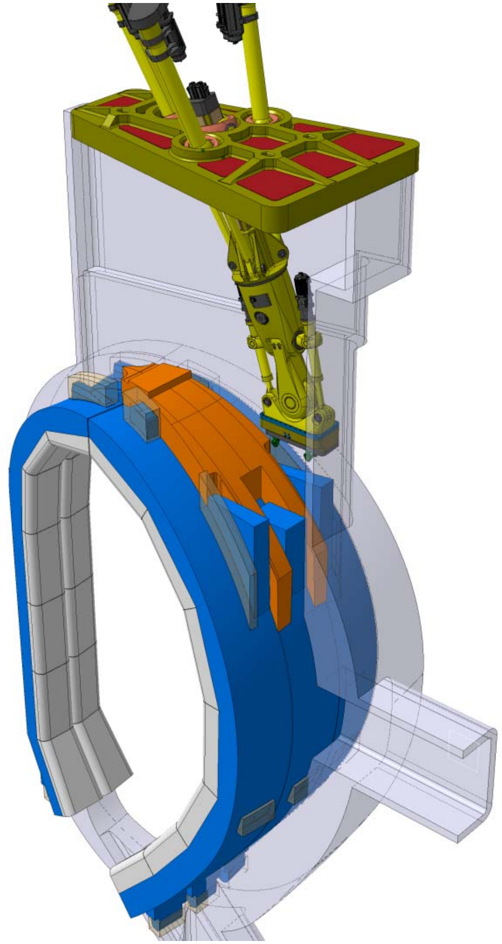
Reactor integration and maintenance

Set-Up: 18 sectors, 3 outboard (OB) and 2 inboard (IB) vertical segments per sector for a total of 90 segments.



Blanket Sector Blanket Segment Blanket Module





Vertical maintenance concept: OB segment removal

Loving et al, Fus. Eng. and Des. 89,2014

Fusion power plant (FPP) safety

Safety objectives = Prevention of radiological hazards

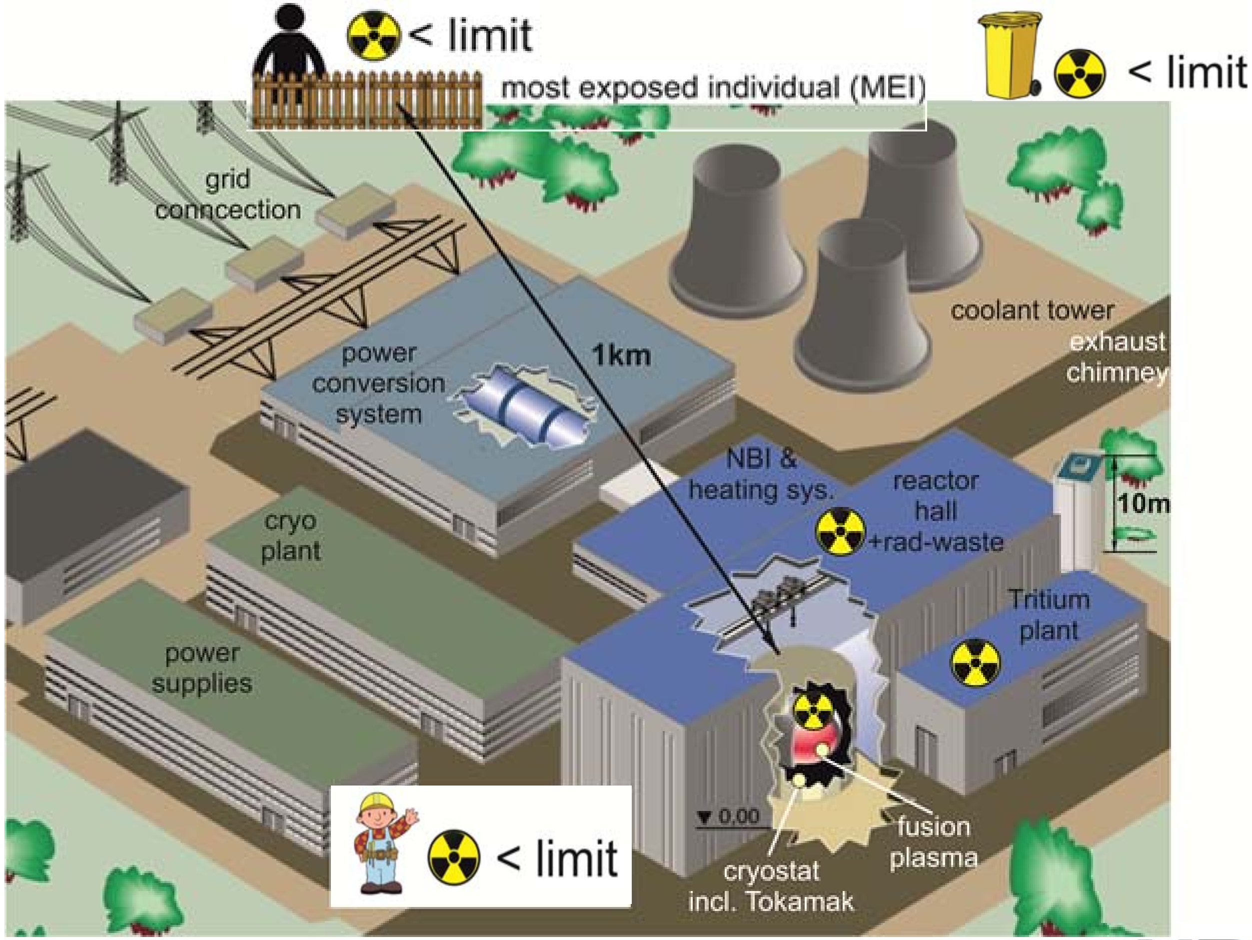
- General public & environment
- Plant workers (ALARA-principle)
- Radioactive waste / deposal volume (ALARA)

Means to realize

1. design & licensing requirements
2. integrated safety analyses / source terms / models & codes
3. radioactive waste management

➡ ***all 3 pillars part of KIT contribution to EUROfusion - WPSAE***

Plant layout of a FPP



FPP Safety Approach

- Participation in definition and formulation of requirements / standards ➡ 1

- Application & development of numerical tools for safety analyses
- Verification & validation of numerical tools
- Development and qualification of processes & procedures

} ➡ 2

- Elaboration of material encyclopedia
- Purification of solid / liquid waste (detritiation of neutron multiplier)
- Proof-of-principle experiment

} ➡ 3

Overall strategy

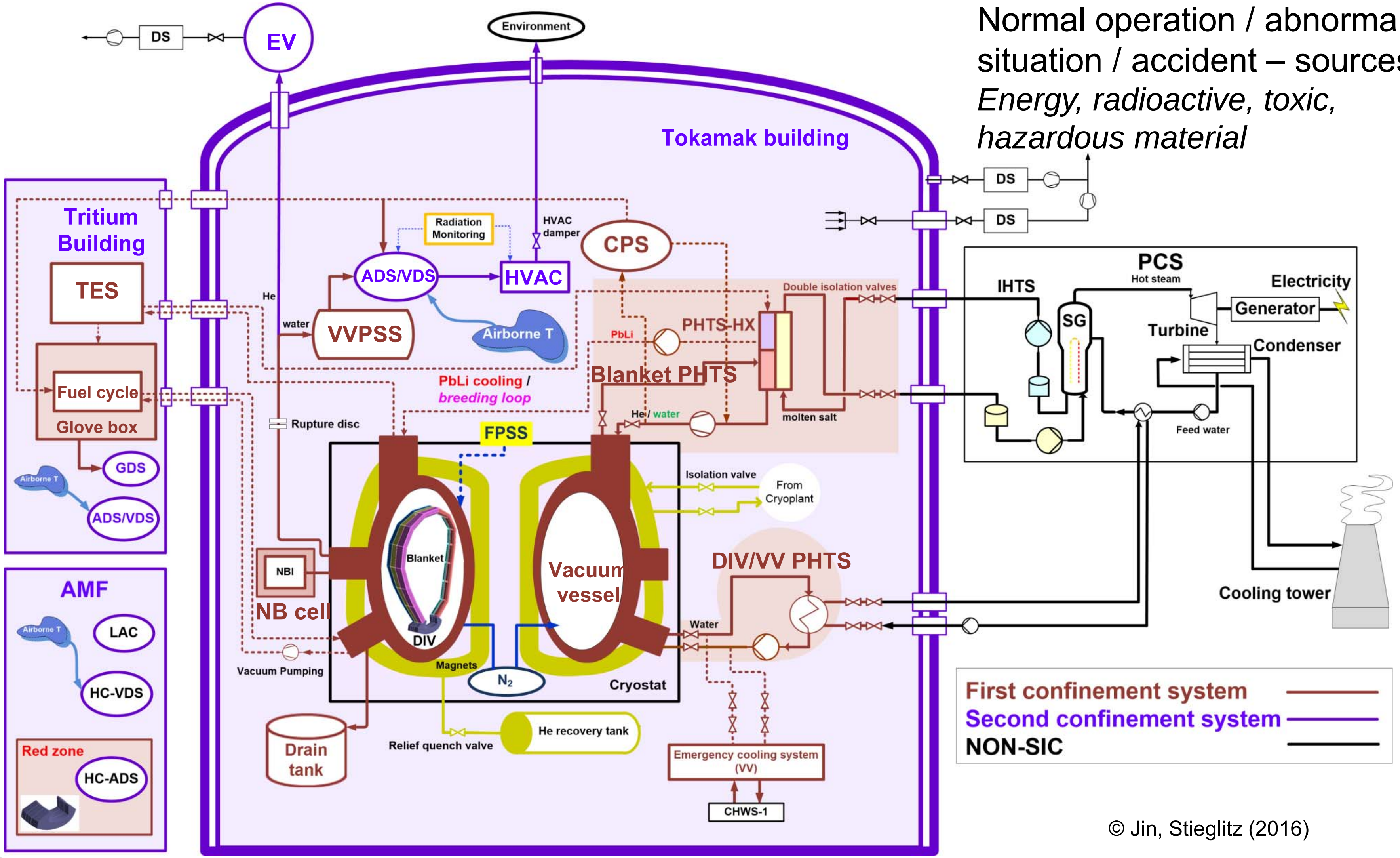
- Building functional blocks to allow executing a safety analysis for the whole FPP
- Contribution to key elements

➡ ***some examples***

1 FPP Safety Design & Licensing Requirements

Karlsruher Institut für Technologie

Elaboration of a confinement strategy for DEMO



Plant safety

Normal operation / abnormal situation / accident – sources: *Energy, radioactive, toxic, hazardous material*

FPP Integrated Safety Analyses

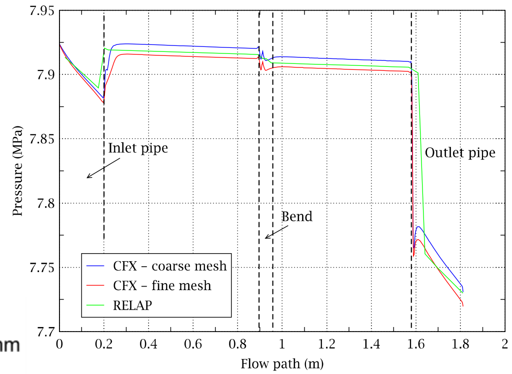
2

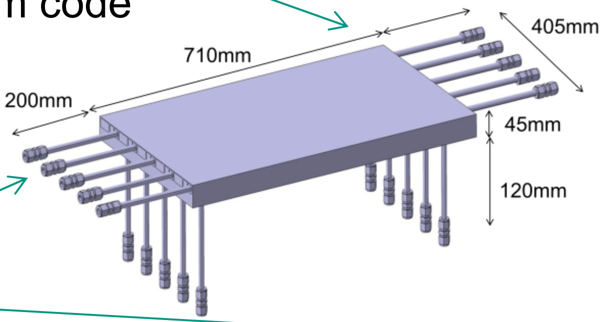
Code application and validation:

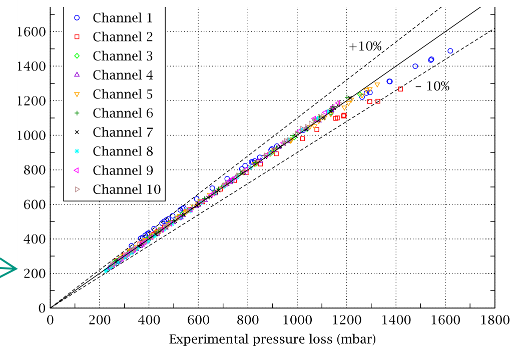
Loss of flow accident (LOFA) in the first wall (FW)

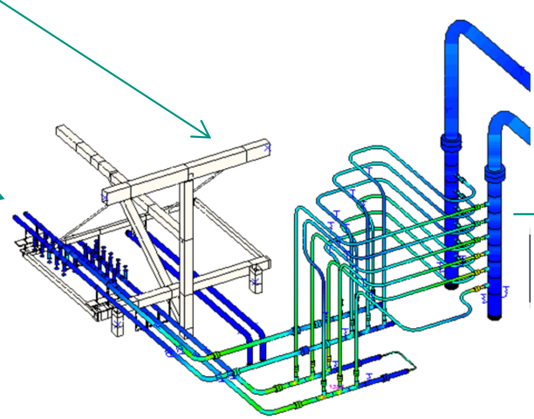
Sequence

- CFD model set-up for one / two channels
- Reduction to simplified model – system code
- ➡ ***Verification***
- Experimental development
  - Design of the test mock-up
  - Isothermal validation
- Integration in the helium loop
- Full scope single experiment
- System analysis
- Full 3D safety analysis
- ➡ ***Validation***









FPP Integrated Safety Analyses

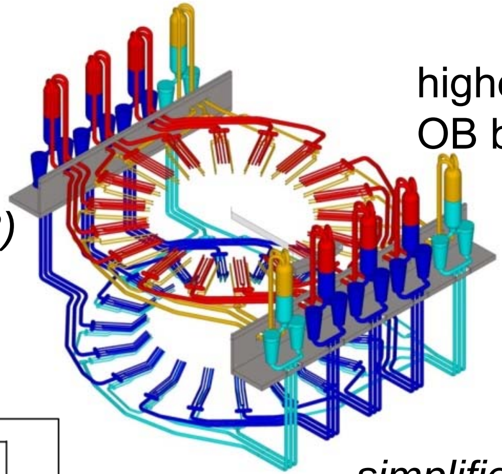
2

Loss of coolant flow (LOCA) in the cooling plate of the breeder unit / FW

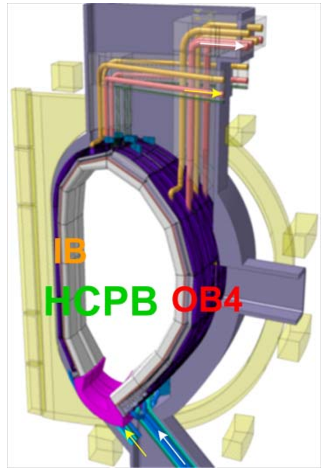
Partial system analyses

HCPB in 18 sectors – primary heat transfer system (PHTS) design:

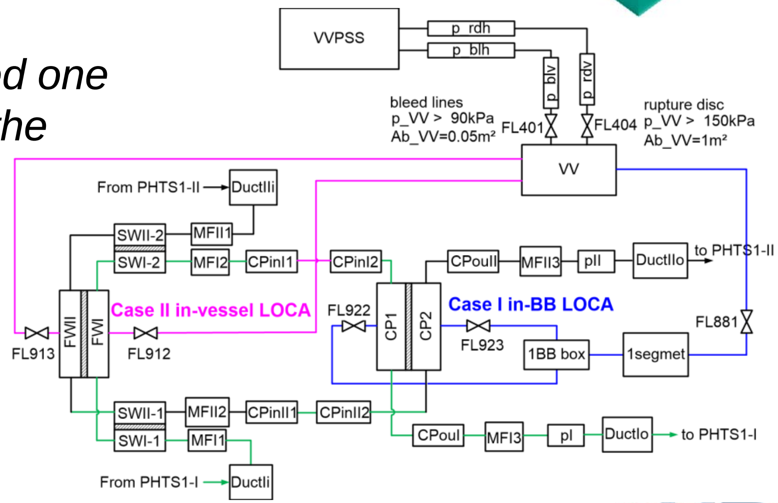
- *6 loops outboard (OB), 3 loops inboard (IB)*
- *1 OB-loop 3 sectors / 1 IB-loop 6 sectors*
- *1 sector: 3 OB segments & 2 IB segments*



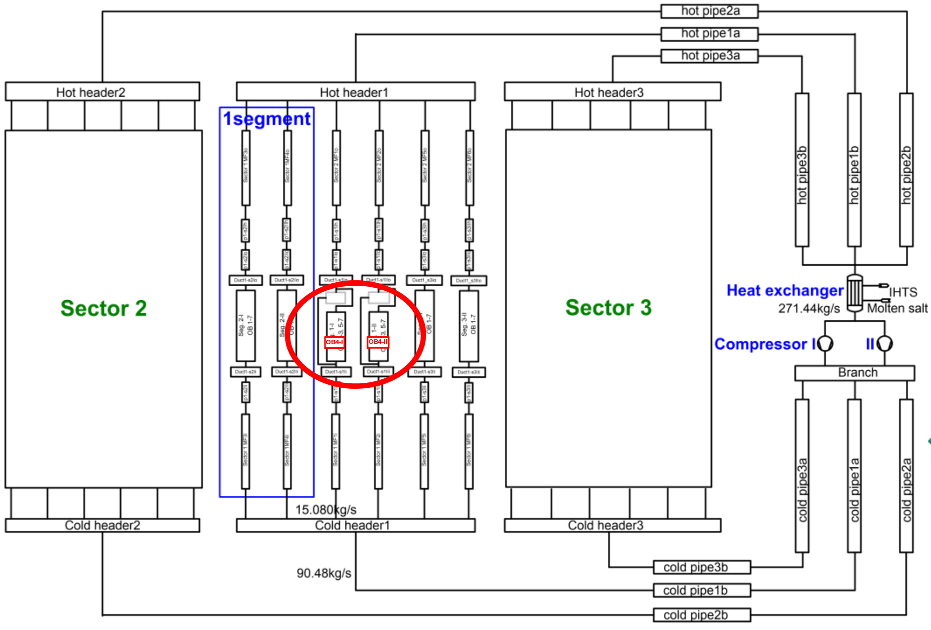
highest loaded OB blanket



simplified blanket model depiction (OB4)



simplified one loop of the PHTS



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FPP - Radioactive Waste Safety

3

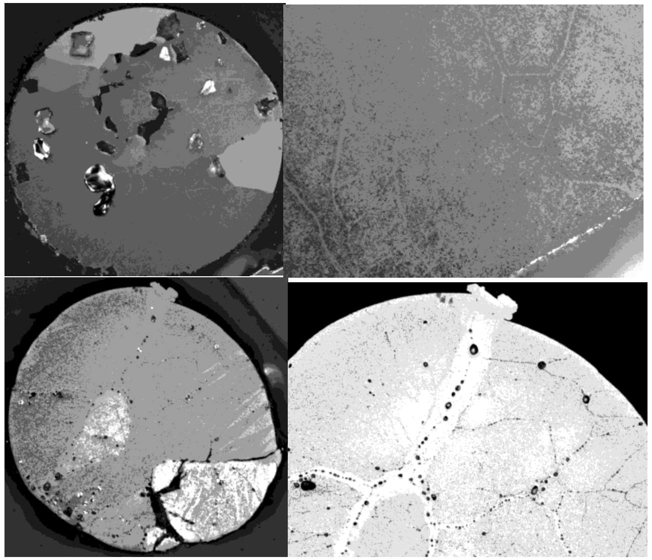
Karlsruher Institut für Technologie

Tritium release from the neutron multiplier

- Determination of detritiation parameters of Beryllium pebbles by annealing

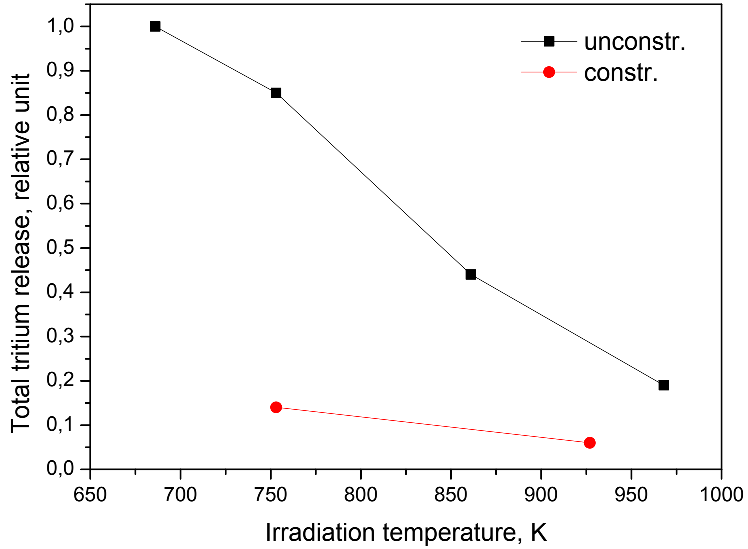
unconstrained, T_{irr} = 968 K

constrained, T_{irr} = 1006 K



Unconstrained pebbles: large pores (~ 40µm)

Constrained pebbles: small pore sizes (<10µm). At highest T_{irr}, open porosity network is well developed.



- **Tritium retention in Beryllium pebbles**
  - Total tritium release decreases with increasing irradiation temperature for both unconstrained and constrained pebbles
  - Residual amount of tritium in constrained pebbles is significantly lower than in unconstrained.

Blanket – Final design - „Integration“

Operational Safety

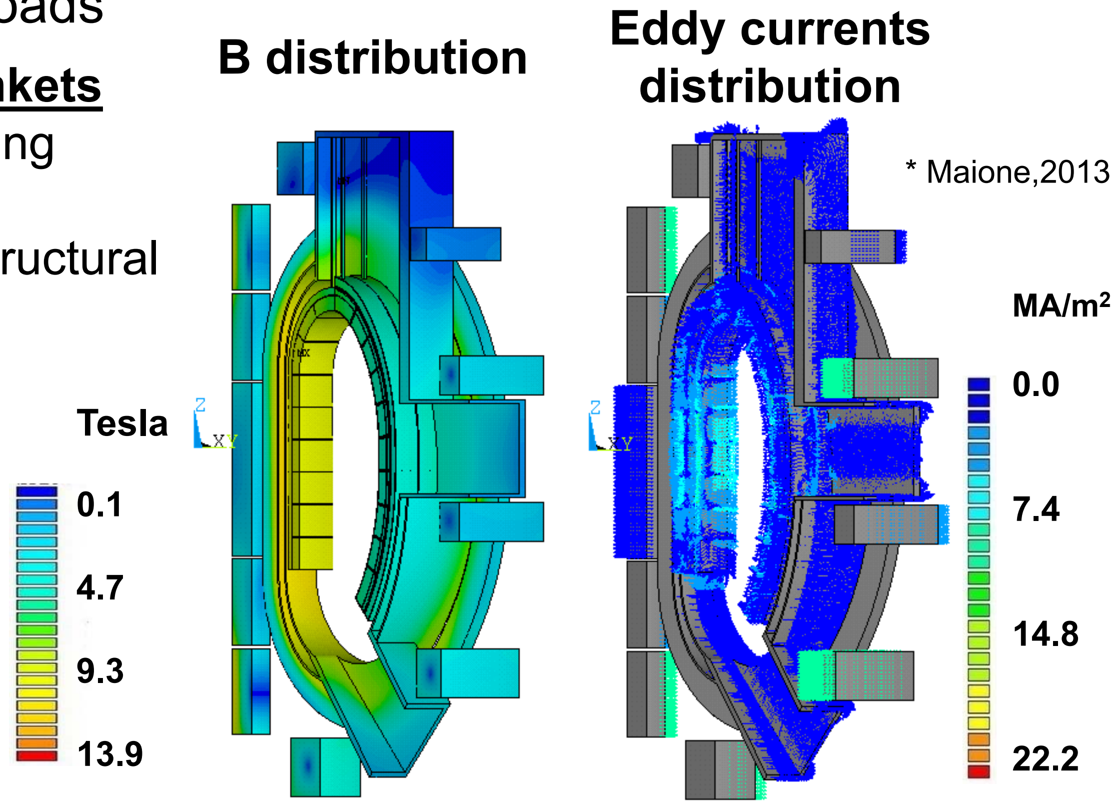
- postulated initiating event (PIE) ➡ event tracking (FFMEA-analysis) ➡ consequences ➡ deterministic approach
- statistical safety assessement ➡ likelyhood of event occurence

Pre-requisite

- validated codes to predict loads

Example : EM analyses of Blankets

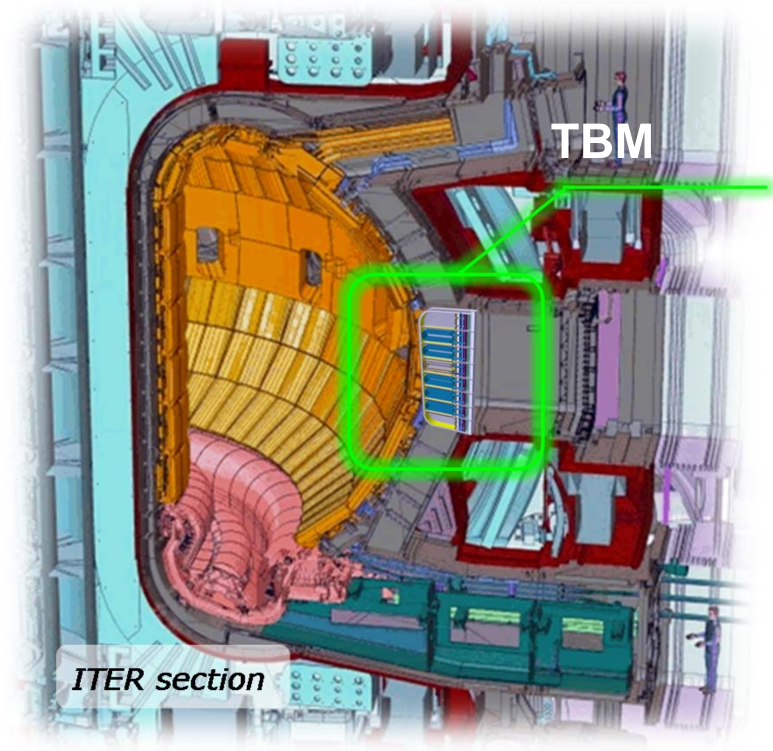
- Ferromagnetic materials during a plasma disruption.
- Coupling of EM-analysis to structural analysis.



ITER – THE NEXT STEP

ITER TBMs

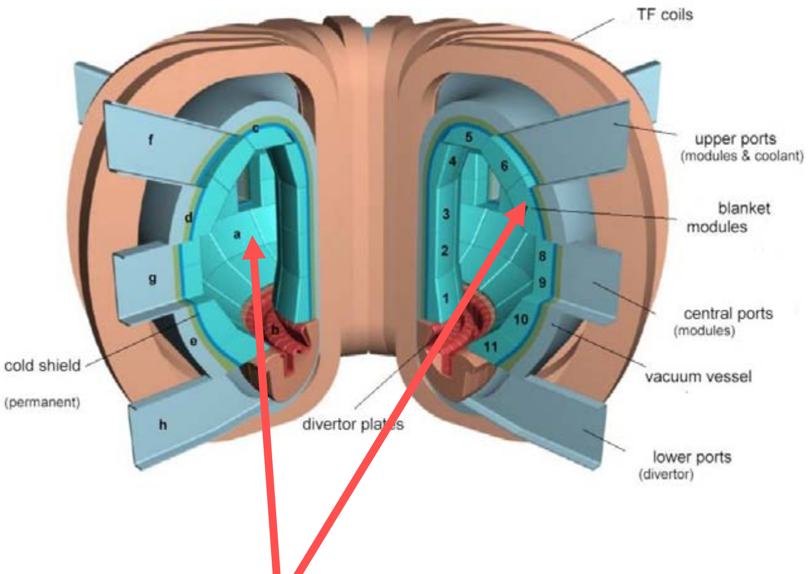
- Test of blanket systems in ITER Test Blanket Programme.
- ITER offers 6 positions for the testing of blanket concepts as Test Blanket Modules (TBM).
- 2 EU concepts (HCPB and HCLL) selected for testing.
- Each TBMs has a volume of about 0.8 m^3 with ~1 m^2 of first wall surface.

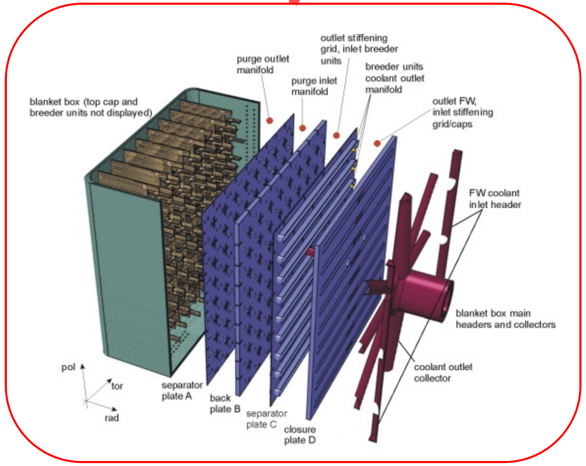


Location of TBM inside equatorial Port Plugs of ITER.

European breeder blanket concepts @ ITER

	HCPB He-Cooled Pebble Bed	HCLL He-Cooled lithium Lead
Structural material	**Ferritic-Martensitic** steel (EUROFER)	**Ferritic-Martensitic** steel (EUROFER)
Coolant	**Helium** (8 MPa, 300/500°C)	**Helium** (8 MPa, 300/500°C)
Tritium breeder, multiplier	**Solid (pebbles bed)** Li_2TiO_3/Li_4SiO_4, Be ^6Li enrich. 40-70%	**Liquid (liquid metal)** Pb-15.7at.%Li ^6Li enrich. 90%
Tritium extraction	He purge gas (~1 bar)	Slowly re-circulating PbLi; extraction outside the blanket



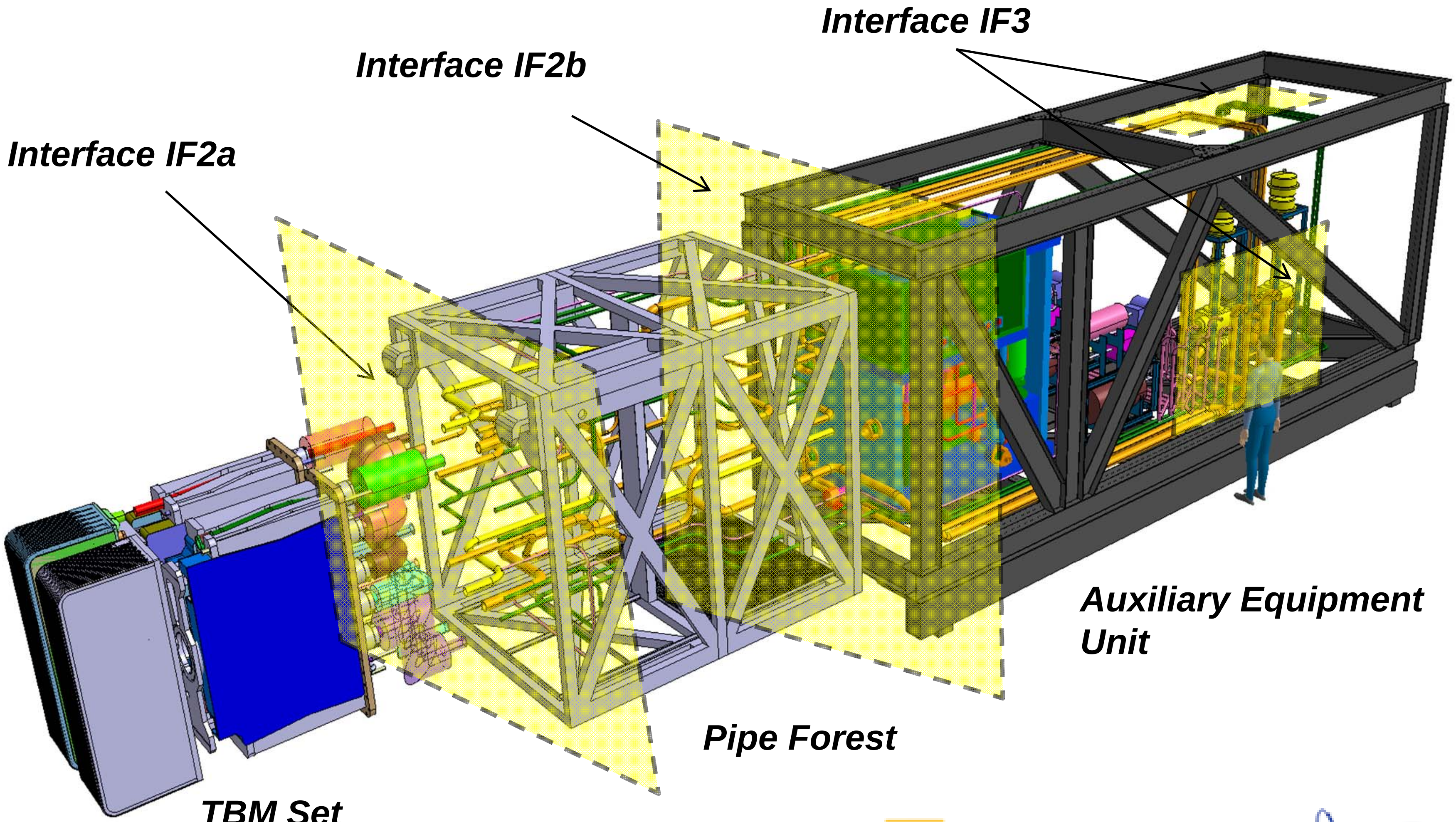


Breeder Blankets modules

Main objectives

- principal functionality
- T- Breeding
- Interface approval (CPS, TES, remote procedures, ………)

EU TBS design & integration



TBS=Test blanket station

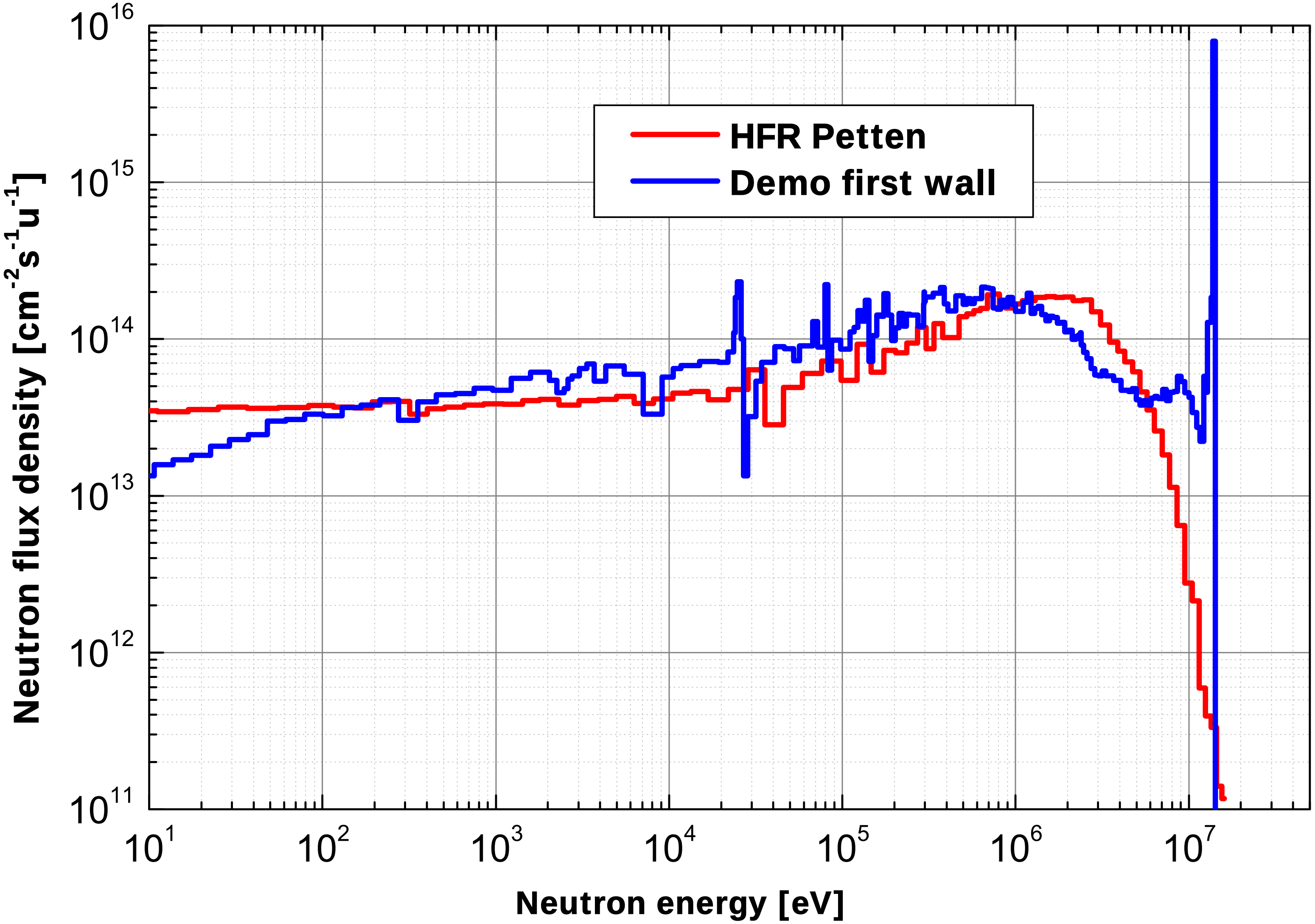
Summary - Blankets

- Breeding Blanket =Key component of fusion power plant
- Key functions
  1. Tritium production to serve Tritium self-sufficiency
  2. Heat removal to allow for electricity production
  3. Shielding contribution to match integrity of magnets and safety .
- Functionality
  1. T- Production: Li as breeder ^{6}Li-enriched dependent on concept, additional multipliers
  2. Cooling: by liquid metals (causing MHD-effects), He (high p) or hybrides of both
  3. Dependent on coolant choice , dedicated material choice ➡ respecting safety ***and*** low activation (waste reduction) aspects.
- Interface-compatibility
  - Power conversion system (PCS) ➡ operational temperature frame
  - Tritium plant ➡ coolant dependent system installations/requirements
  - Remote handled replacement, Transfer decommissioning
- Fusion power plant safety = LWR Safety + fusion specific aspects
- Plant integration - challenging puzzle to be learned within ITER
- Most credible currently developed blanket options Helium Cooled Pebble Bed (HCPB) and the Helium Cooled Lithium Lead (HCLL)
- ITER-Program with 6 test blanket modules (TBM) essential for a DEMO

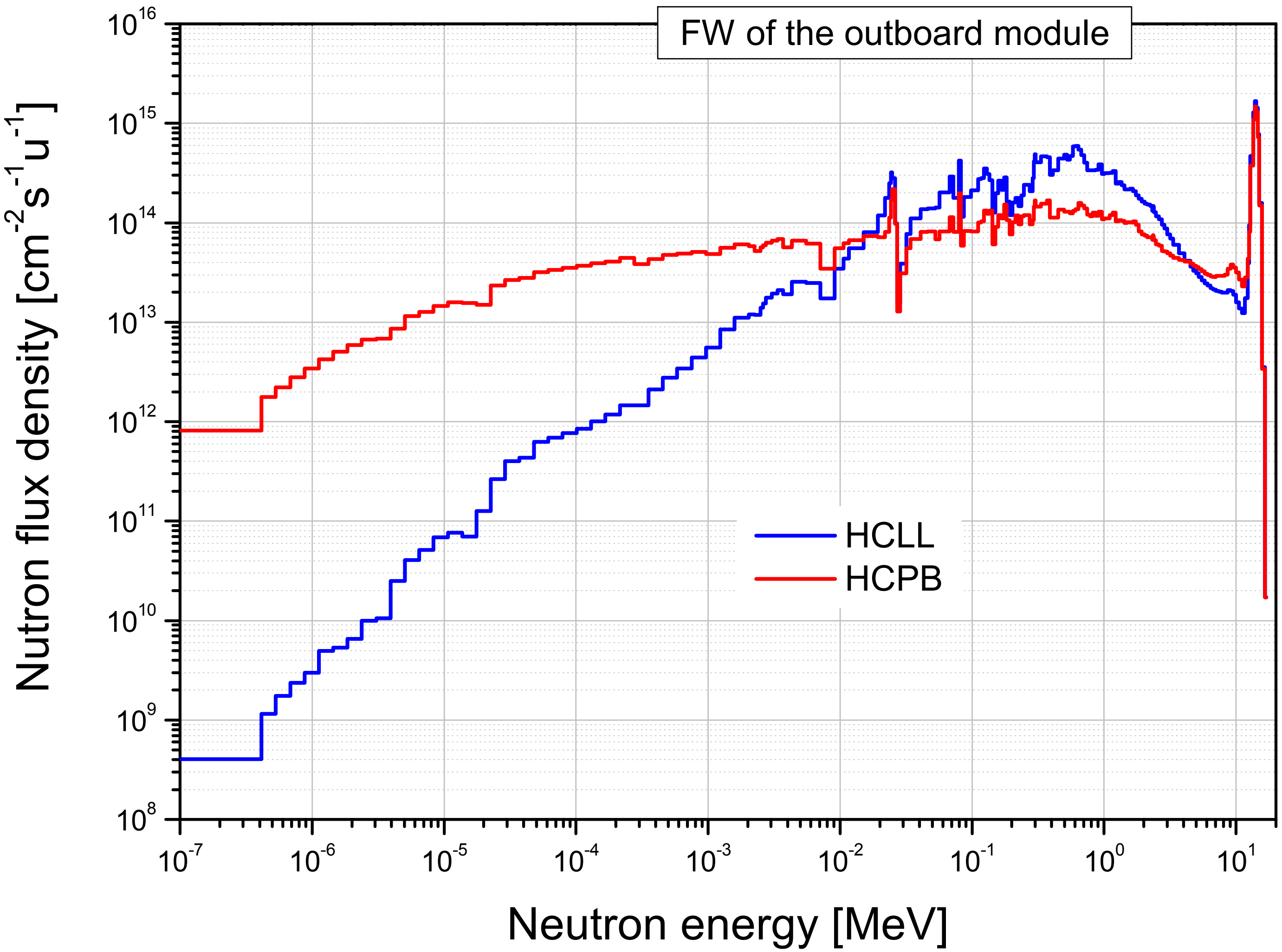
➡ **Blanket Design is one of the "CROWN" challenges in Fusion Engineering**

ADDITIONAL TRANSPARENCIES

Neutron flux spectra: fusion vs. fission



HCPB/HCLL First Wall Neutron Spectra



Blanket – Final design - „Integration“

Operational Safety- postulated initiating event (PIE)

- What happen in case of full station black-out ?

Bondary conditions

- end of life –blanket (➡ maximum decay heat)
- all emergency cooling not available
- no manual plant operating measures

Results for HCPB Blanket

- Temperatures below structural degradation limit of Plasma facing components ➡ integrity ensured

➡ Protection goals: Cooling and confinement matched !!!!