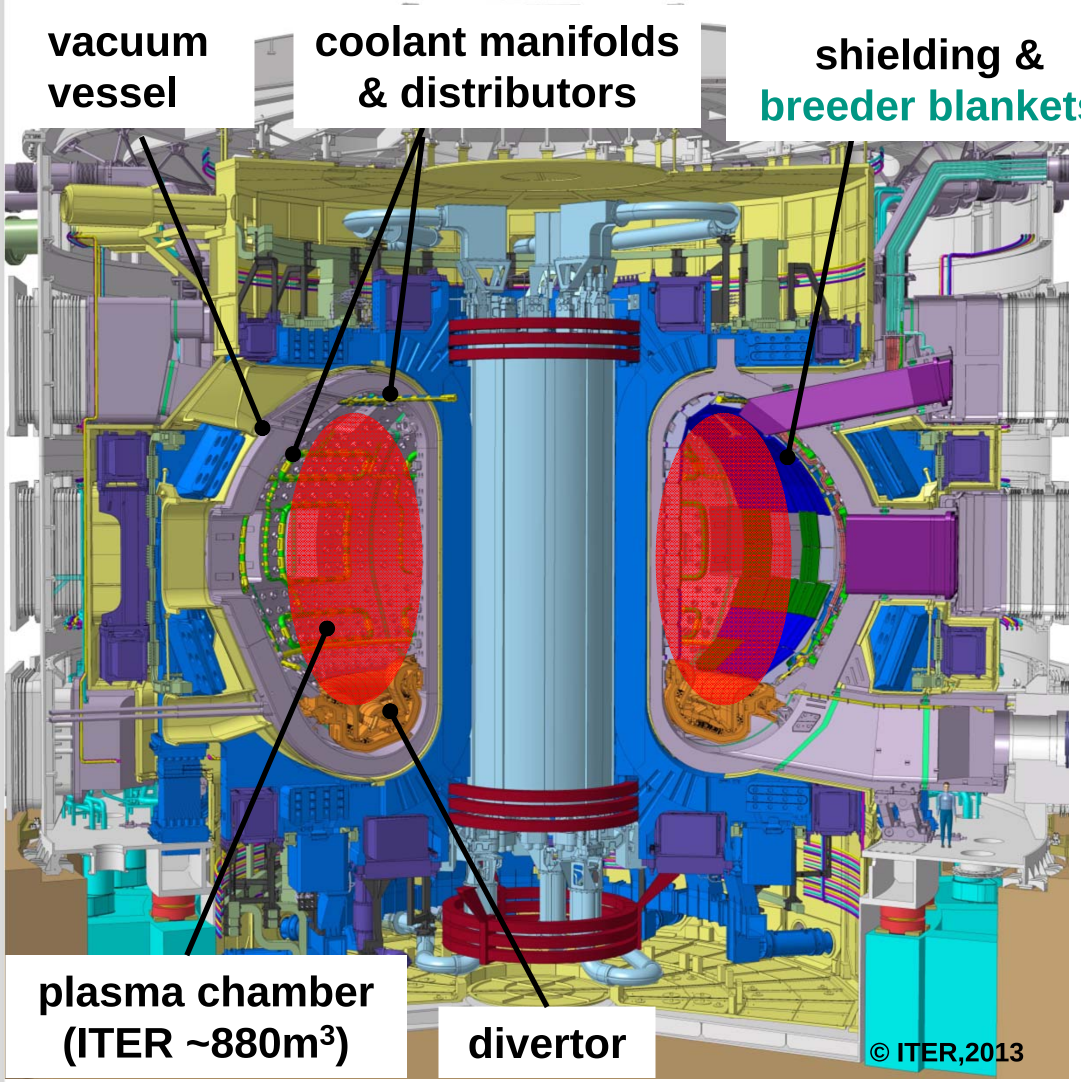
Blankets - key element of a fusion reactor - functions, design and present state of development

R. Stieglitz, L.-V. Bocaccini, K. Hesch

INSTITUT für NEUTRONENPHYSIK und REAKTORTECHNIK (INR)

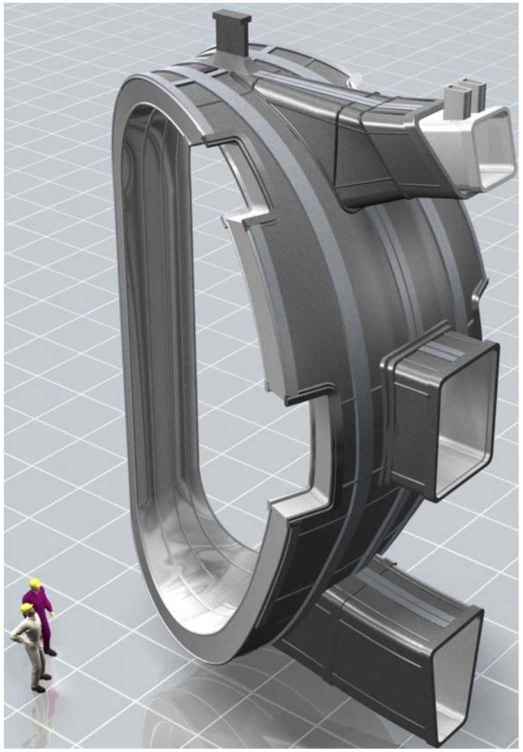
- Fundamental functions ➡ functionality
- Operational frame ➡ structural & eng. requirements
- Reliability, Efficiency ➡ basic design
- Maintenance, safety ➡ final design &integration
- Blanket development ➡ validation
- ITER Testblankets, DEMO Blankets
- Summary

Fusion Reactor – Thermo-nuclear core -ITER



Top level blanket functions

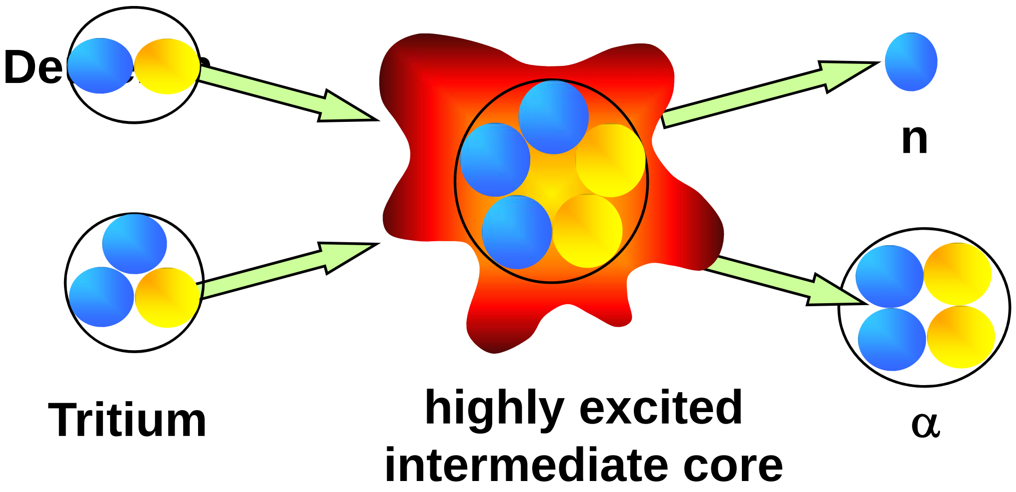
- Tritium breeding
- heat removal
- contribution nuclear shielding



Blanket - Fundamental function- „Breeding“

How to breed Tritium ?

- **Fusion – reaction**



neutron (14.1MeV)
(unaffected by B-confinement)
- ➡ fuel generation „breeding“
- ➡ nuclear heating
- ➡ material activation

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

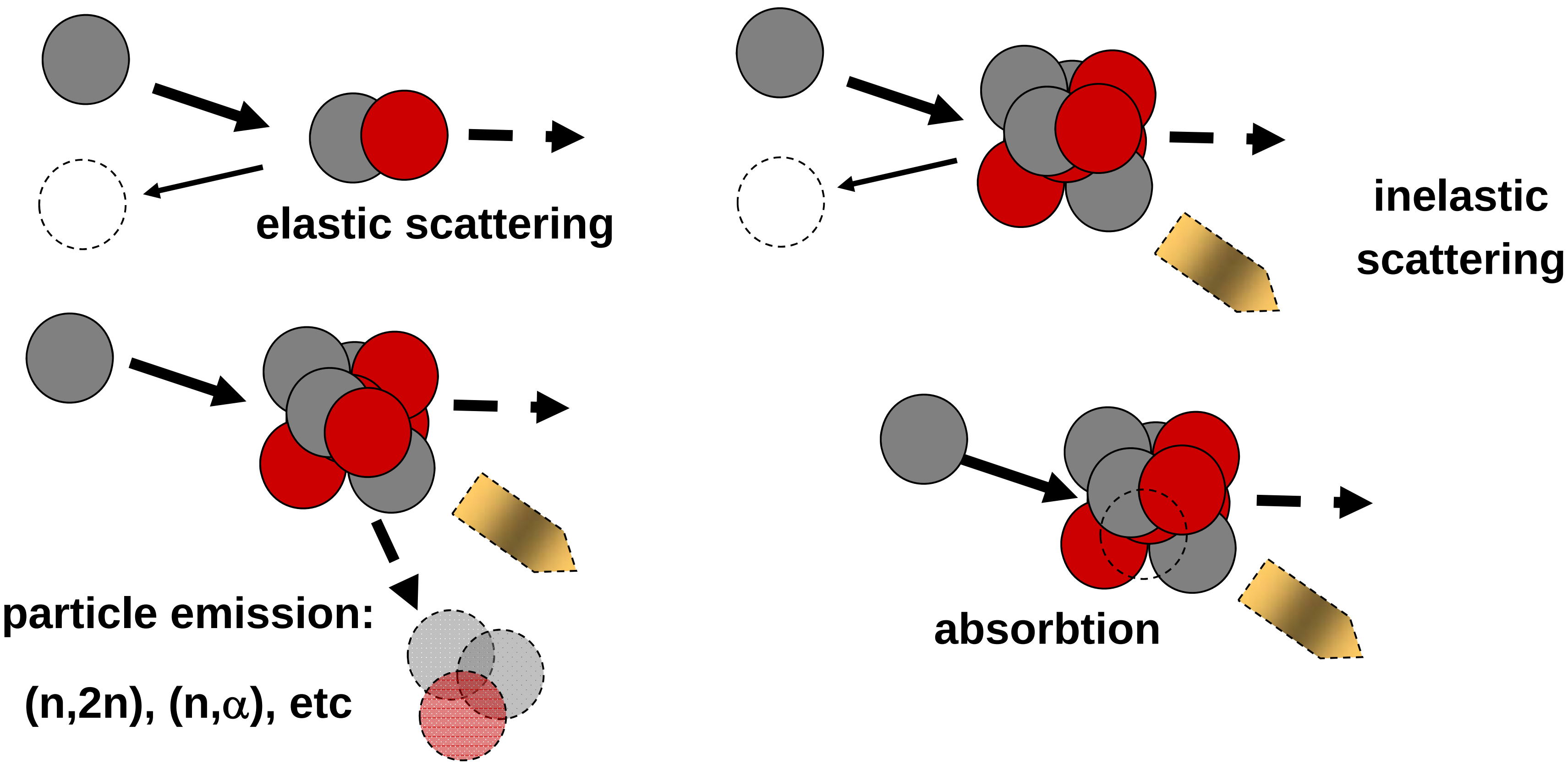
$$^{2}\mathbf{D} + {}^{3}\mathbf{T} \longrightarrow {}^{4}\mathbf{He}\ (\alpha) + \mathbf{n} + 17.6\ \text{MeV}$$

Capture neutron in nuclear reaction producing tritium

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

Neutron interaction with matter

- Several interactions possible



- Crucial parameter: nuclear cross-section σ (measured in barn=10^{-24}cm^2)
- σ dependent on incident neutron Energy (E) and angle (φ)

Blanket - Fundamental function- „Breeding“

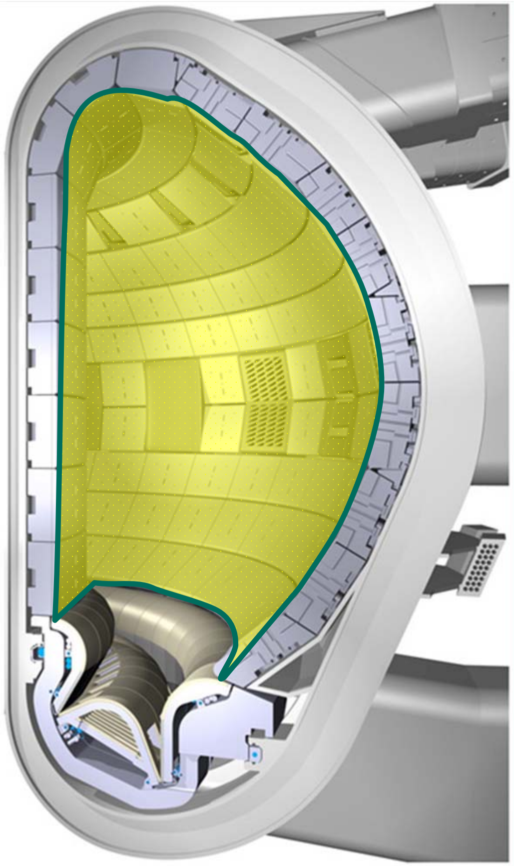
- **Which nuclide / element / material ?**

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

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

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

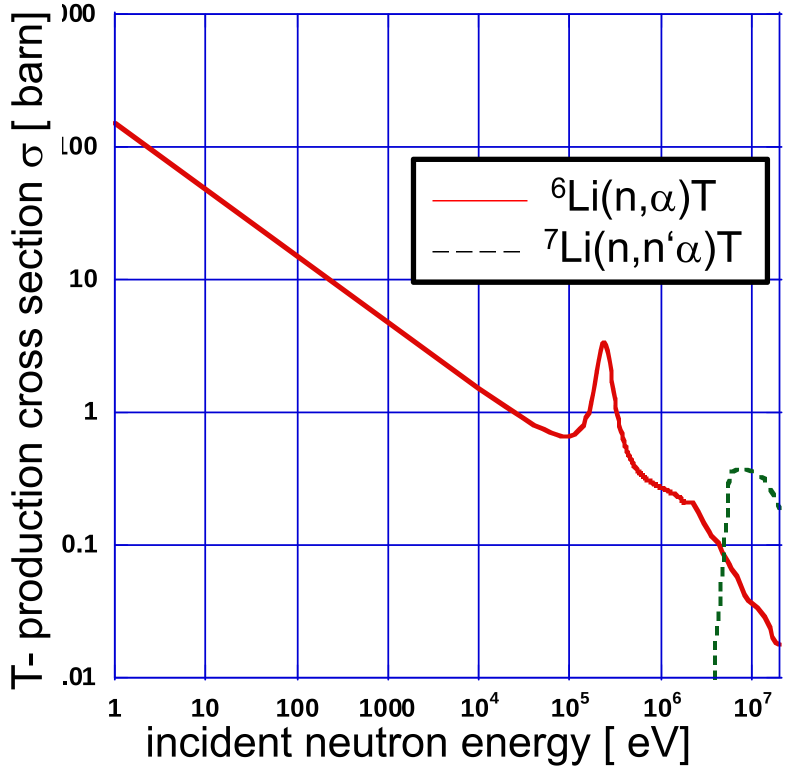


- **How to prove tritium breeding capability?**
  - neutronic calculation (➡ method/data/geometry !)
  - calculation validation against experiment(s)

Blanket - Fundamental function- „Breeding“

Suitable Lithium-isotopes ?

- ^{6}Li- high cross-section for low energies (loss of neutron)
- 7Li –activation energy threshold >6MeV
- Natural composition: 92.5% ^{7}Li , rest ^{6}Li.
- ➡ **local ^{6}Li enrichment mandatory**



Which form of Li-adequate ?

Requirements neutronic

- High density, negligible absorption

Engineers

- chemical, mechanical, thermal stability, good tritium release behaviour, compatibility with structural material and coolant, irradiation behaviour

	Mass density [g/cm^3]	Li number density [10^{22}cm^{-3}]
Li_4SiO_4 (solid)	2.39	4.8
Li_2TiO_3 (solid)	3.43	3.63
Pb-Li (eutectic, liquid)	9.54 (500K)	0.517

Blanket - Fundamental function- „Breeding“

Production of Tritium from Li ?

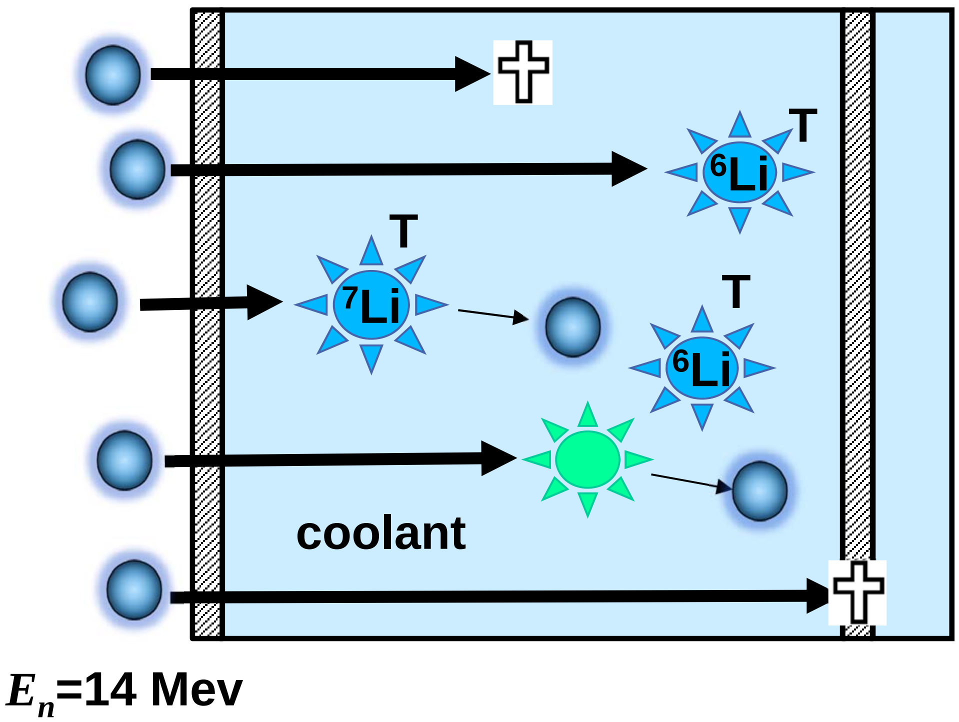
reactor requires

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

(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 are required



Blanket - Fundamental function- „Breeding“

Neutron multiplication ?

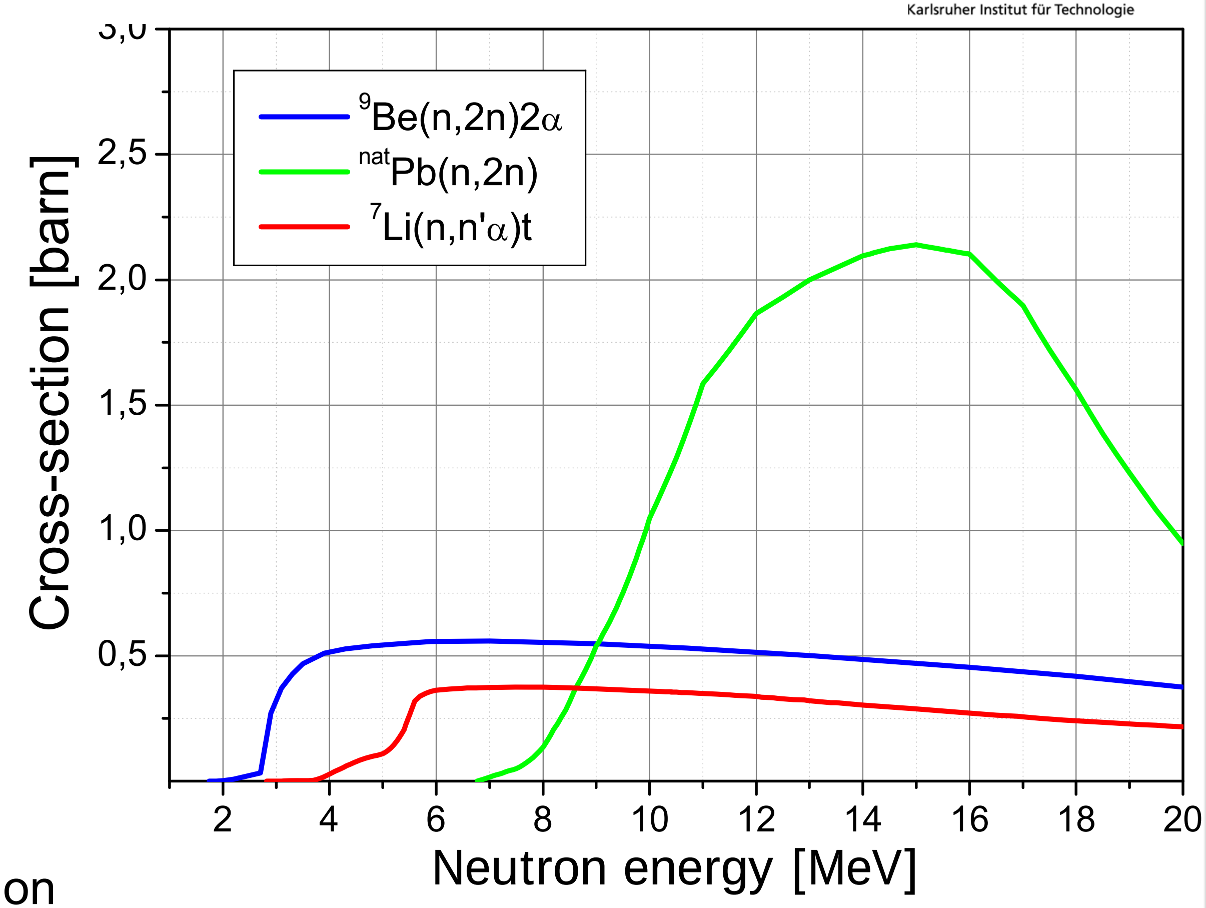
Required (n,2n) reactions
with high σ in
Energy range up to 14MeV

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



RESULT ➡ 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

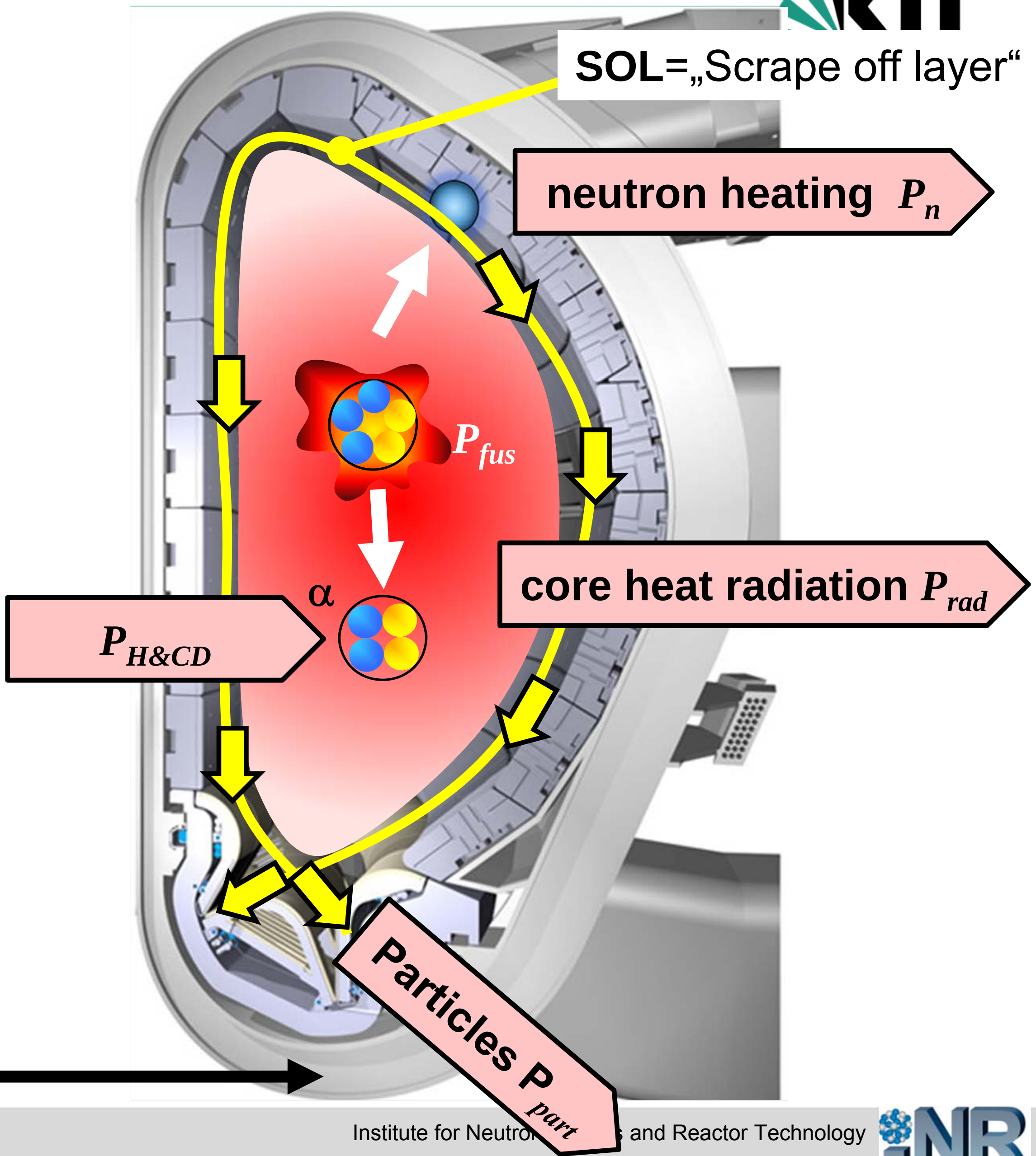
DEMO with *R*=9m

Blanket Area A=1000m²

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

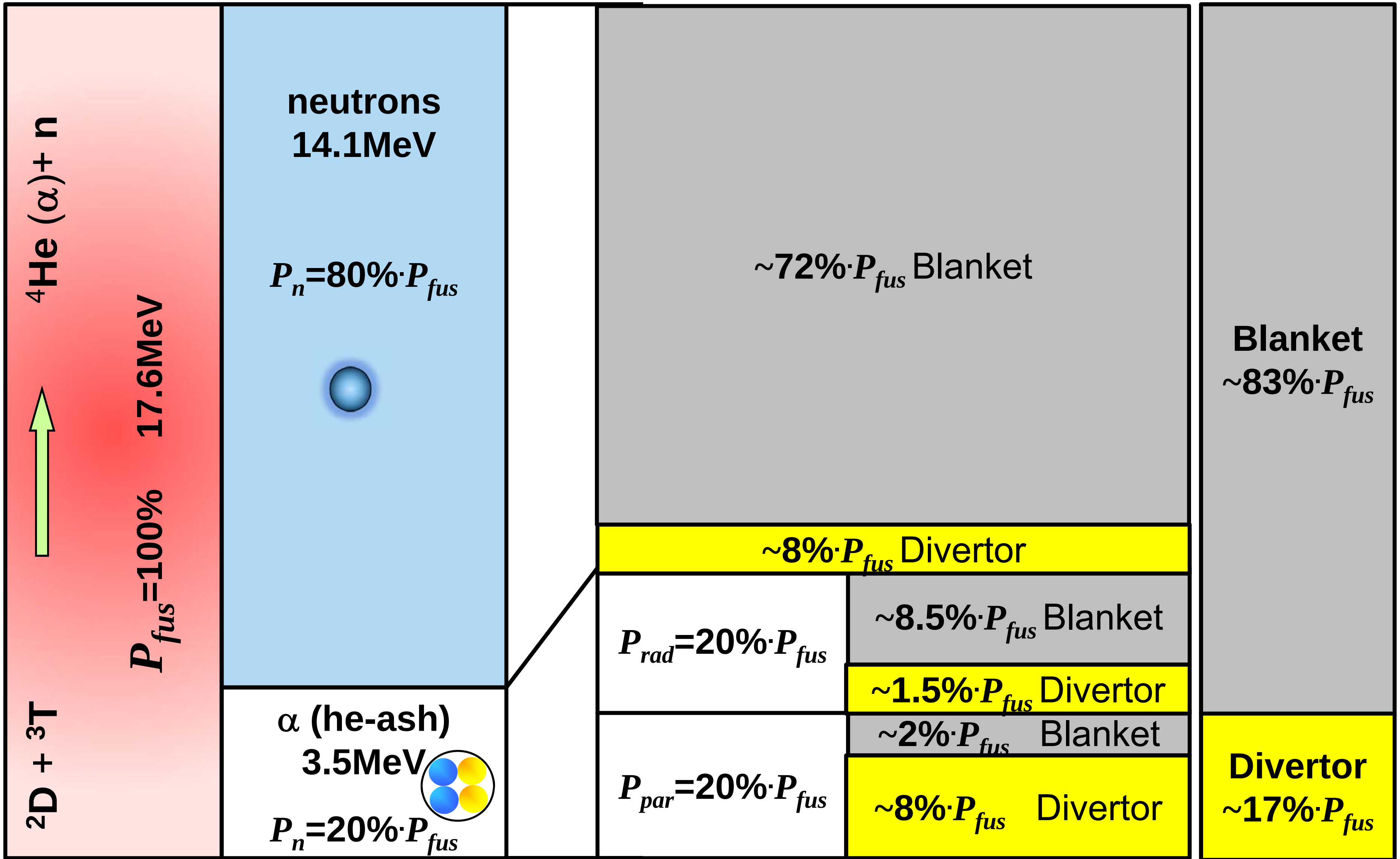
Divertor

- q_{part}=10-(20)MW/m²



Blanket - Fundamental function- „Cooling“

- Power flow distribution



Blanket - Fundamental function- „Cooling“

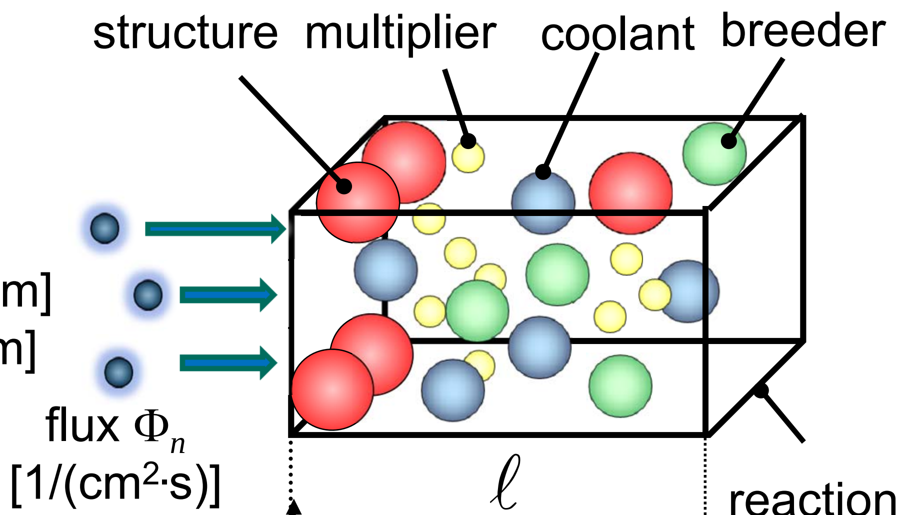
Volumetric heating by P_n - What is behind that ?

- **Interaction of different nuclei with matter scoping all reactions**
  - elastic and inelastic scattering,
  - absorption,
  - particle emission

  and associated γ-ray emission)

- Essential $\Sigma = N \cdot \sigma$

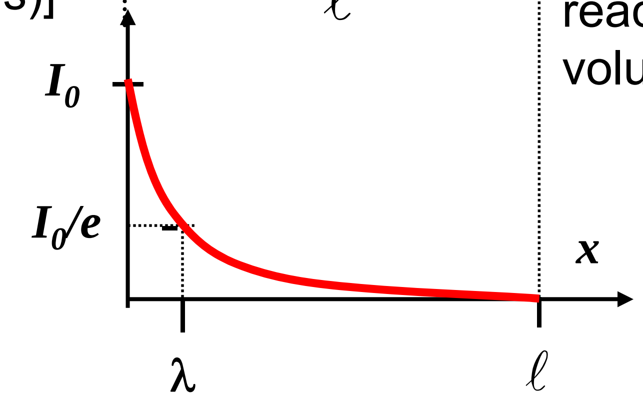
  Σ=macroscopic nuclear cross-section [1/cm]
  σ=microscopic nuclear cross-section [1/cm]
  N=number nuclei [1/cm^3]



Lambert-Beer-Attenuation law

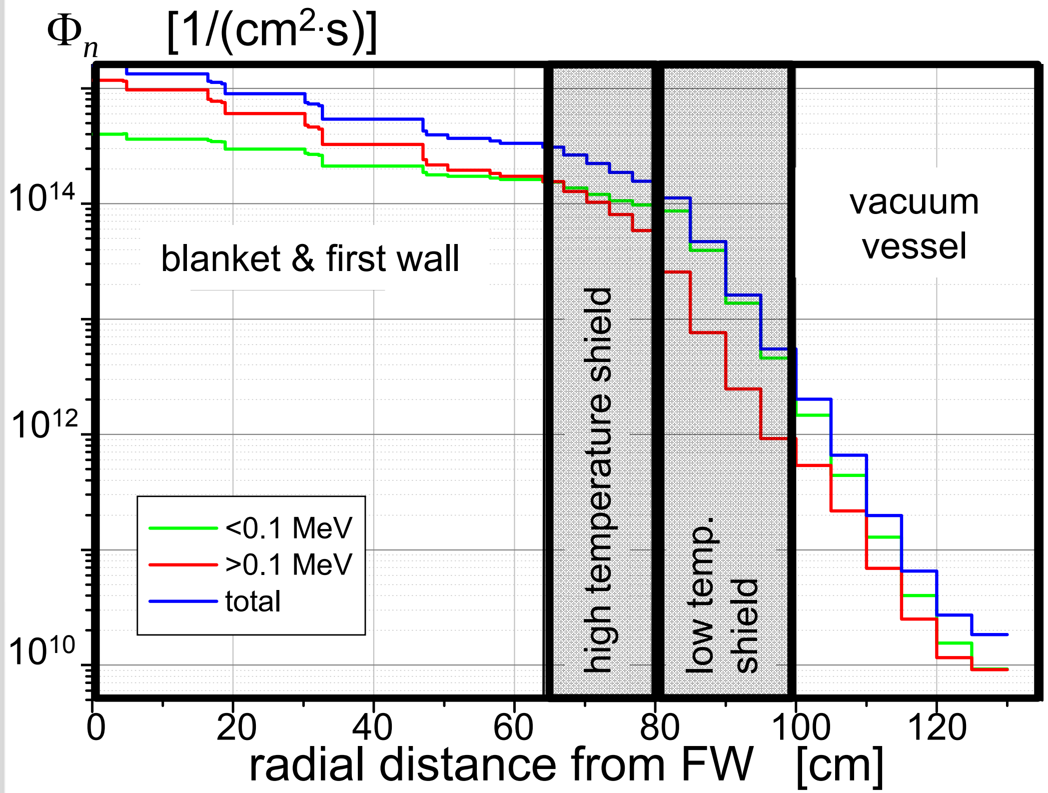
$$I_x = I_0 \cdot e^{-\Sigma x}$$

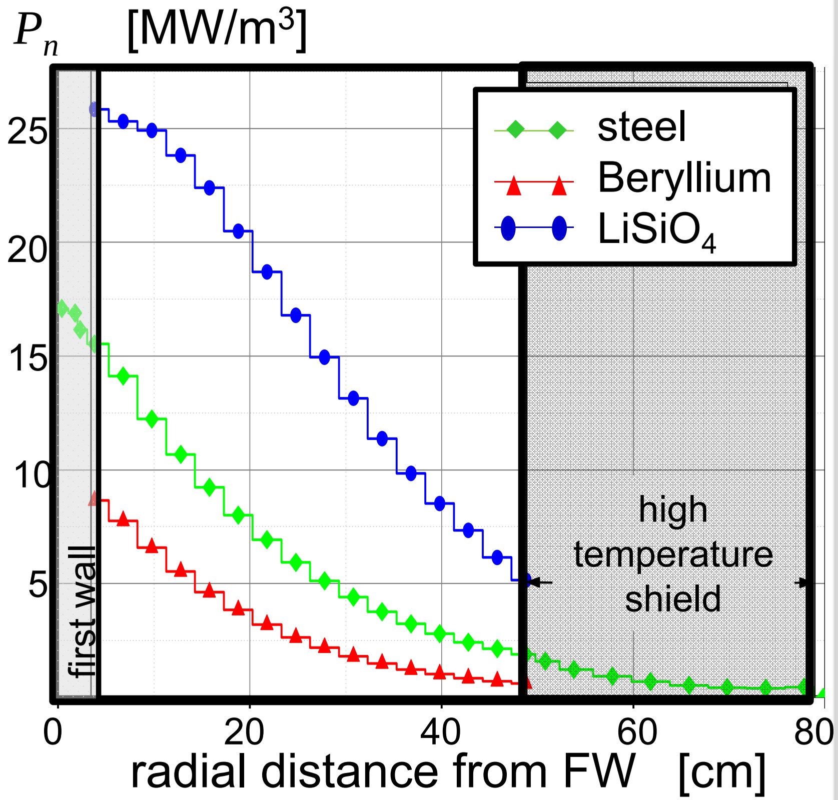
- $x=\Sigma^{-1}=\lambda$ mean free path (av. travelling distance before collision)
- $\Sigma \cdot dx =$ collision probability of neutron within dx



Blanket - Fundamental function- „Cooling“

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





Magnitude Example:

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

$< q_{rad} = 0.5$ [MW/m²]

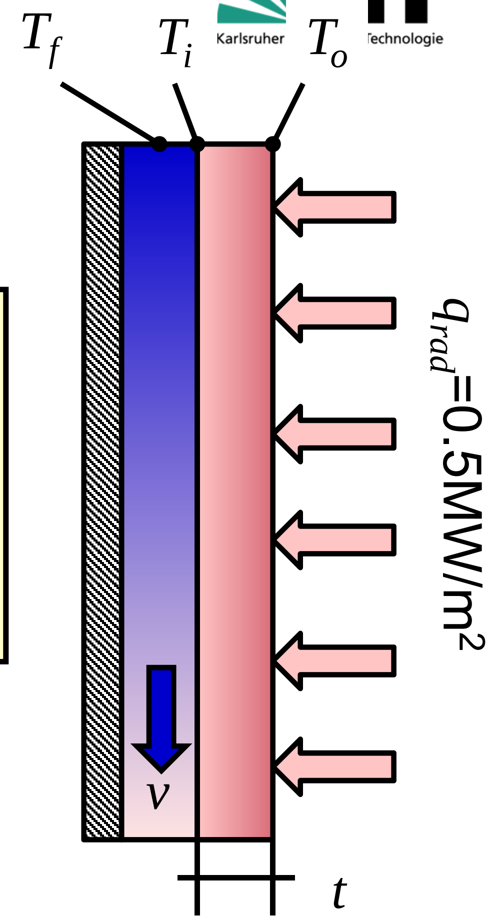
<100MW/m³ LWR

Blanket - Fundamental function- „Cooling“

Wall surface heat flux caused by q_{rad}

Requirement: $T_{mat} < T_{max,material}$

Where ? Outer side of first wall (FW) T_o



Parameters

- T_f = bulk fluid temperature
- T_o = outer temperature FW
- T_i = inner temperature FW
- t = wall thickness
- λ = heat conductivity
- k = heat transfer coefficient

Example *

- T_f = 300°C
- t = 5mm
- λ = 20W/(mK)
- k = 8.0000 W/(m²K)

(v_{He}=80m/s, v_{PbLi}≈0.5m/s)

$$T_i = T_f + \frac{q_{rad}}{k} \qquad T_o = T_i + \frac{q_{rad} \cdot t}{\lambda}$$

$$T_i = \left(300 + \frac{0.5 \cdot 10^6}{8 \cdot 10^3}\right)°C = 362.5°C$$

$$T_o = \left(362.5 + \frac{0.5 \cdot 10^6 \cdot 5 \cdot 10^{-3}}{20}\right)°C = (362.5 + 125)°C = 487.5°C$$

almost upper steel temp. !!!

* Boccaccini, 2012, lecture

Blanket - Operational functions- „Structures“

Thermal and other loads cause additional material loads !!!

Requirement: $\sigma_{max} < \sigma_{Design}$ Where ? Everywhere, to be demonstrated

- σ_{max} = max. stress in Blanket
- σ_{Design}= max allowable material stress (material data base!!)

Several stress types present

- *primary stresses* = pressure, mech.loads (bend, torque,….)
- *secondary stresses* = thermal loads
- *alternating stresses* = cyclic loads

Thermal loads on FW –plate

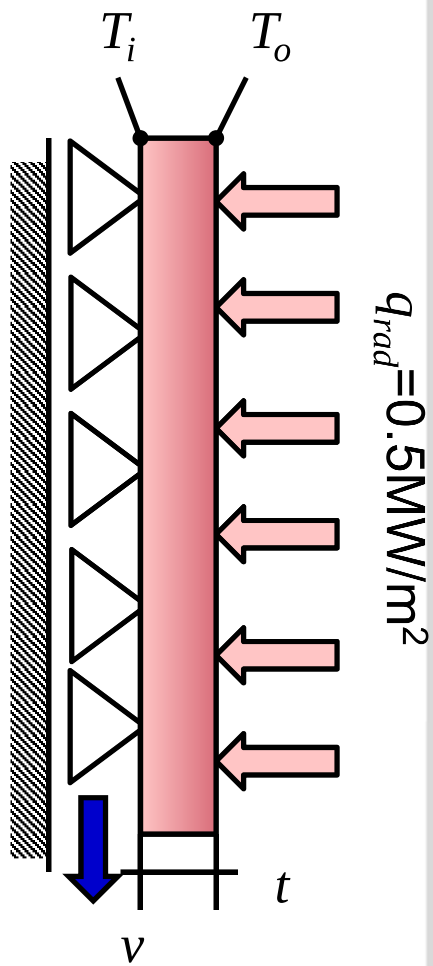
- α = thermal exp. coefficient
- E = modulus of elasticity
- ν = Poisson ratio

$$\sigma_{th,\max} = \frac{\alpha \cdot E \cdot (T_o - T_i)}{2(1-\nu)} = \frac{\alpha \cdot E \cdot q_{rad} \cdot t}{2(1-\nu)\cdot \lambda}$$

Example*

- α =1.8·10^{-5} 1/(K)
- E = 1.8·10^{11} Pa
- ν = 0.3, t = 5mm
- $(T_o$-$T_i)$ = 125°C
- q_{rad}=0.5MW/m^2

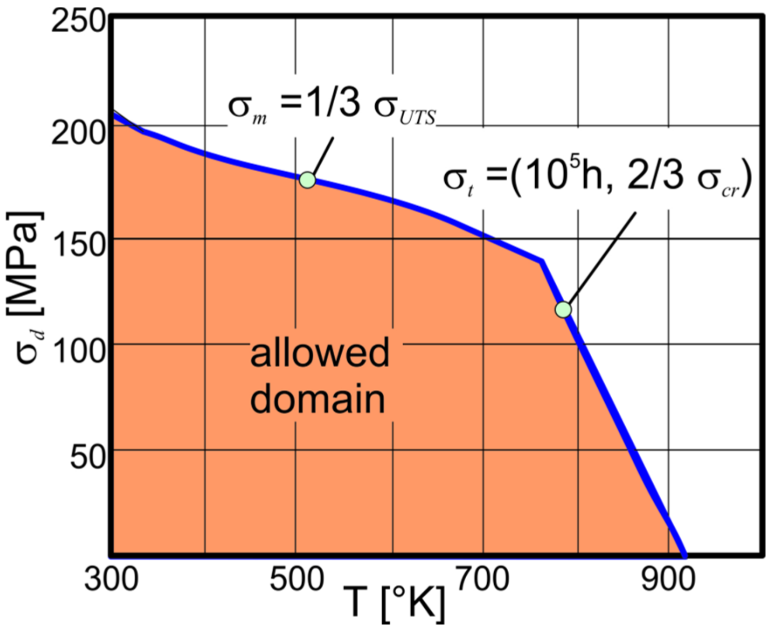
$$\sigma_{th,\max} \cong 290 MPa$$



* Boccaccini, 2012, lecture

Blanket - Operational functions- „Structures“

- **Design demonstration according to material data base ***



* Tavassoli et al., J. Nuc. Mat. 329-333 (2004), 257

- σ_d = design stress
- σ_m = stress mises
- σ_{UTS}=ultimate tensile strength
- σ_t = fatigue strength
- σ_{cr} = creep strengh

Stress criteria for elastic deformation**

- Primary stresses=equilibrium of forces & moments
  - pressure, membrane,bending body forces
  - ➡ not self-limiting
  - ➡ form factor f load type dependent
- Secondary stress = strain-controlled (lot load contr.)
  - thermal loads, joints
  - ➡ self-limiting
  - ➡ experience factors data base related

** US Nuc. Reg. Com. regulatory guide ,2012

Practical example

- primary stresses from internal pressure (f =1)+ bending (f=1.5) pressure ➡ $\sigma_{prim} \leq f \cdot \sigma_m$
- total stress σ_{tot}($\sigma_{tot} = \sigma_{prim} + \sigma_{sec}$) ➡ $\sigma_{tot} \leq 3 \cdot \sigma_m$
- trom data sheet σ_m=132MPa (T=773°K) ➡ $\sigma_{tot} \leq 396 MPa$

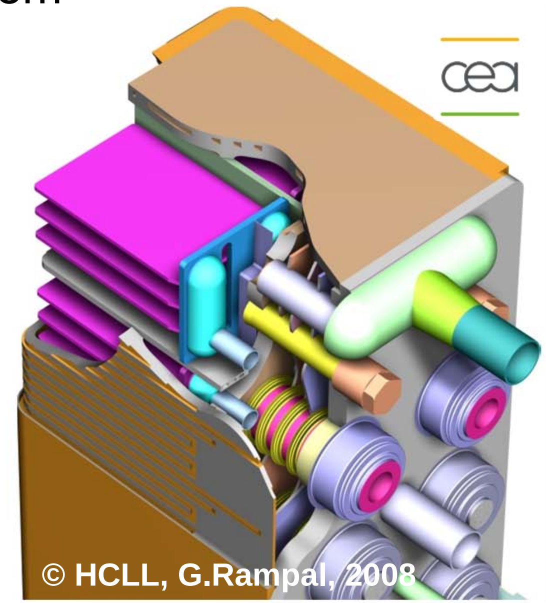
Blanket – Basic functions- „Interfaces“

Interface-functions

- coolant temp. to operate efficiently Power Conversion System (PCS)
- measure to extract tritium from coolant/breeder
- ISI&R and maintenance/extraction

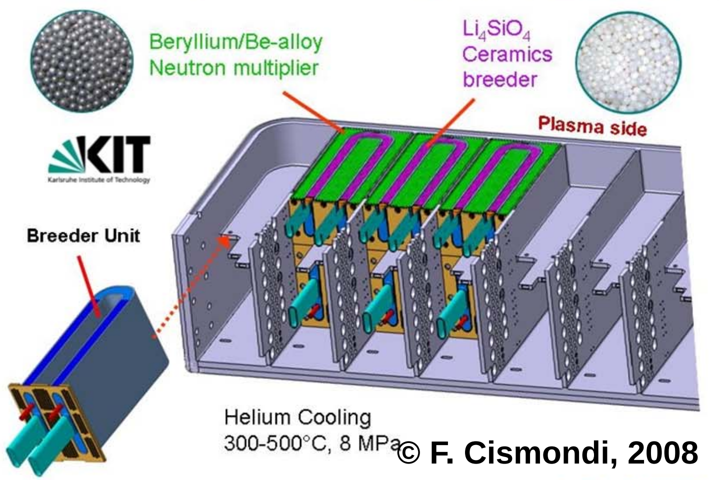
Mainly two blanket lines existent

- Liquid Metal 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}

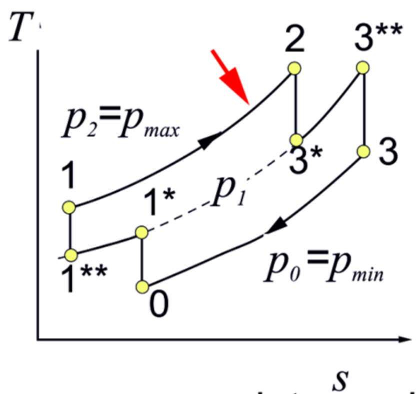
PCS Types

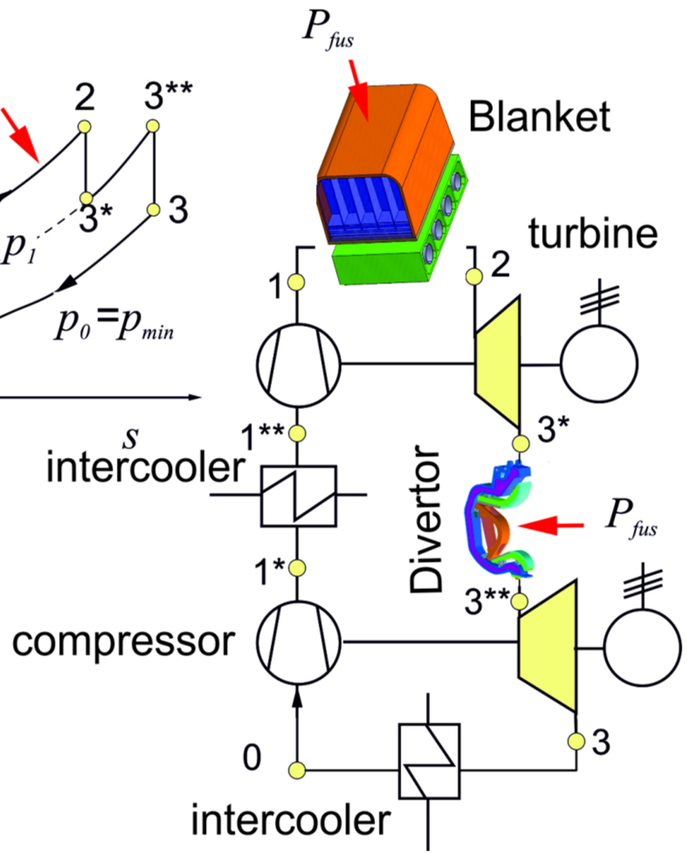
- Joule-Brayton (Gas turbine cycle)
- Clausius-Rankine (steam turbine)

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





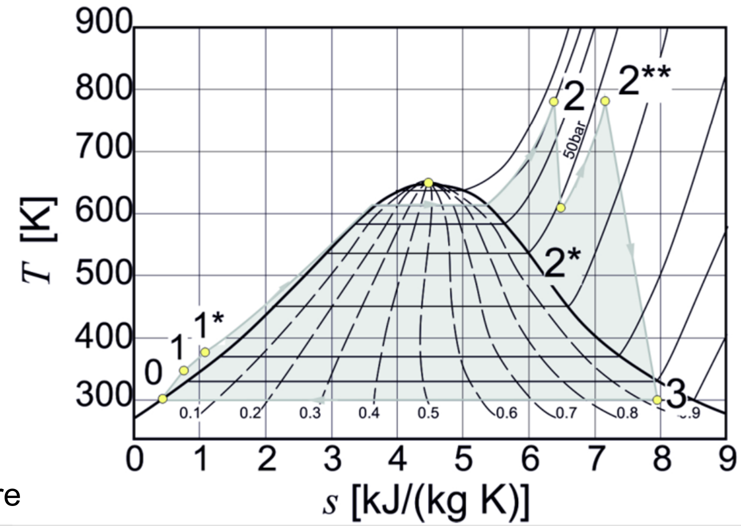
1432MW Blanket (He)
335MW Divertor
1976MW Blanket (PbLi)
248MW Divertor
HCLL Blanket, DEMO
*G. DuBois, Belgatom 2002

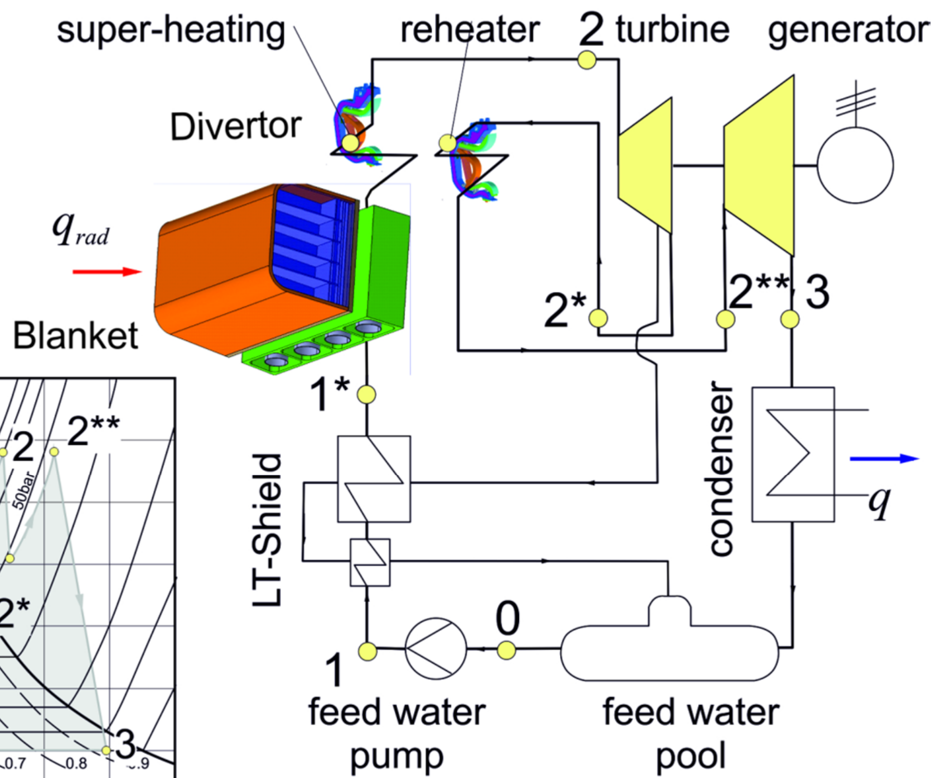
Blanket – Basic functions- „Interface➡PCS“

Clausius- Rankine Process

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

P_{fus} DEMO*	4050 MW
$P_{el,n}$	1500 MW
Plant efficiency, $P_{el,net} / P_{fus}$	37 %
P_{pumps}	400 MW
η_{th}	42 %

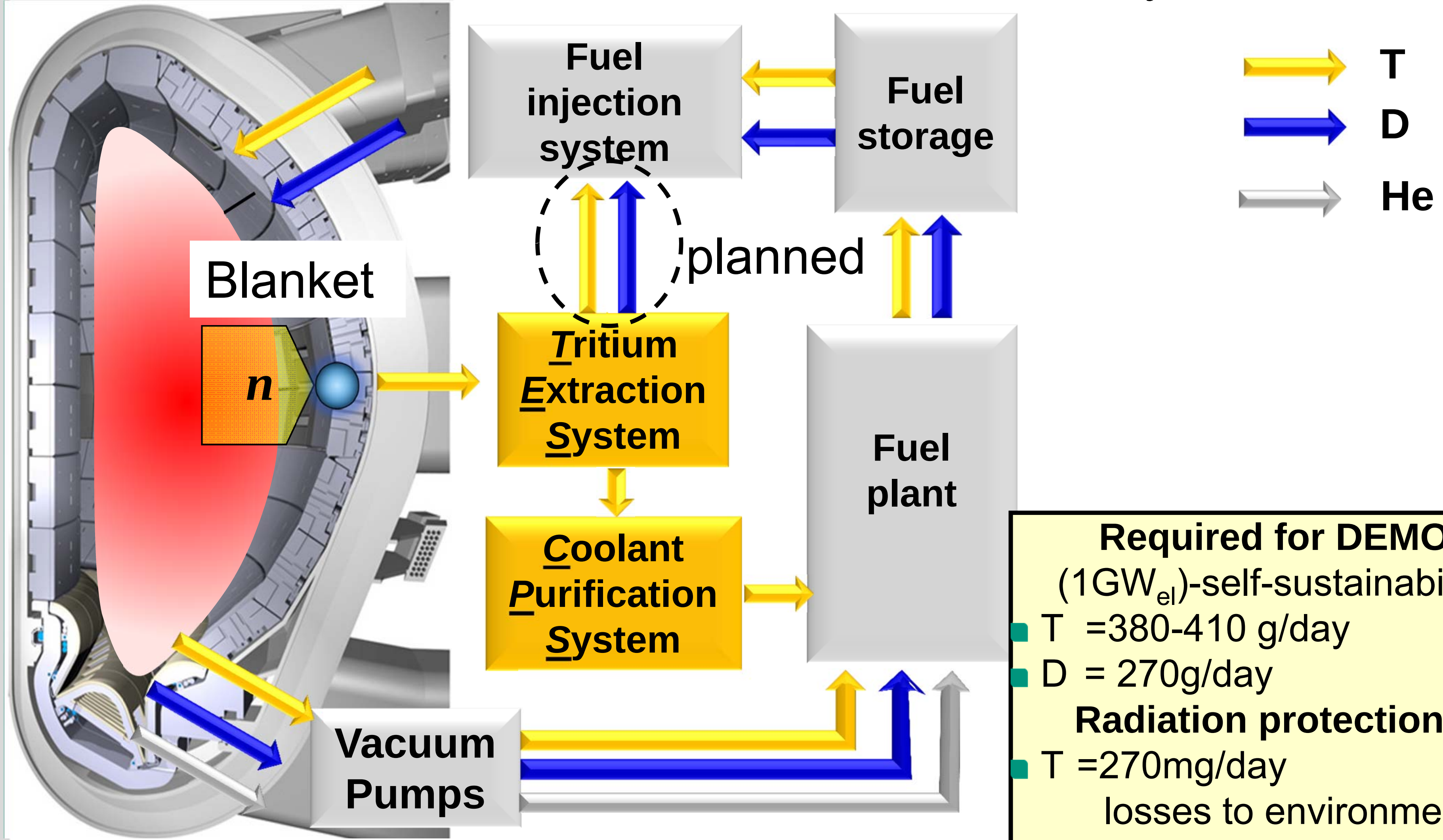




* Boccaccini, 2012, lecture

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
- T =270mg/day losses to environment

Blanket - Basic functions- „Interface➡tritium plant“

- **Tritium management = coolant dependent ***

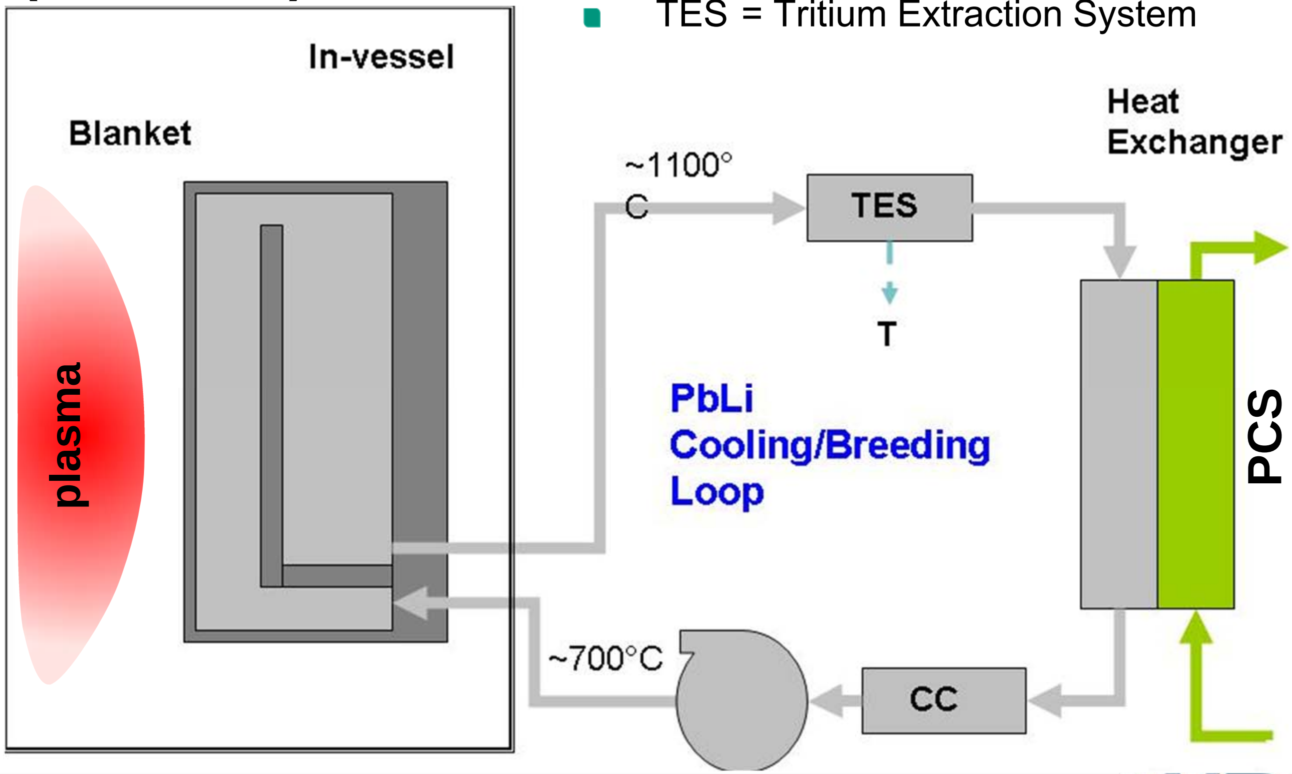
Potential coolants

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

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

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

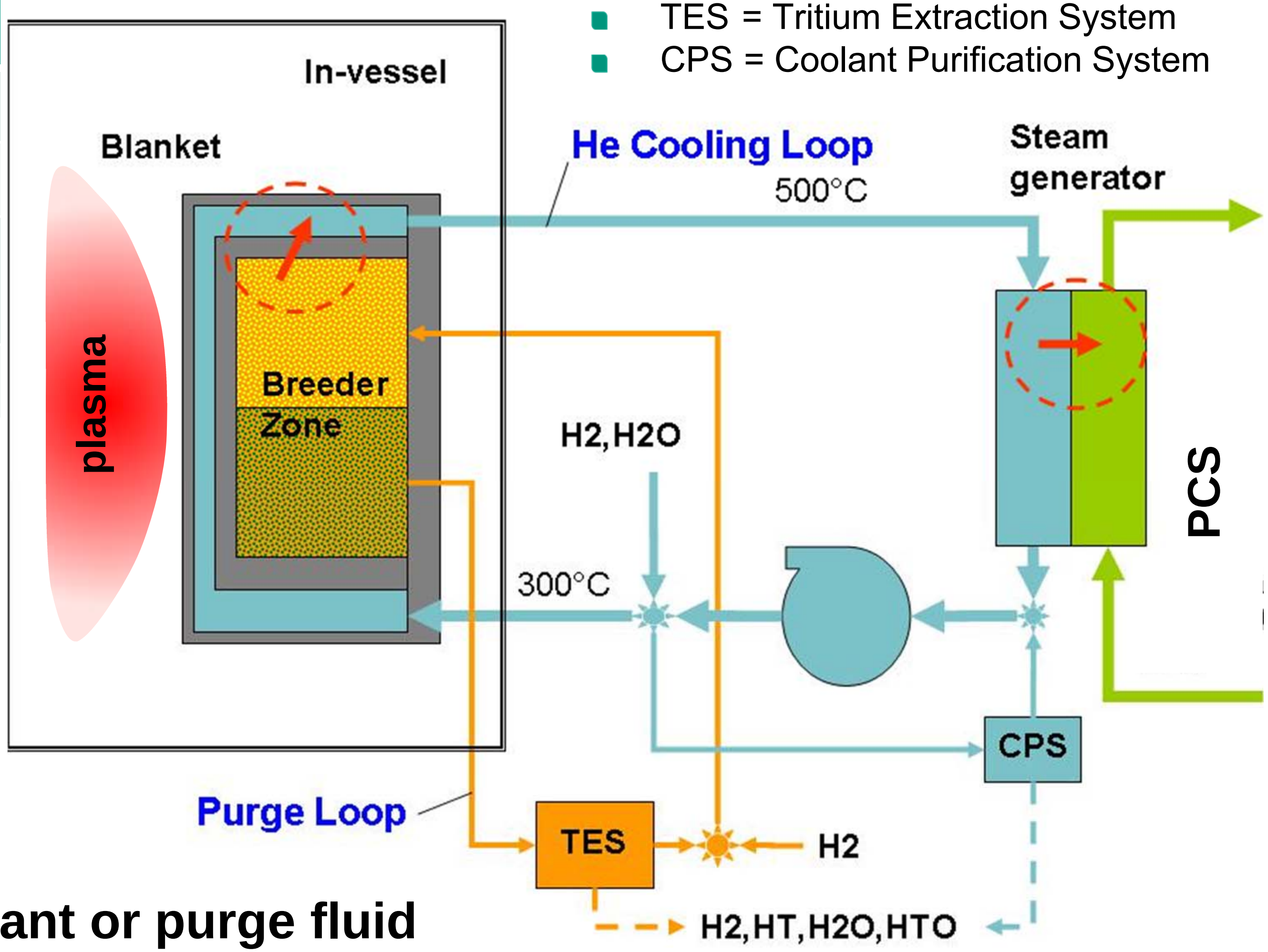


Blanket - Basic functions- „Interface➡tritium plant“

- **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 functions- „Transfer fluid“

- Optimal coolant ?

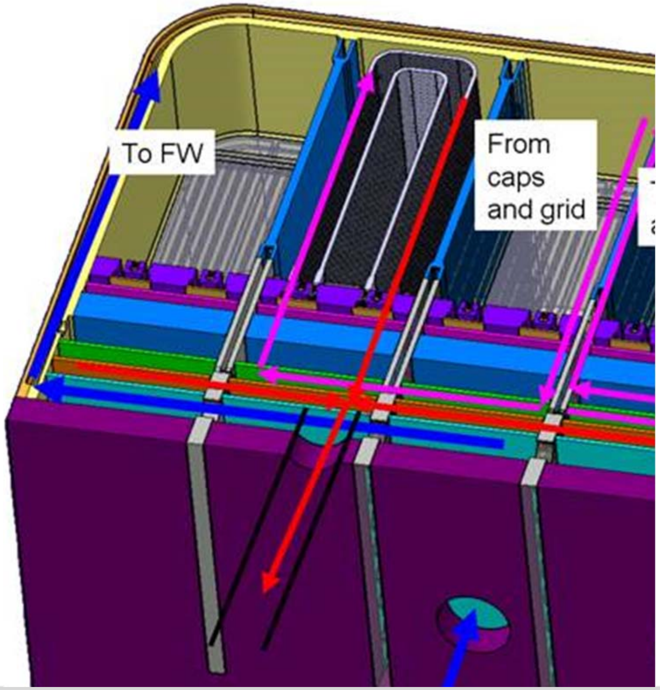
PbLi /Li	Helium	Water	Salt (FLiBe)	Criteria
++ + (if elec. Insulation) - -	+ - ++	++ - - 	0 0 -	**Coolant capacity** ▪ ΔT (heat transfer) ▪ pressure ▪ Magnetohydrodynamics
0	++		0	**Coolant chemistry**
++ ++	- - - -	+ 0	+ ++	**Balance of Plant** ▪ pumping power ▪ thermal inertia
+(PbLi)/- (Li) +(PbLi)/- (Li)	++ 0	- - -		**Tritium** ▪ breeding /T-Inventory ▪ extraction
- - +	++ -	- -	- - 0	struct. material compatibility ▪ corrosion ▪ erosion
-- (PbLi)/ -Li - - 0	++ ++ ++	0 - -	0 - - -	safety/decomissioning ▪ activation (incl. T-inventory) ▪ chemical interaction (H_2O,O_2) ▪ decommissioning

➡ all transfer fluids poses challenges and require R&D

Blanket – Basic design - „Structures“

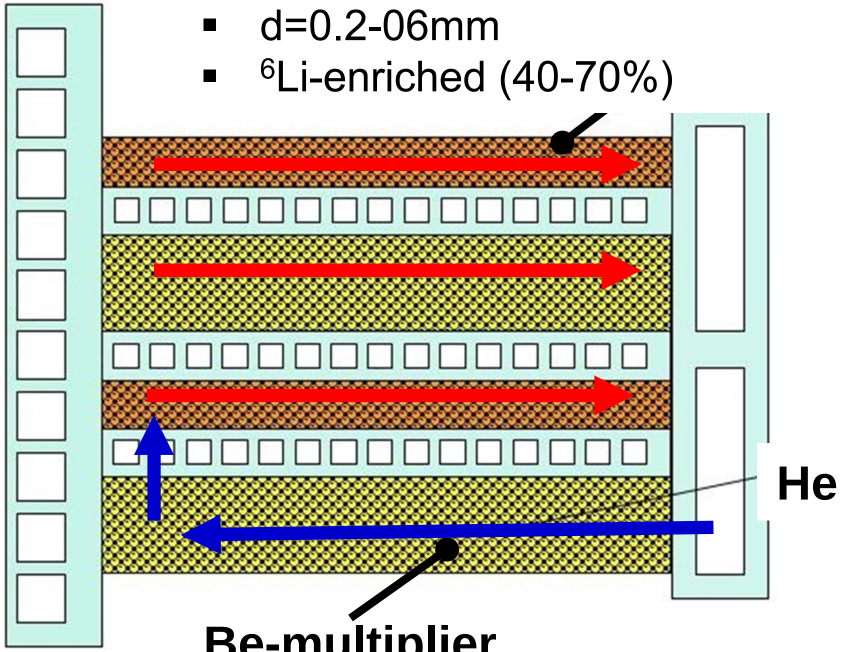
Fundamental design – HCPB blanket

- 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



Ceramics breeder

- Pebble bed 64% packing factor
- d=0.2-06mm
- ^{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

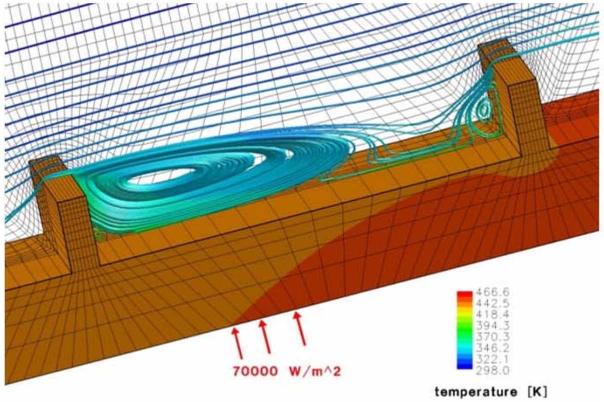
Now computations may start

- Thermal-hydraulics
- Thermo-mechanics
- Transient behavior

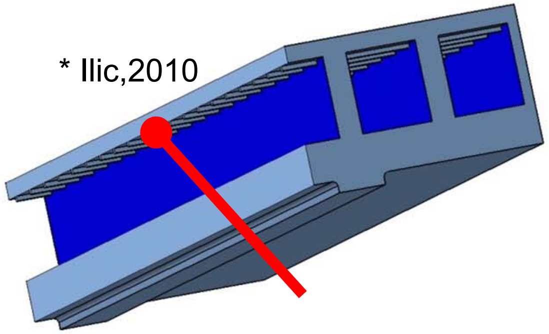
Example HCPB blanket

improved FW-Cooling

- structuring of coolant ducts



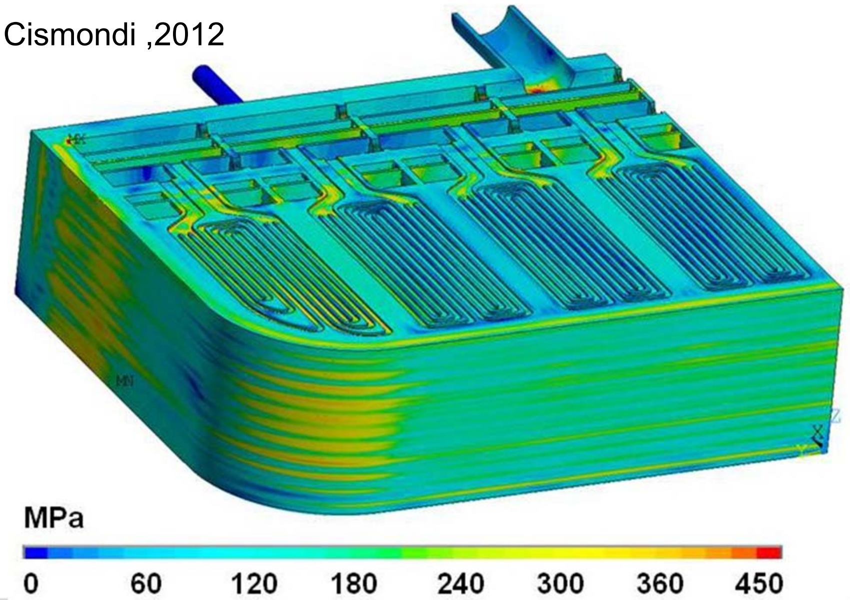
* Ilic,2010



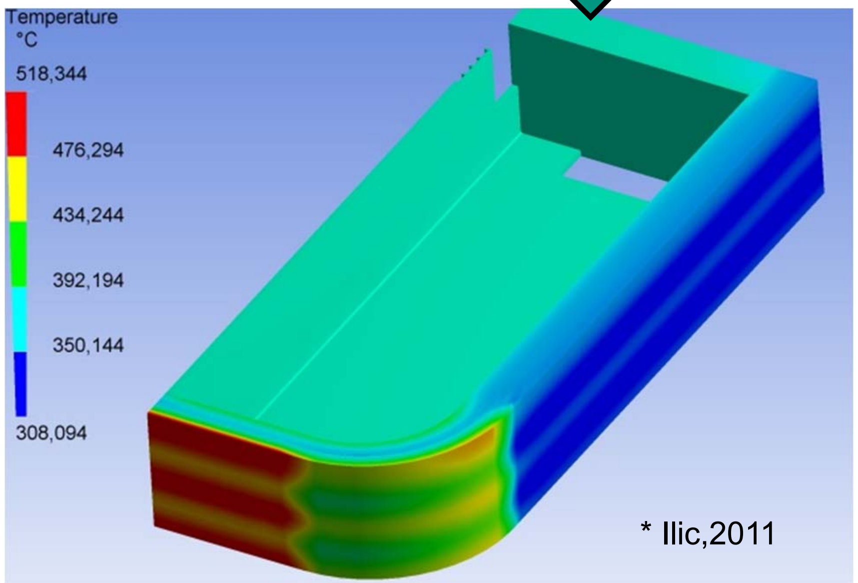
$k \approx 7150$ W/m²K

stress distribution

* Cismondi ,2012



temperature distribution



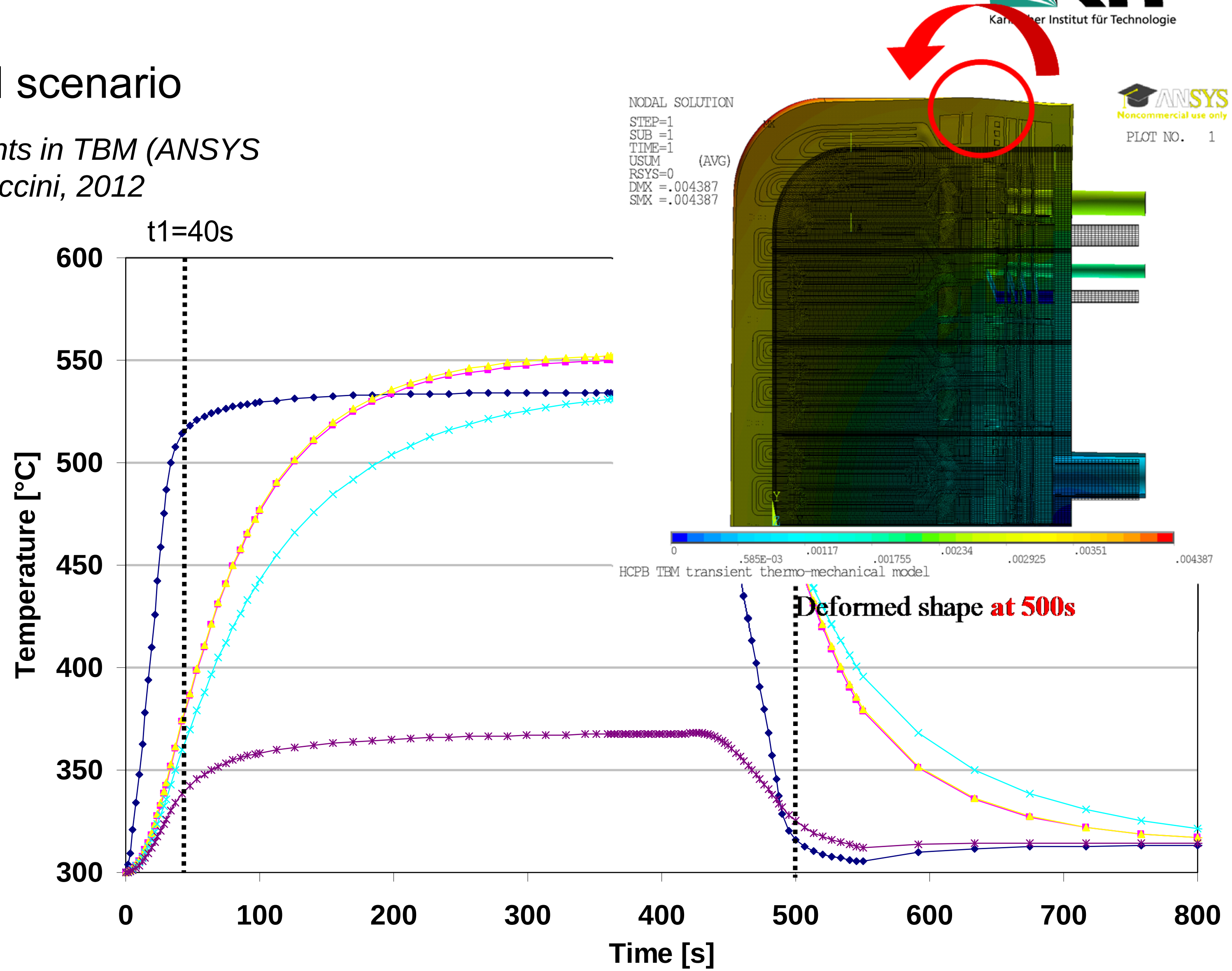
Blanket – Basic design - „Verification“

HCPB

Transients

- ITER typical scenario

Temperature transients in TBM (ANSYS Calculations), Boccaccini, 2012



Blanket – Basic design - „Fabrication “

HCPB

How to fabricate modules ?

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

Example HCPB blanket

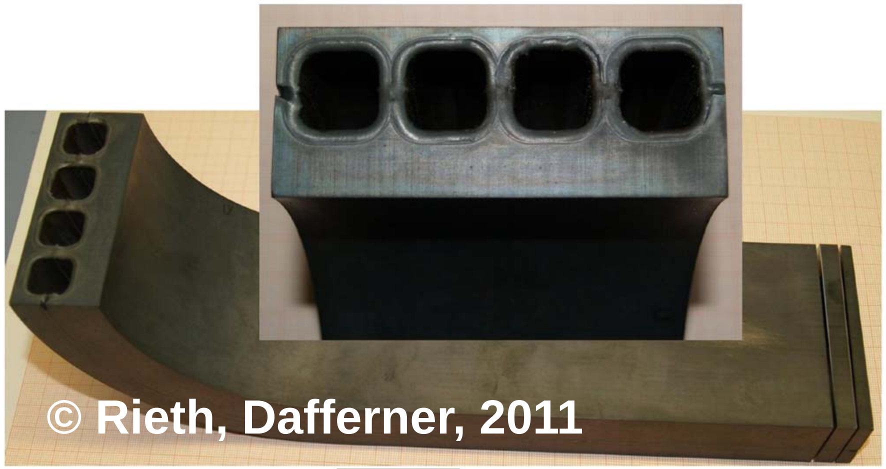
First wall coolant ducts

- **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

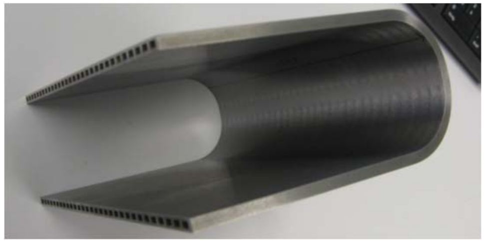
© Full scale FW- mock-up

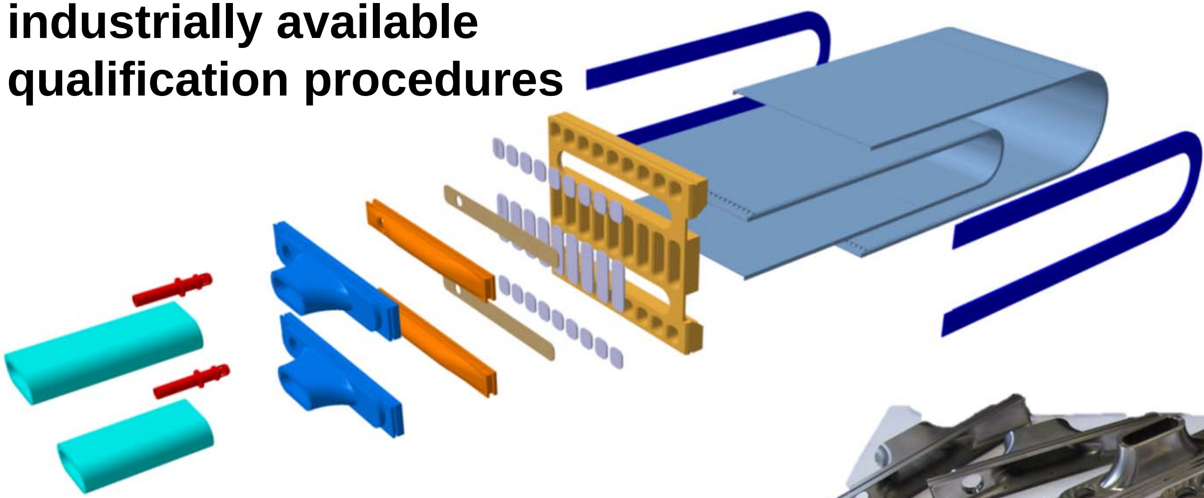
Blanket – Basic design - „Fabrication “

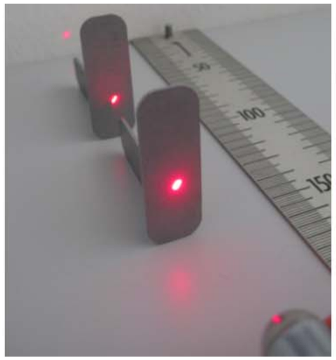
HCPB

Breeder units

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







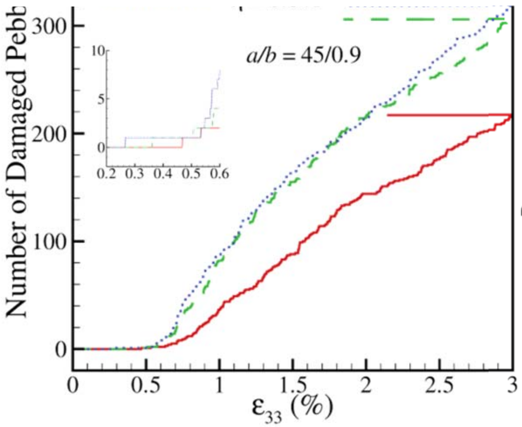
Blanket – basic design - „Fabrication“

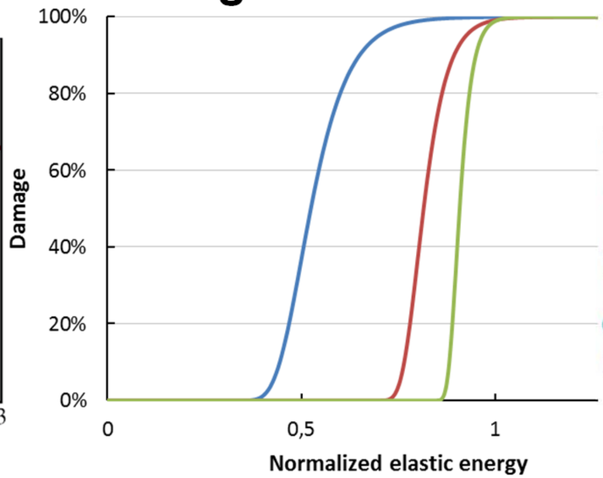
HCPB

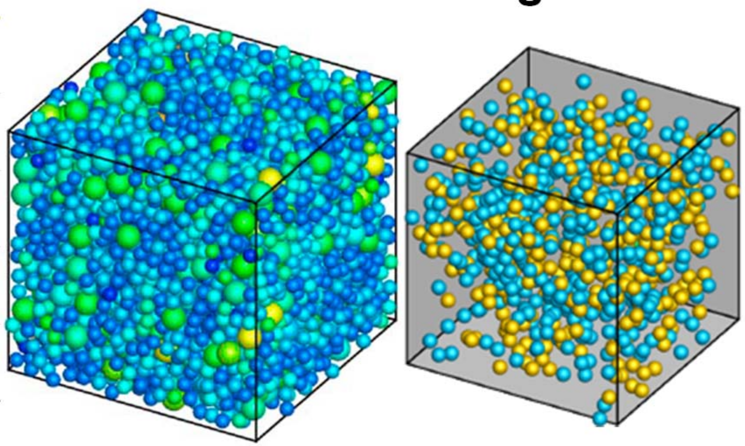
Breeder particle beds and multiplier

- breeder production by melt spraying

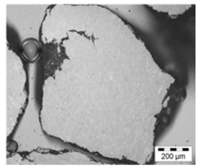
- Pebble bed characterization
  - packing factor
  - damage
  - life-time&rad. damage models



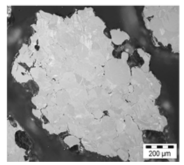




- Beryllium pebbles
  - successful fabrication of $Be_{12}Ti$
  - grain size characterization& process optimization



GS~10-30 µm

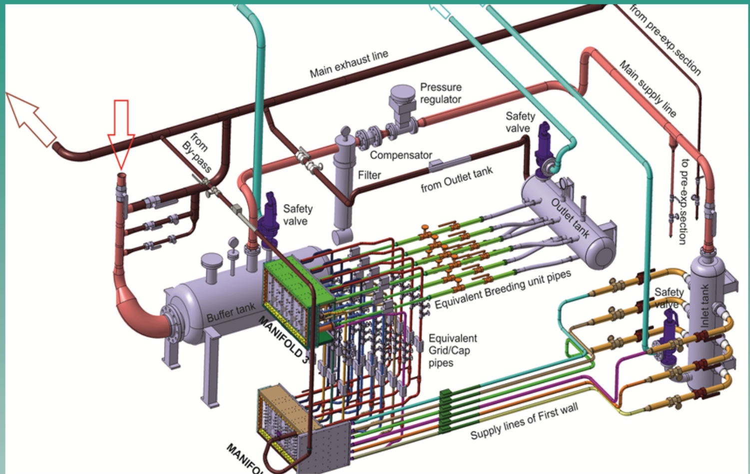


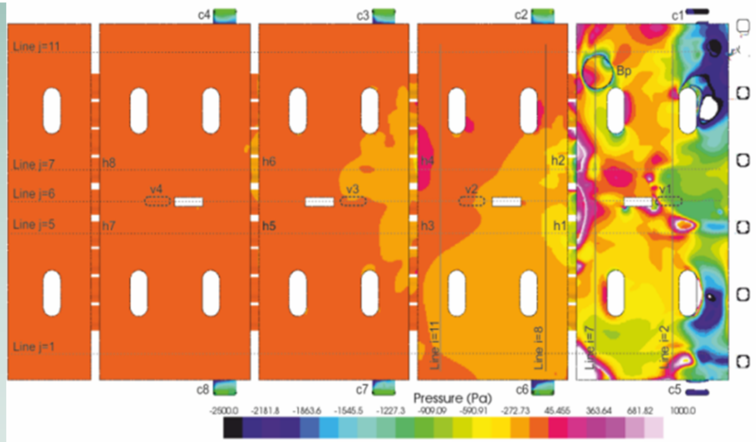
GS~30-60 µm

Blanket –Design - „Validation“

HCPB

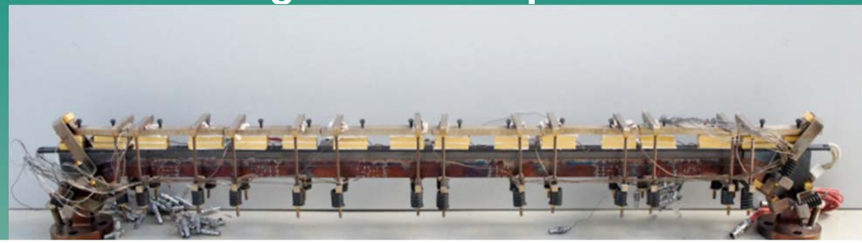
Blanket hydraulics manifold/distributor (GRICAMAN)

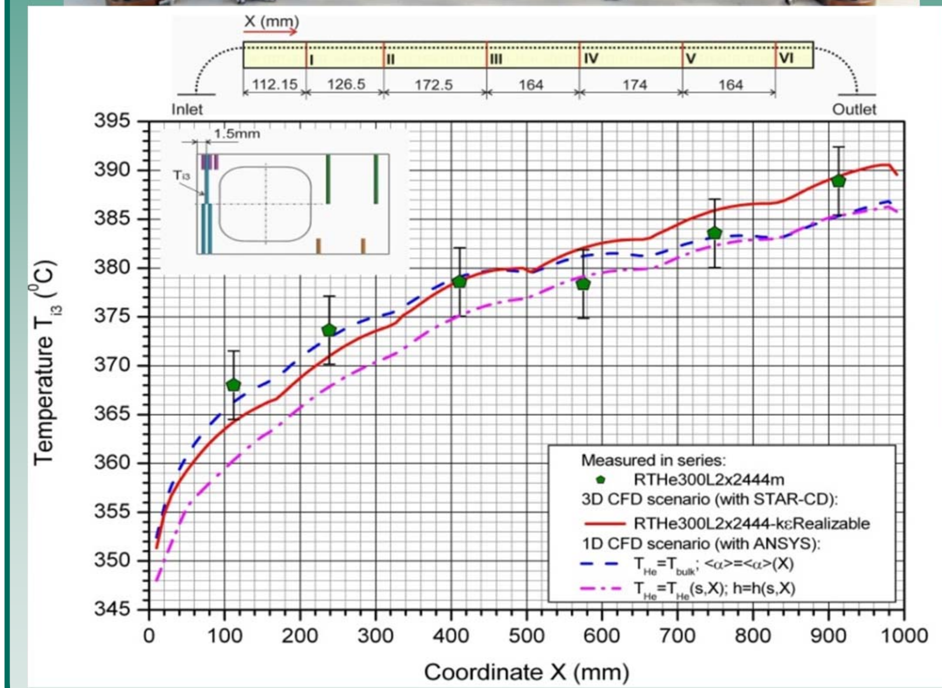




Flow distribution of TBM manifold system simulated and verified against experiment in 1:1 fabricated mock-ups

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

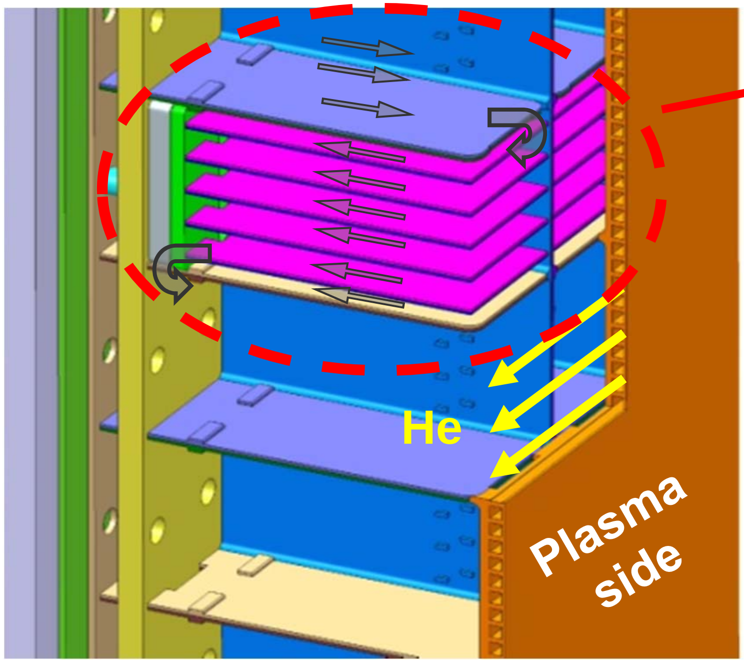
Blanket – Basic design - „Structures“

Fundamental design – HCLL blanket

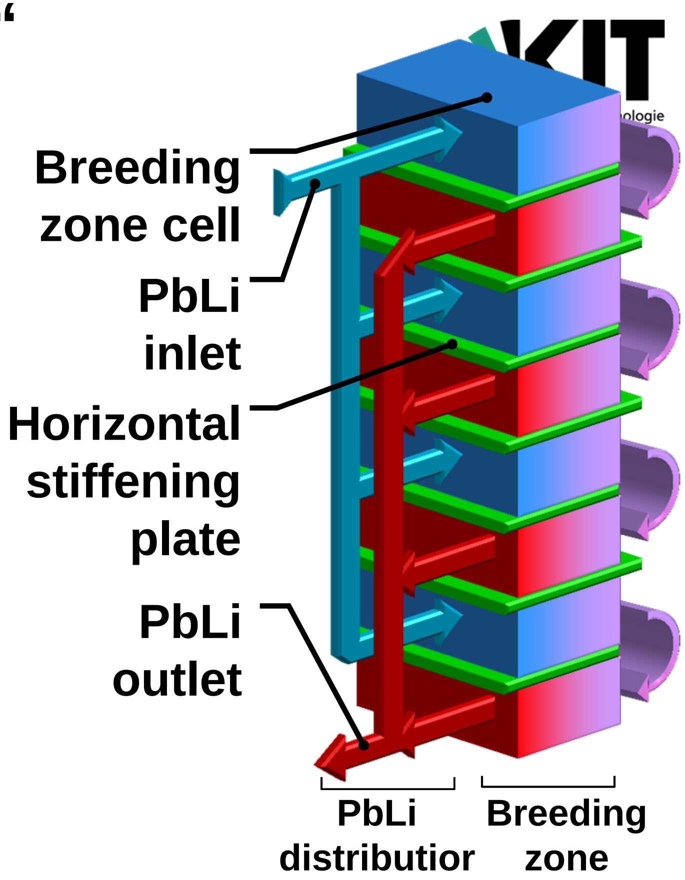
- simple coolant/breeder/multiplier set-up homogenously mixed

Challenges

- Interaction of magnetic field with moving liquid ➡ magnetohydrodynamics (MHD)
- Corrosion of structures by lead
- Low soluability of Tritium in PbLi



modular breeder units



Design aspects (similar as HCPB)

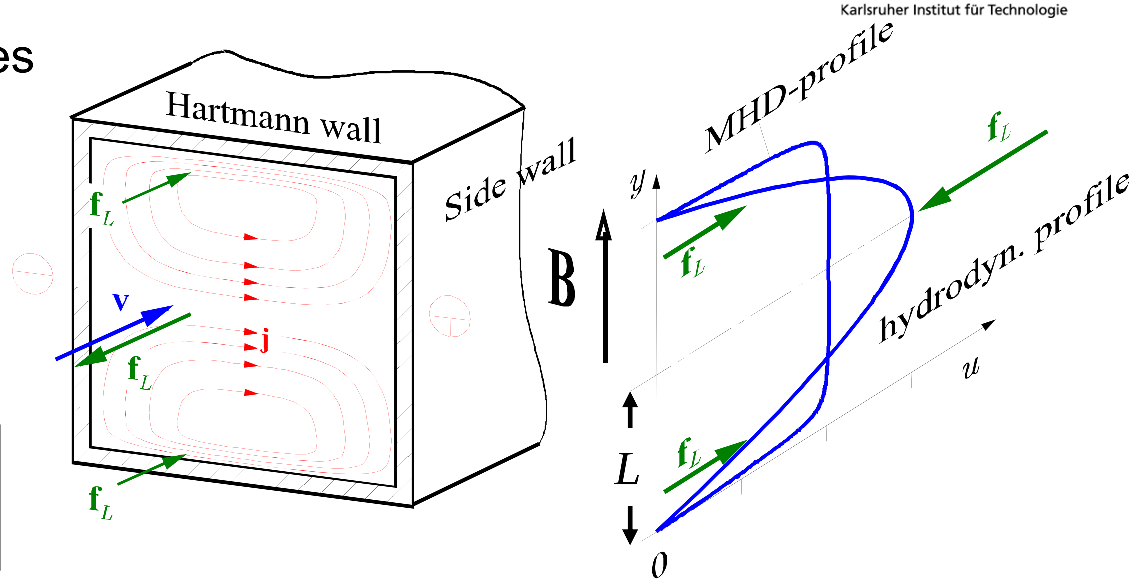
- modular breeder units ➡ mass fabrication
- robust simple modules ➡ pressure resistant
- central feeder /collector units reduced replacements efforts

HCLL

Blanket – Basic design - „Verification“ HCLL

Magnetohydrdynamics MHD

- Motion **v** of LM in B-field induces electric field E
- E drives electric current j
- j x B induces Lorentz Force F_L
- F_L opposing fluid motion



Hartmann - number

$$Ha = LB\sqrt{\frac{\sigma}{\rho\nu}} = \frac{\text{electromagnetic forces}}{\text{viscous forces}}$$

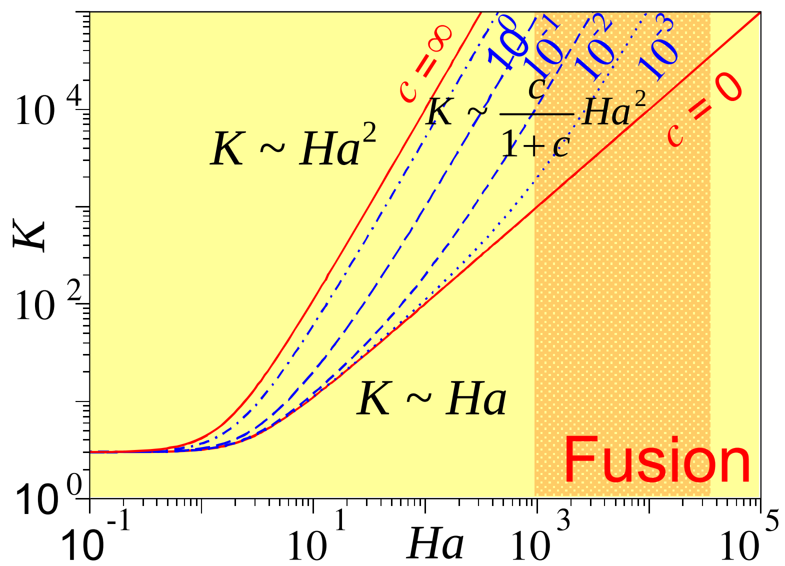
- fusion application Ha~ O(10)^4
- ➡ flow dominated by MHD-effects

Other impacts caused by MHD

- increased Δp dependent on wall conductance ratio c

$$c = \frac{t_w \sigma_w}{L\sigma}$$

- Multi-channel effects by electric currents entering neighboring ducts ➡ Δp ↑
- ➡ electrical separation and/or low **v** mandatory



Blanket – Basic design - „Verification“

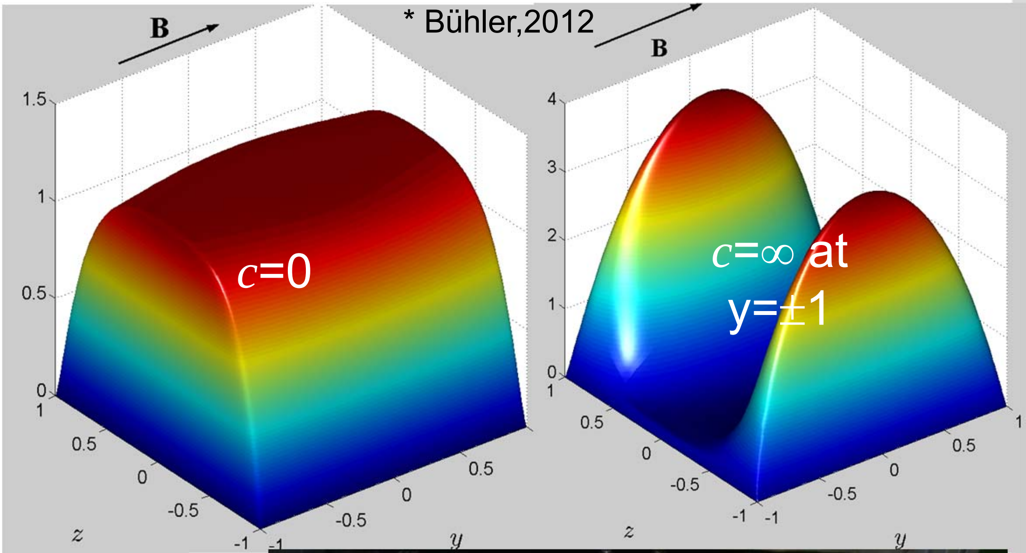
HCLL

Magnetohydrdynamics MHD

- strange velocity profiles dependent on wall conductivity c

Example Ha=50

➡ MHD adapted flow arrangement required to ensure TH-integrity

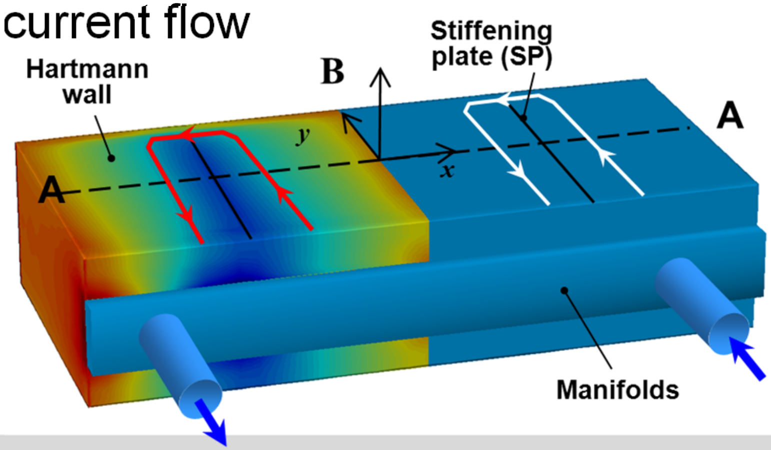


MHD -experiments

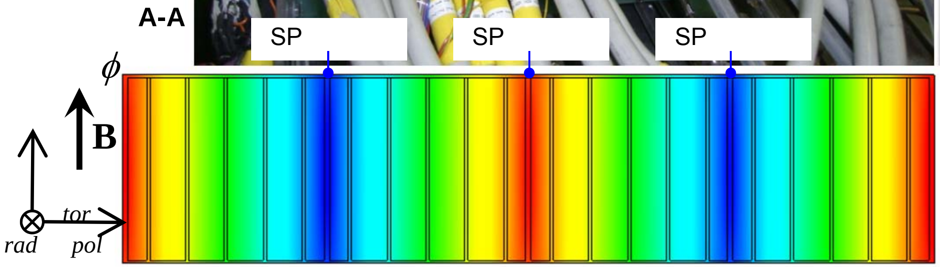
- Flow velocity depicts as electric potential ϕ on walls

$$v \approx \frac{1}{B}\frac{\partial \phi}{\partial x}$$

- Multi-channel effects reduced by counter-current flow



* Bühler,2011



Blanket – Basic design - „Verification“

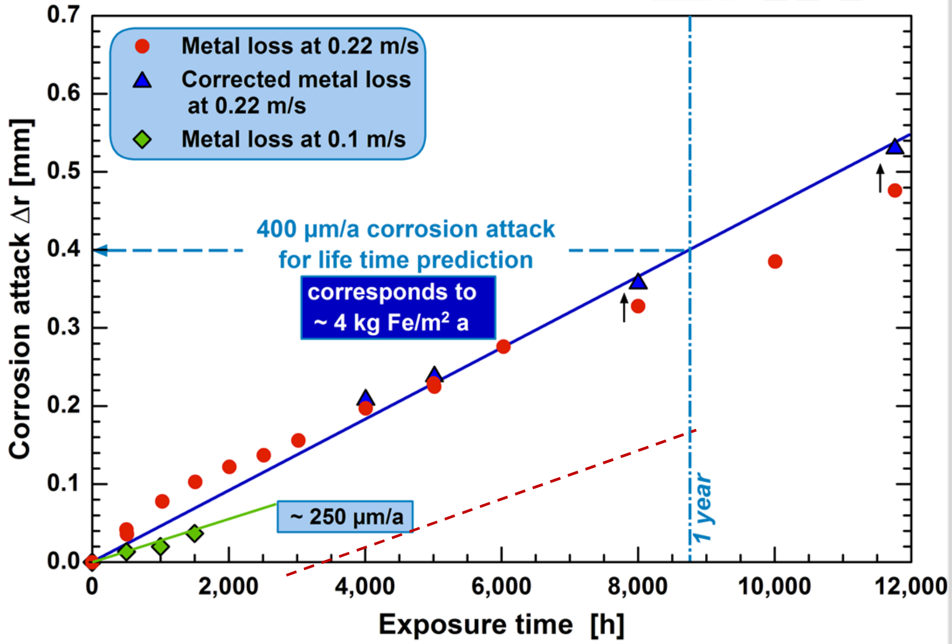
HCLL

- liquid metal **corrosion** of steels due to dissolution attack of alloy constituents.

Example: RAFM-steel in flowing PbLi

- **Corrosion rates velocity dependent, vary between 250 and 400 µm/year.**

*Konys, J. Nuc. Mater., 417 (2011) 1191.

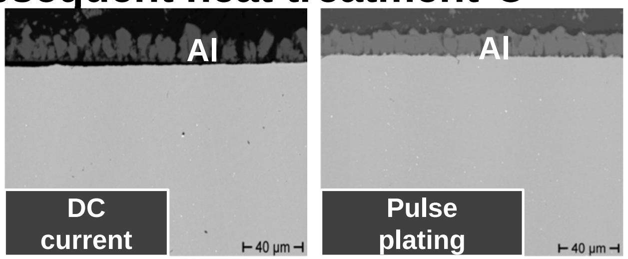


- Protective **coatings** with aim
  - corrosion reduction
  - Tritium permeation barrier
  - reduction of electric current densities

Example: pluse-plating of Al on RAFM-steel

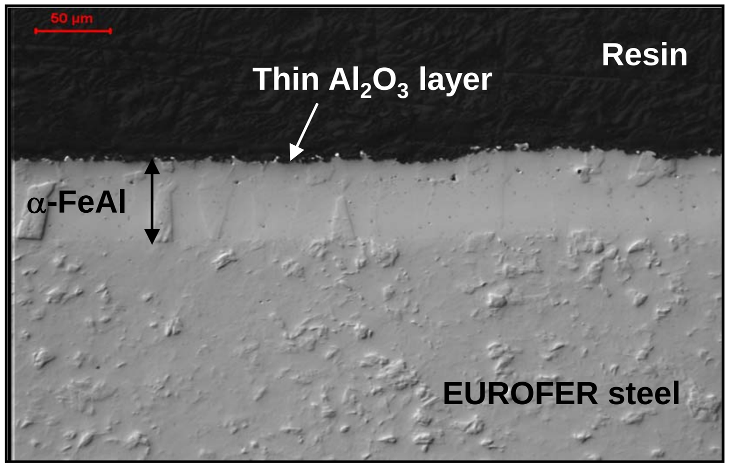
- **electrodeposition process ①**
- **Subsequent heat treatment ②**

①



W. Krauss, J. Nuc. Mat., 417, 1233 (2011)

②



Micro structure after heat treatment

Institute for Neutron Physics and Reactor Technology

Blanket – Final design - „Integration“

Requirements for a FPP

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

\+ decommisioning, repository, …

Limiting component factors:

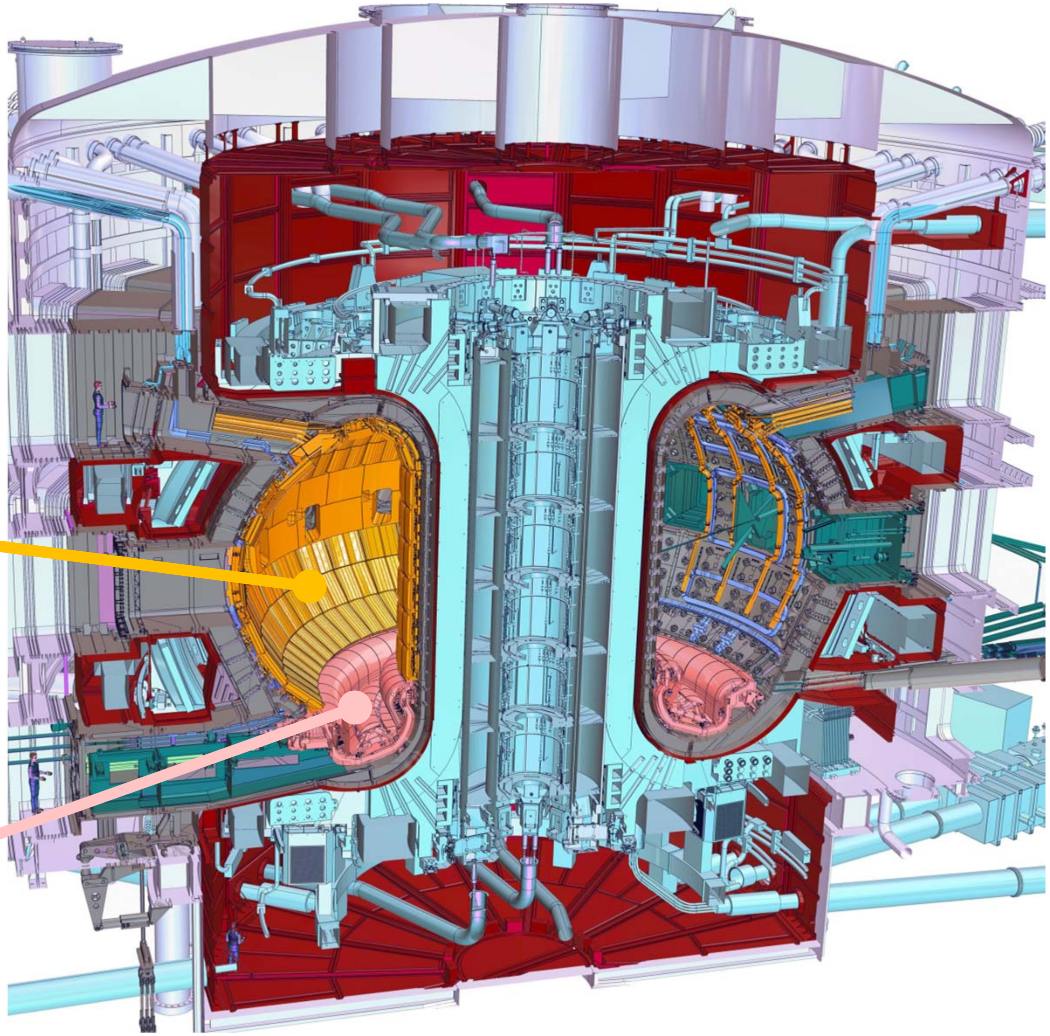
- Plasma facing components
- accumulated dose
- fatigue, creep,…..

Blanket

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

Divertor

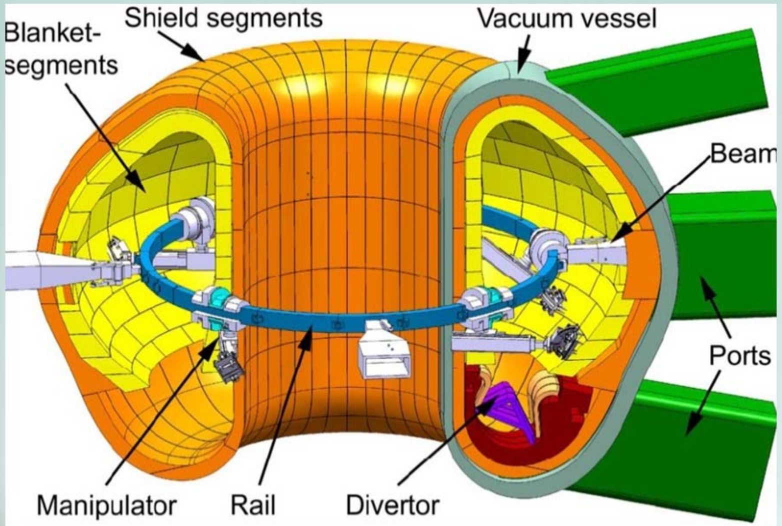
- mat. damage 15-30dpa
- fatigue 10-20MW/m^2
- ➡ remote extraction
- ➡ life-time 1.5-2.5years



Blanket – Final design - „Integration“

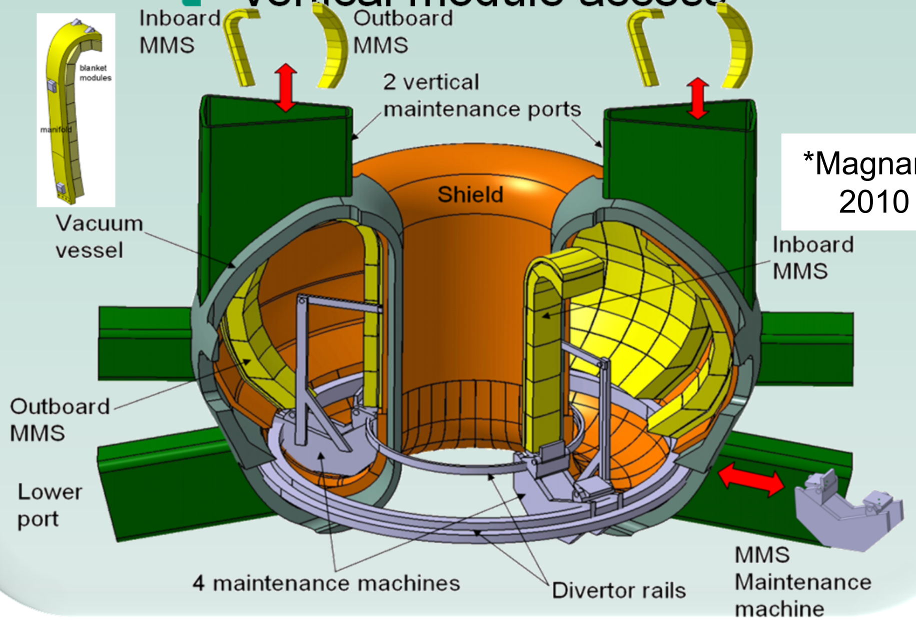
ITER configuration

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



Multi-Module-Segment (MMS)

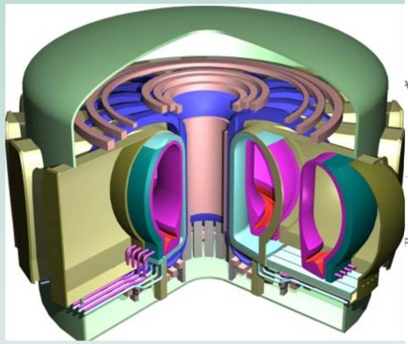
- rail based maintenance
- vertical module access

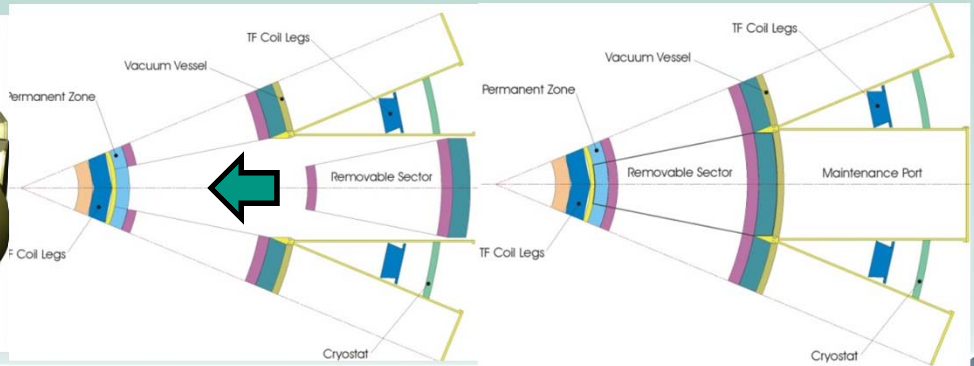


*Magnani, 2010

Large sector concept

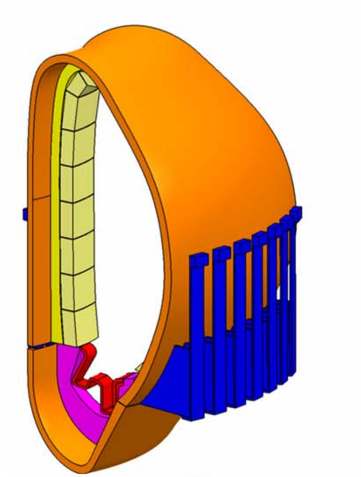
- horizontal access
- horizonatal seeming

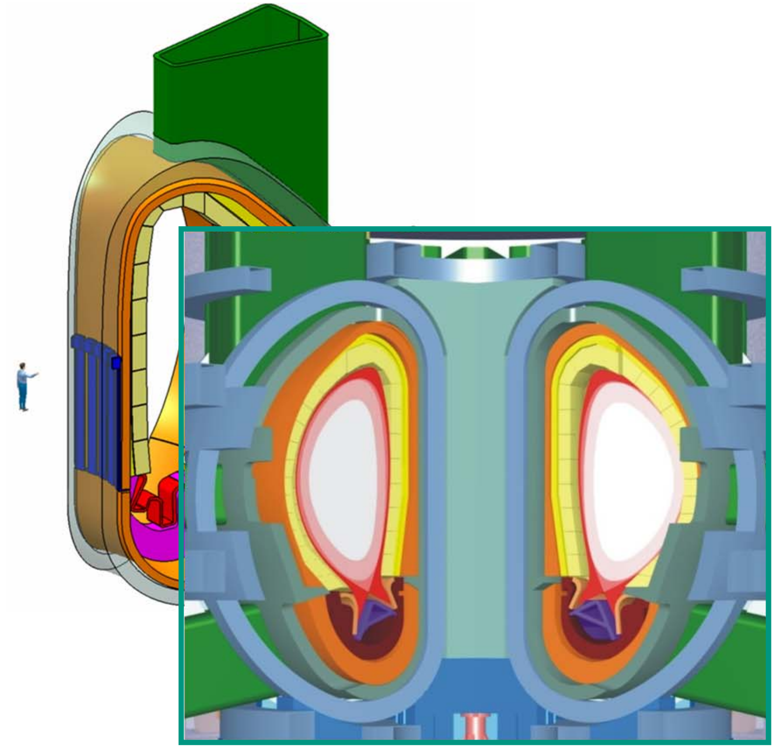


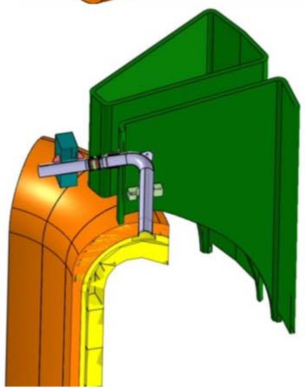


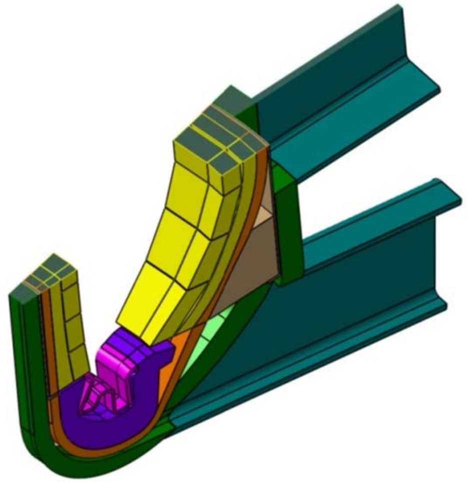
ARIES, US-study

Blanket – Final design - „Integration“



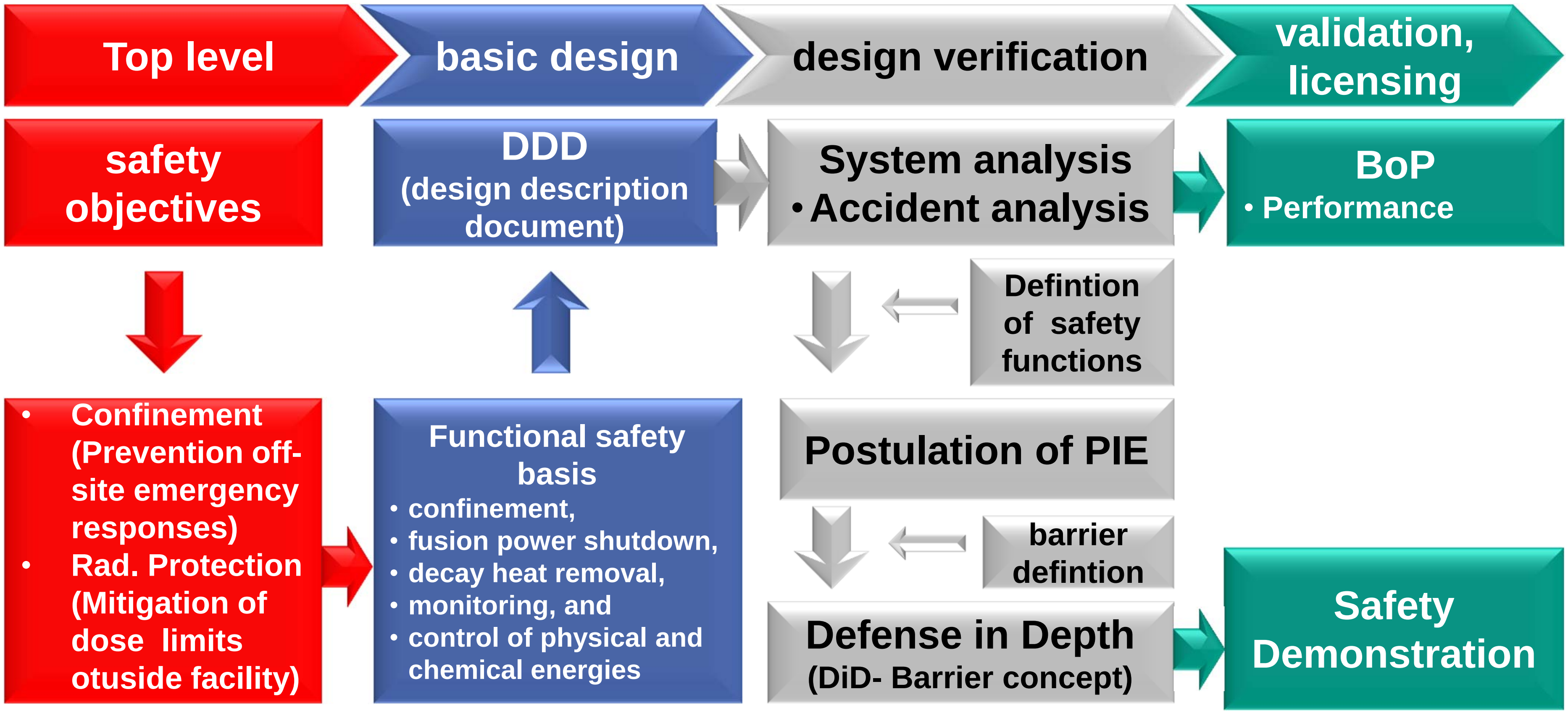




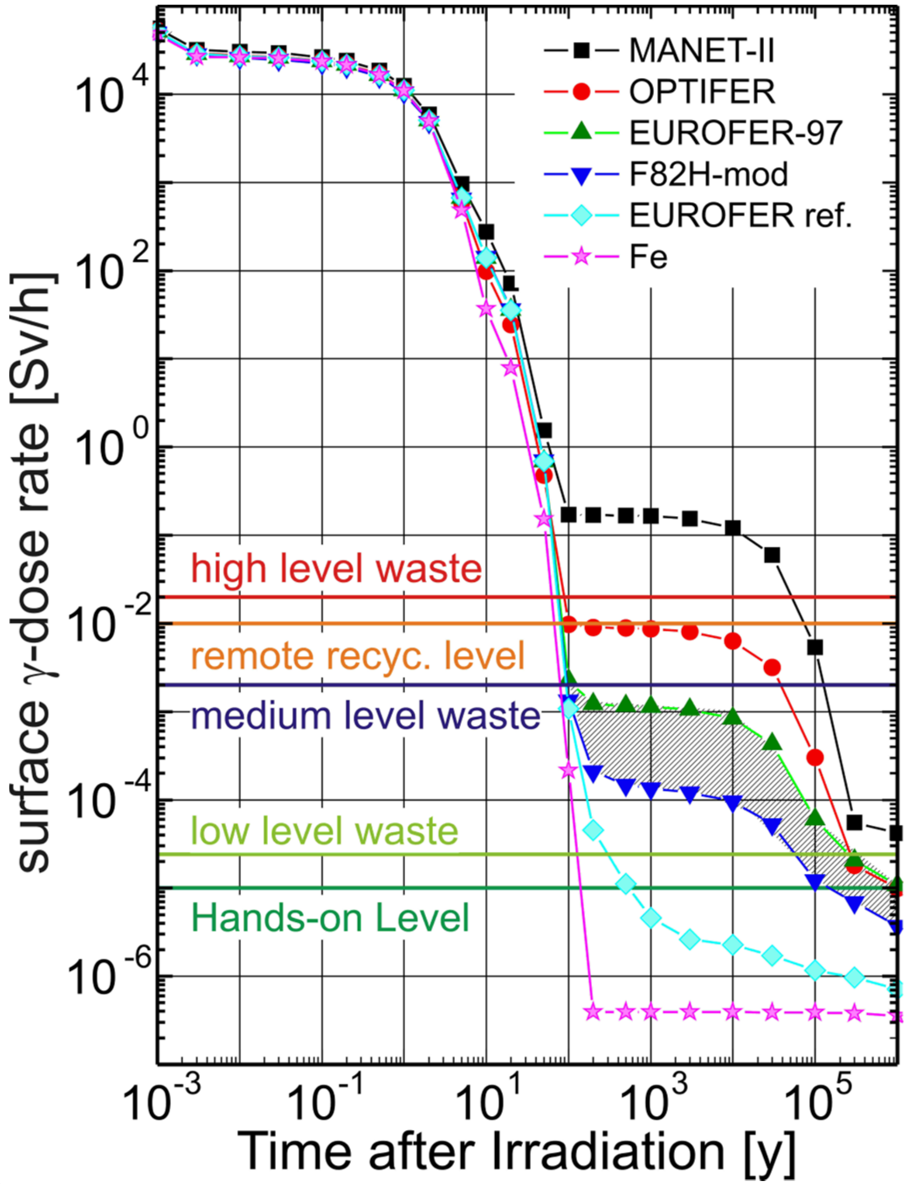


Plant – Final design - „Safety- Licensing“

- ALARA principle (*A*s *L*ow *A*s *R*easonable *A*chievable) for
  - normal and off-normal events (low event frequency)
  - design robustness and material choice (activation, self-limiting design)
  - maintenance, reprocessing and disposal
- Safety demonstration (sequential nature)



Blanket – Final design - „Integration“



Long term irradiation (12.5 MWa/m^2) of a DEMO reactor first wall
***Fischer, 2012**

Design safety - 1st step material

- activation
- remote handling
- decomissioning, post-processing
- …

RAFM 8-10%CrWTaV steels

- reference fast decaying Fe- alloys
- „Low level waste“ after 80-900y
- Reduced amount of HLW
- Impurities Nb, Mo dominate grey domain

➡ Material irradiation data base @ fusion specific spectrum still „sparse“

➡ IFMIF (Int. Fusion Material Irradiation Facility) mandatory

Blanket – Final design - „Integration“

Operational Safety

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

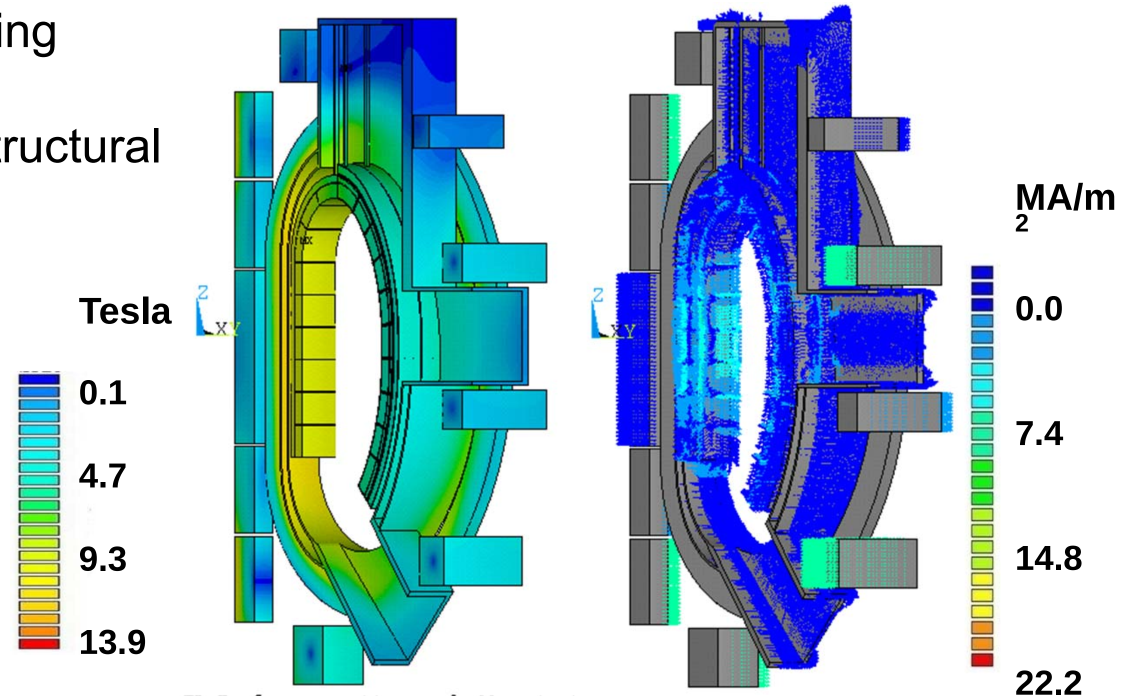
Pre-requisite

- validated codes to predict loads

Example : EM analyses of Blankets

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

B distribution | **Eddy currents distribution**



Blanket – Final design - „Integration“

Operational Safety- postulated initiating event (PIE)

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

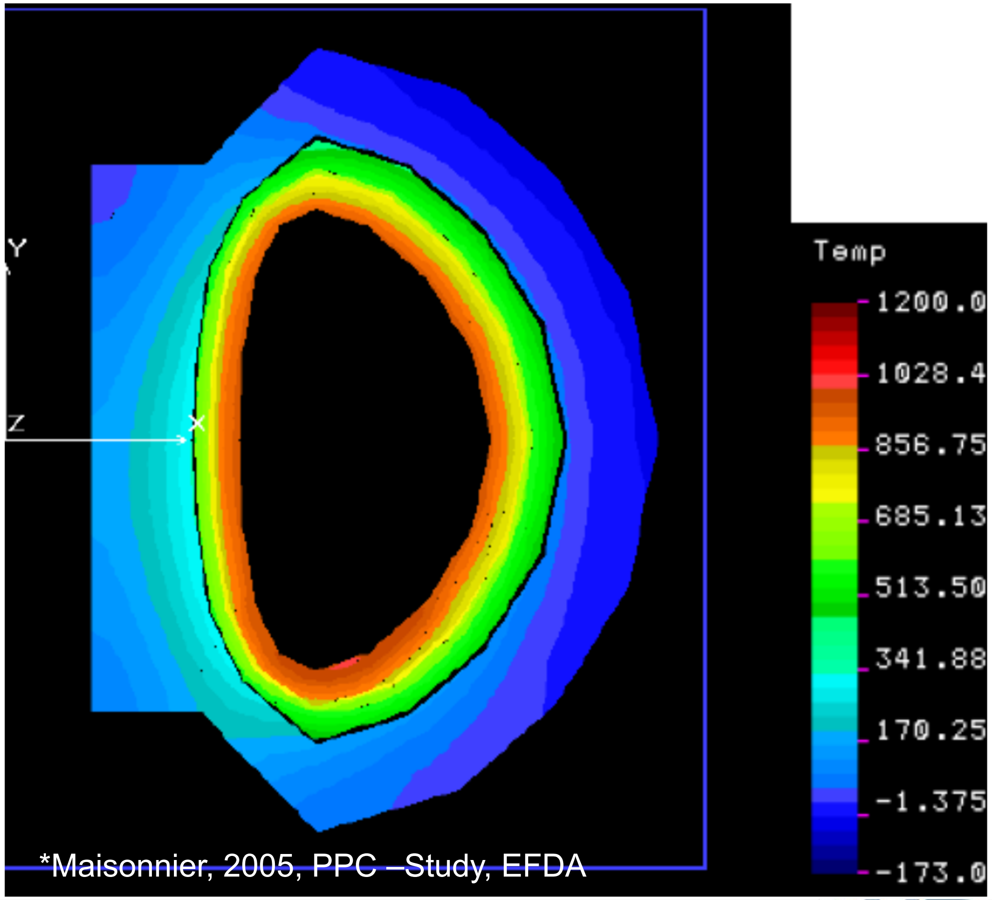
Bondary conditions

- end of life –blanket (➡ maximum decay heat)
- all emergency colling 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 !!!!

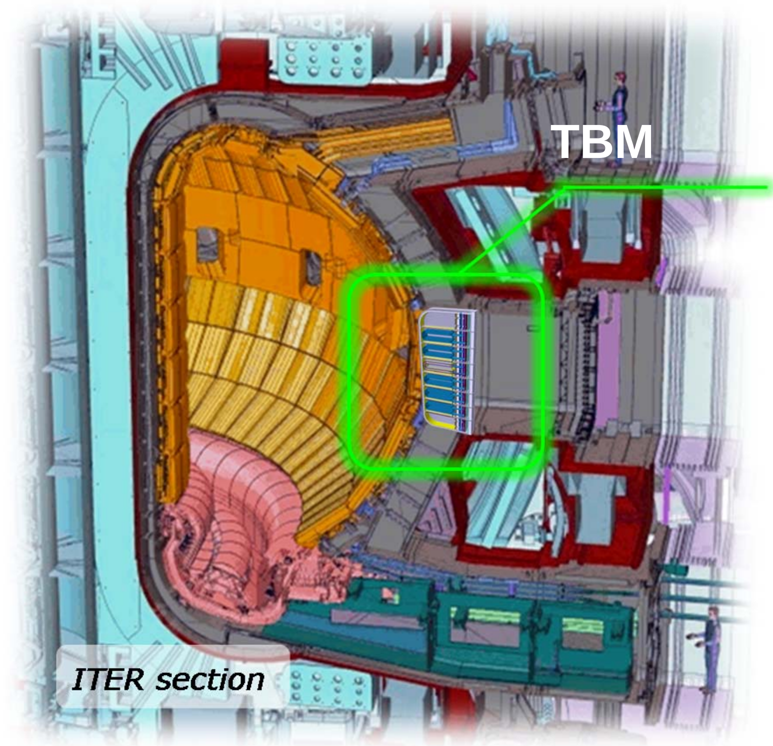


*Maisonnier, 2005, PPC –Study, EFDA

ITER – THE NEXT STEP

ITER TBMs

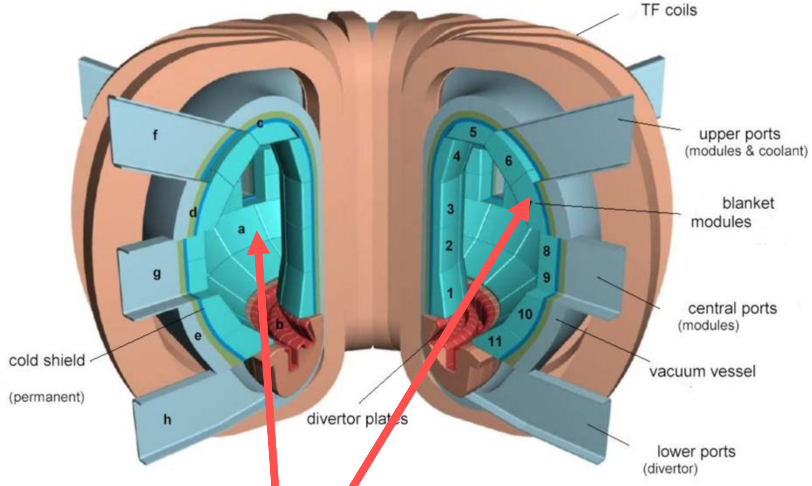
- Test of blanket systems in ITER Test Blanket Programme.
- ITER offers 6 positions for the testing of blanket concepts as Test Blanket Modules (TBM).
- 2 EU concepts (HCPB and HCLL) selected for testing.
- Each TBMs has a volume of about 0.8 m^3 with ~1 m^2 of first wall surface.

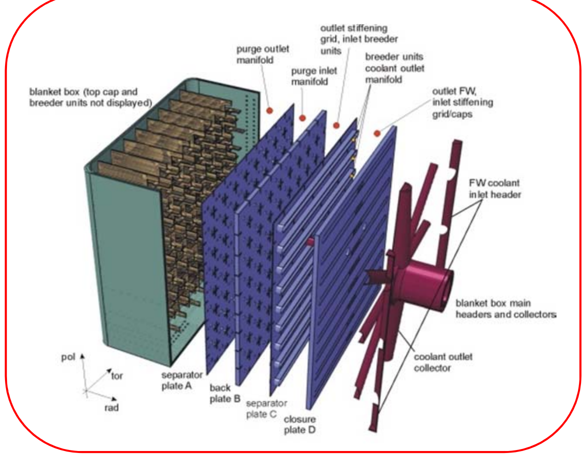


Location of TBM inside equatorial Port Plugs of ITER.

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



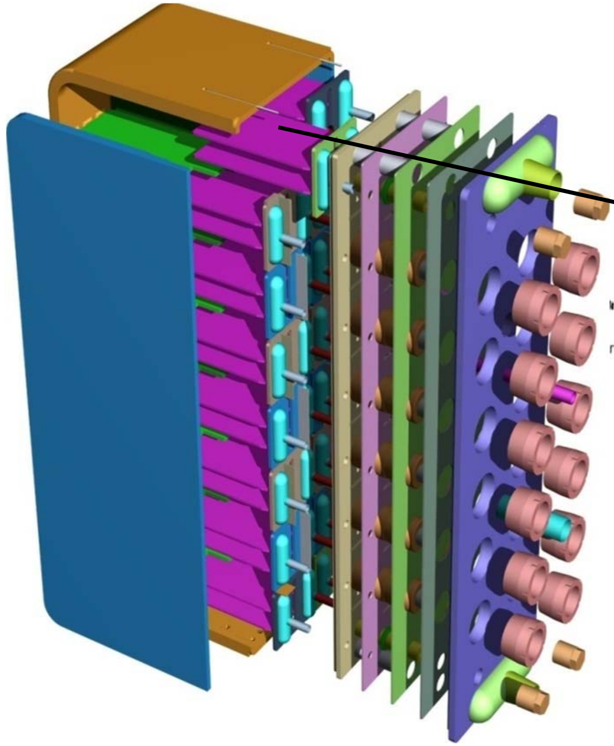


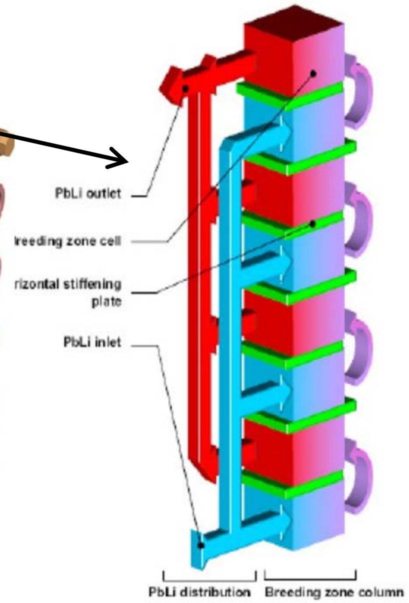
Breeder Blankets modules

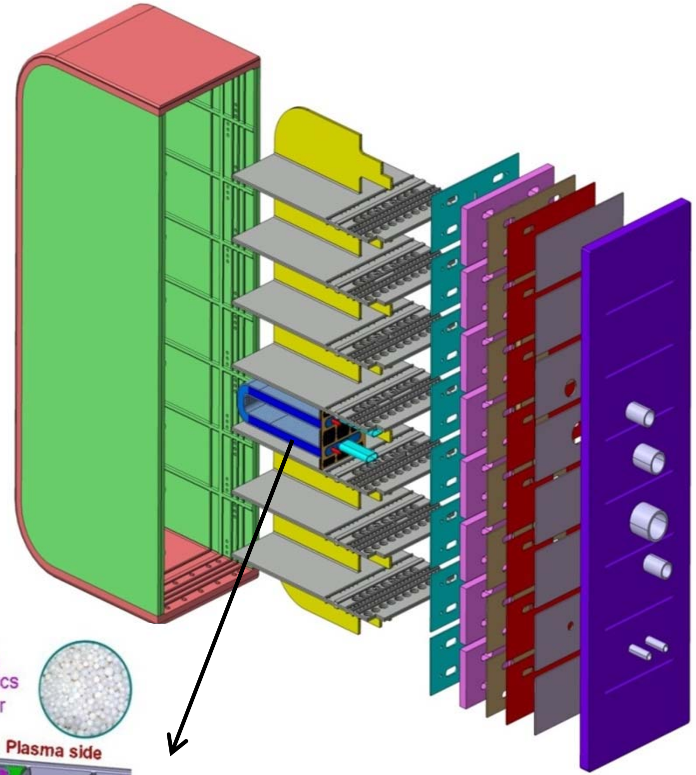
Main objectives

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

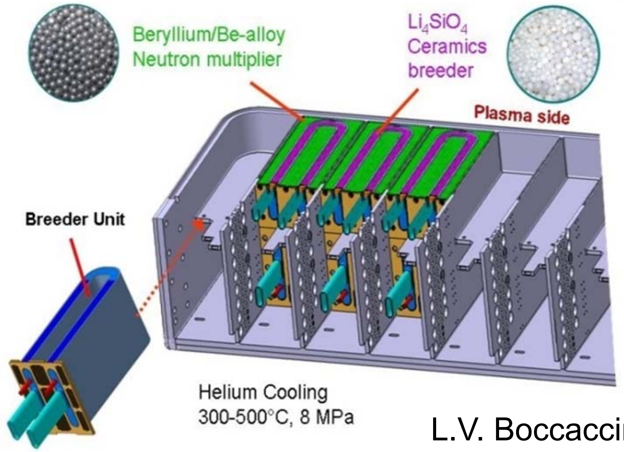
EU Test Blanket Modules







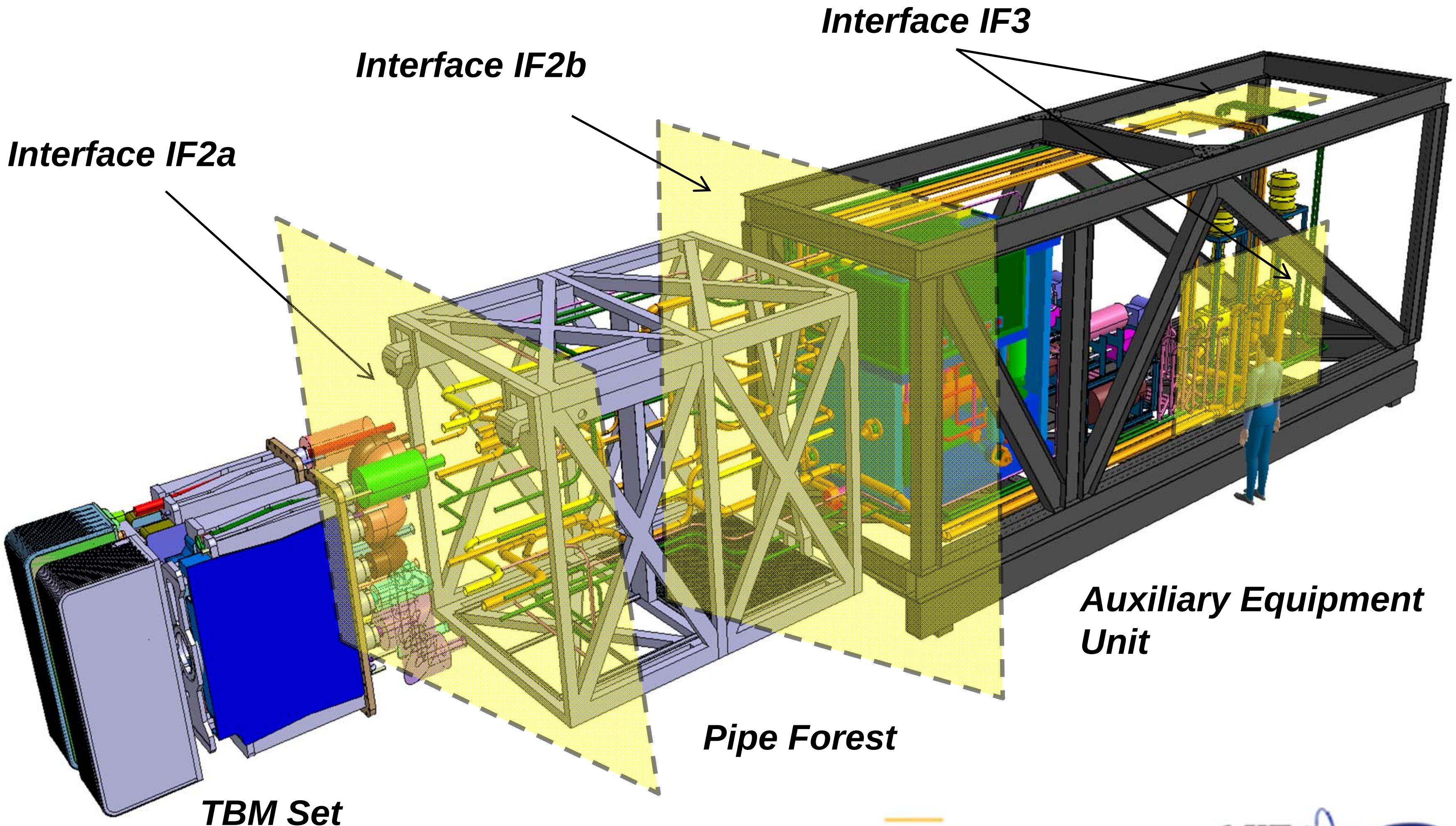
HCLL TBM



HCPB TBM

L.V. Boccaccini, et al., Fus. Engng. Des., 2011, p.478.

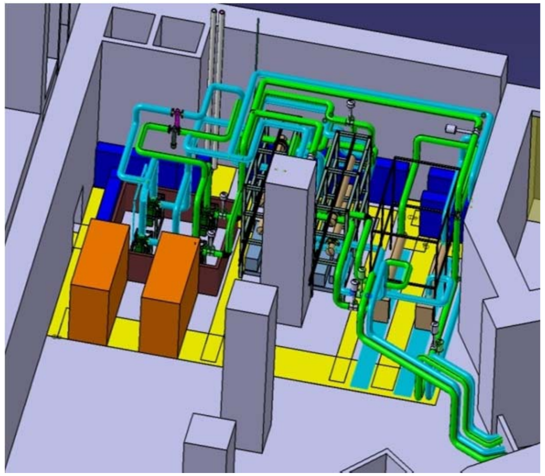
EU TBS design & integration

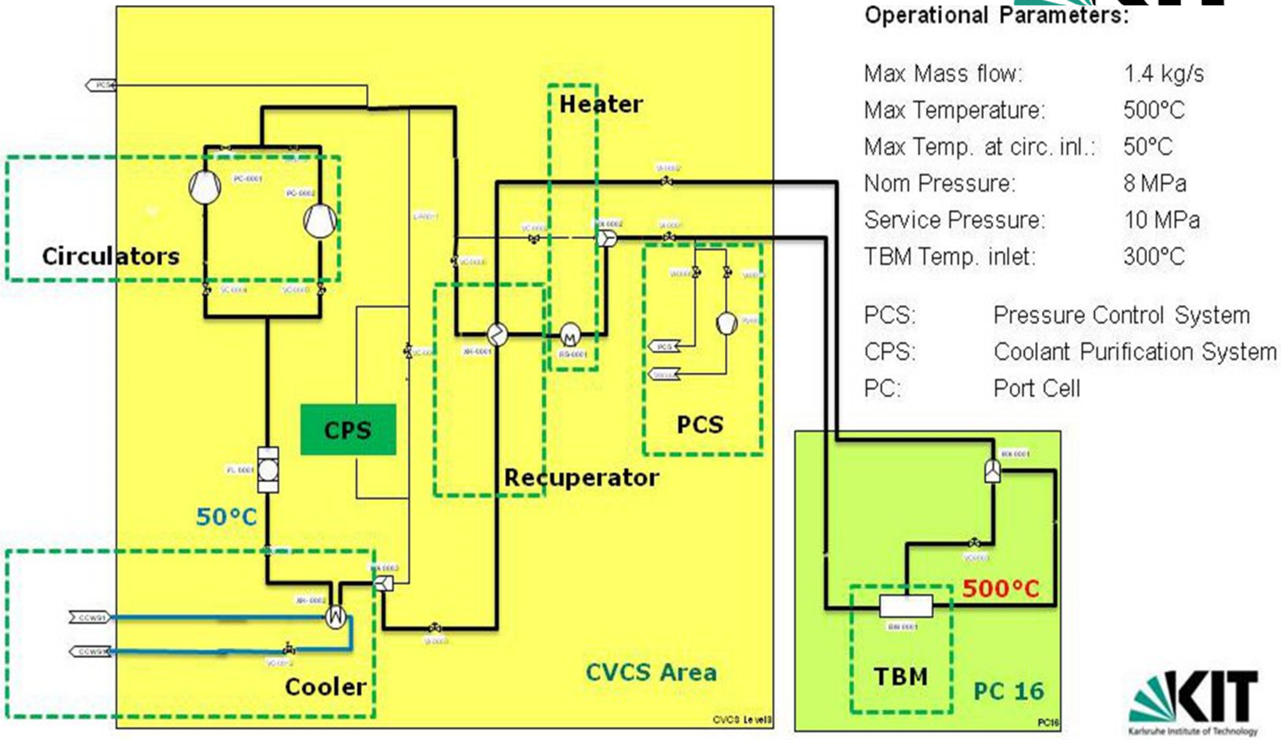


TBS=Test blanket station

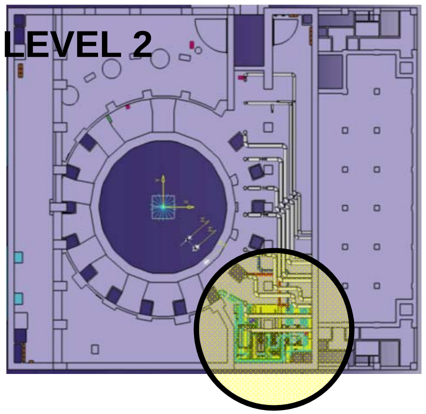
Helium Cooling Systems

Aiello, Fus. Engng. Des.,2011, 602.





Both HCLL and HCPB HCS are arranged in the CVCS area (in a reserved space of about 222 m²).



Key system for safety/reliability of TBS.

- **Key function: cooling of FW**
  - **surface (0.8 m²) , $q_n \approx$ 0.78 MW/m², $q_{rad} \approx$0.5 MW/m².**

Key system for safety/reliability of TBS.

- **Key components & operation**
  - **Helium compressor: stage centrifugal turbo**
  - **driven by asynchronous motor (magnetic bearings).**
  - **All the rotating parts in helium (canned)**
  - **low temperature operation $T_{max,He} \approx$ 50°C**

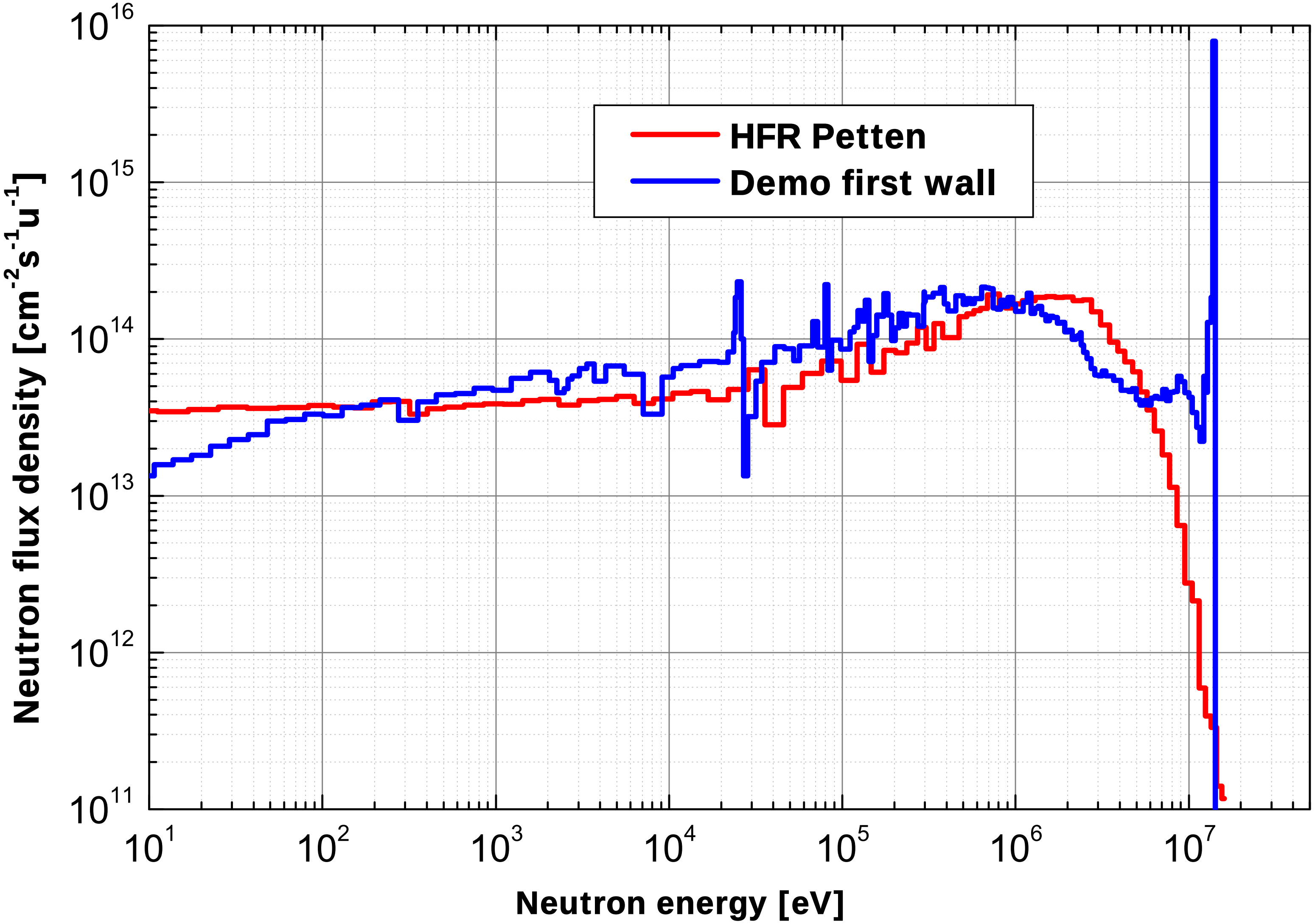
Summary - Blankets

- 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
- 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

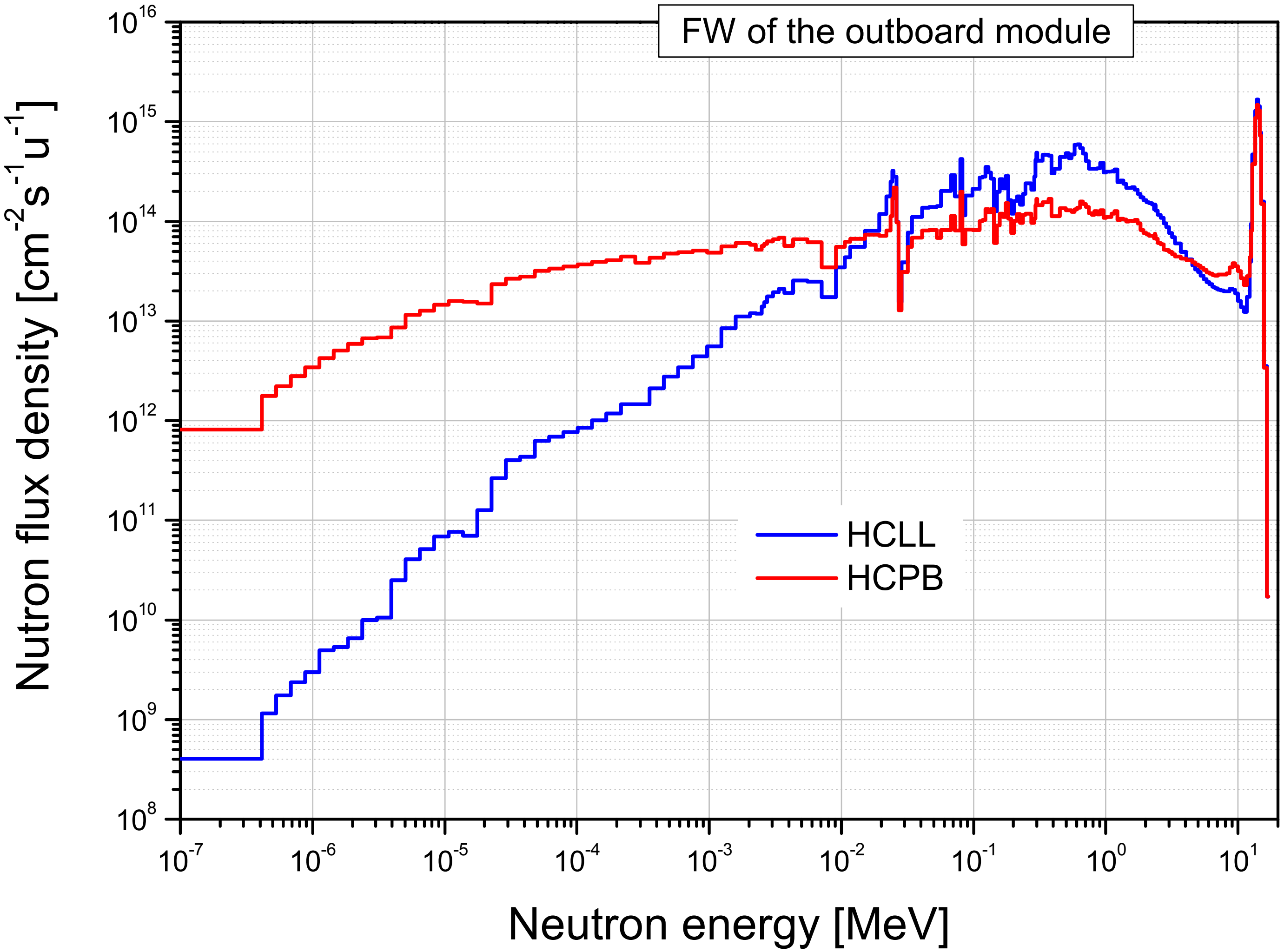
➡ **Blanket Design is one of the "CROWN" challenges in Fusion Engineering**

ADDITIONAL TRANSPARENCIES

Neutron flux spectra: fusion vs. fission



HCPB/HCLL First Wall Neutron Spectra



Tritium CONSUMPTION of a
2700 MW Fusion, ~1000 MW electrical Power Plant :

Karlsruher Institut für Technologie

Note: 1eV = 1.602 10^{-19} As*V = 1.602 10^{-19} Joule

charge

1.) Energy per fused tritium atom (17.6 MeV in Joule):

$17.6 \cdot 10^{6} * 1.602 \cdot 10^{-19} = 2.82 \cdot 10^{-12}$ Joule;

2.) Fusion frequency = P/E = $2700 \cdot 10^{6}$ J/s / $2.82 \cdot 10^{-12}$ J = $9.57\ 10^{20}$ 1/s;

3.) Tritium mass flow = 3 * mass of proton (neutron) * frequency =

$3 * 1.67 \cdot 10^{-27}$ kg * $9.57 \cdot 10^{20}$ * 24 * 60 * 60 * 1/day = **0.41kg/day**

Tritium T (^3H):	**~ 0.41 kg/day**	**~ 150 kg/fpy**
Deuterium D (^2H) :	**~ 0.27 kg/day**	**~ 100 kg/fpy**

fpy = full power year