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Tritium Breeding and blanket technology

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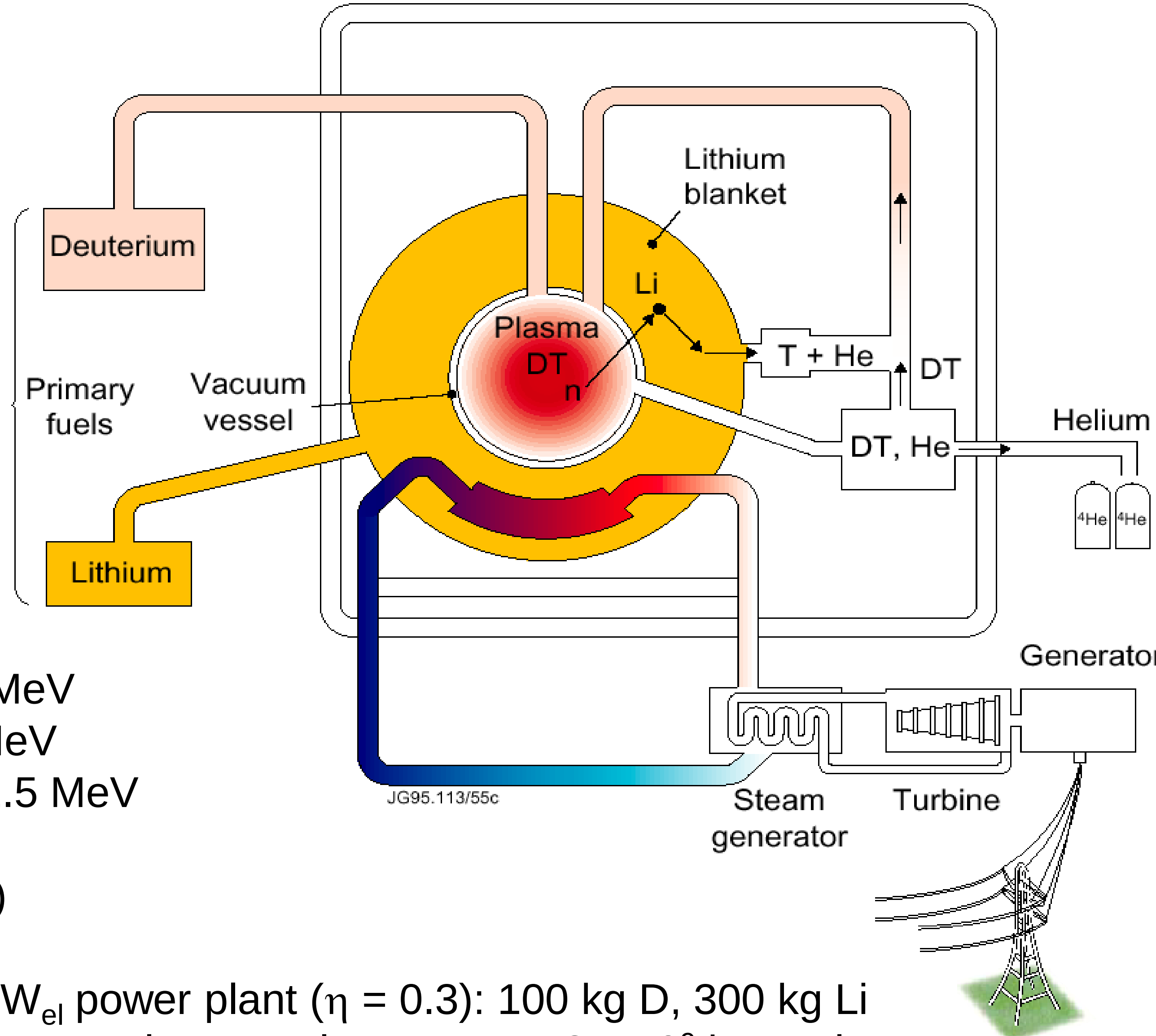
DPG School “The Physics of ITER”

Bad Honnef, 26.09.2014

Introduction: principle of a fusion power plant



D + T → He + n + 17.6 MeV

^{6}Li + n → He + T + 4.8 MeV

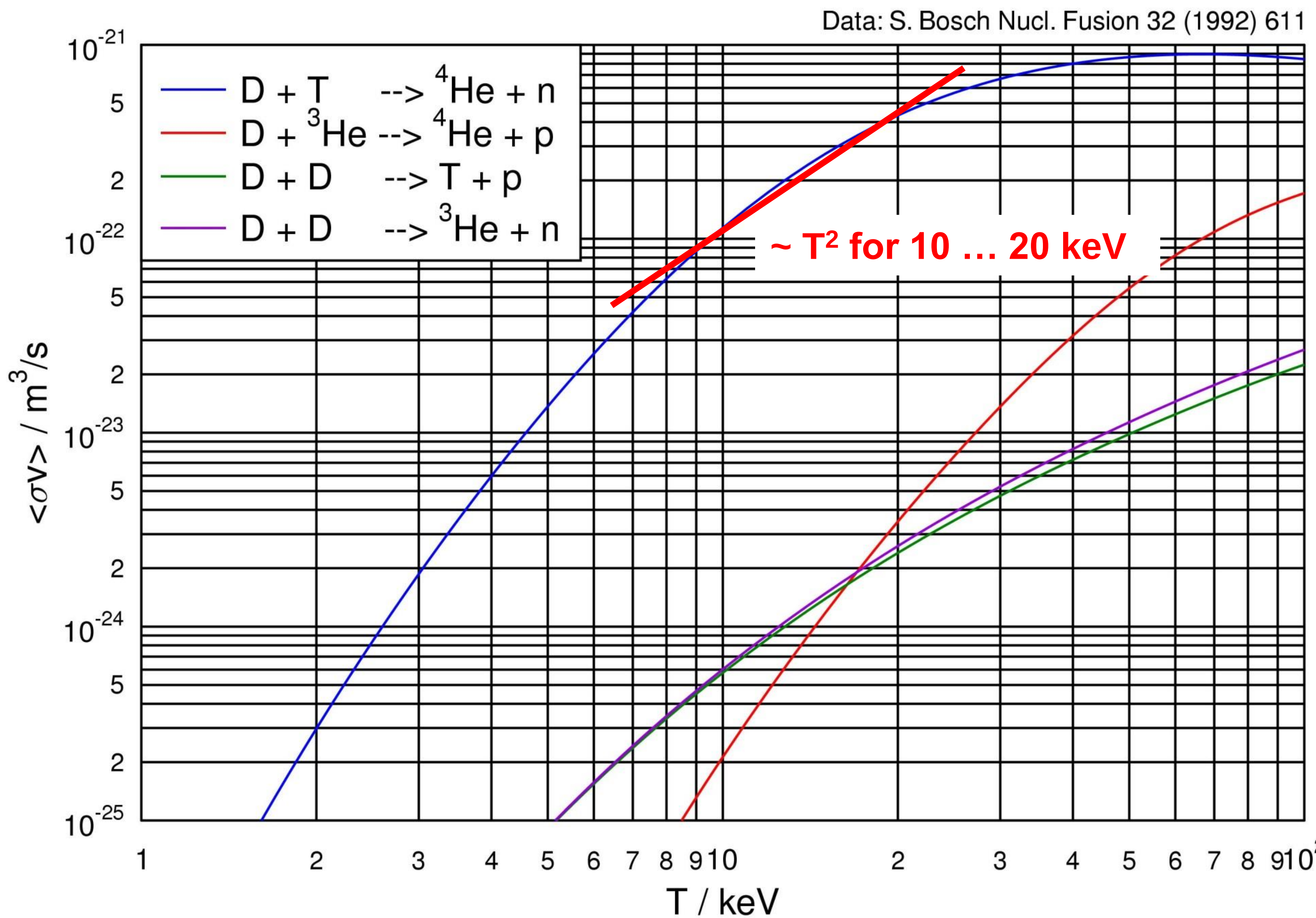
^{7}Li + n → He + T + n' – 2.5 MeV

(1 MeV = 1.602 x 10^{-13} J)

Annual consumption 1 GW_{el} power plant (η = 0.3): 100 kg D, 300 kg Li

Annual consumption 1 GW_{el} coal power plant: 3 x 10^9 kg coal

Fusion rates in a thermal plasma



Blanket design

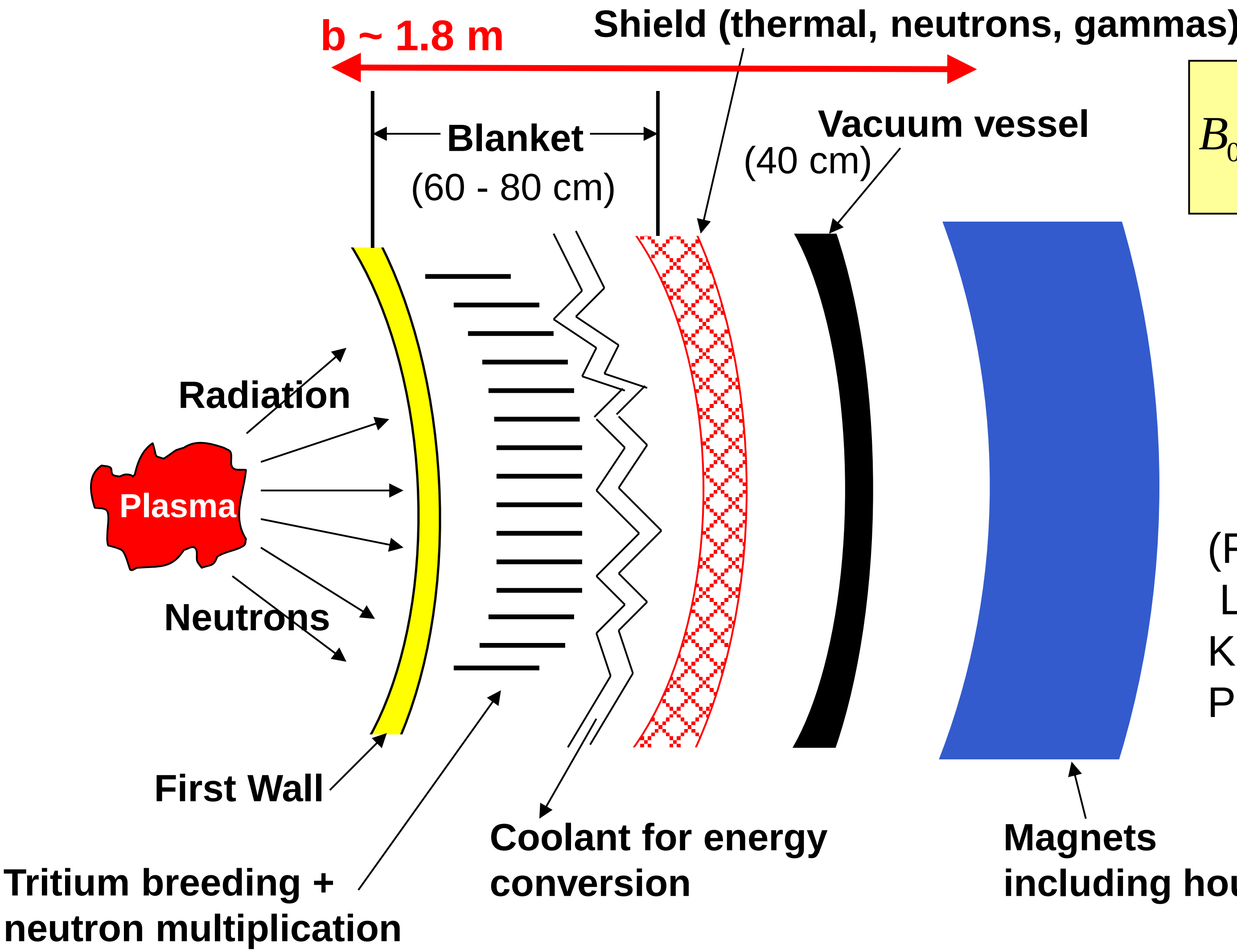
The blanket is a key components of a fusion reactor, with the following functions:

- Tritium breeding
- Power exhaust
- Radiation shielding

Important aspects for blanket design:

- Tritium breeding rate TBR > 1
- structural integrity maintained for long operation (high neutron fluence)
- efficient heat exhaust (high thermodynamic efficiency)
- low activation
- Low tritium retention
- Good tritium confinement

Radial build of a tokamak reactor



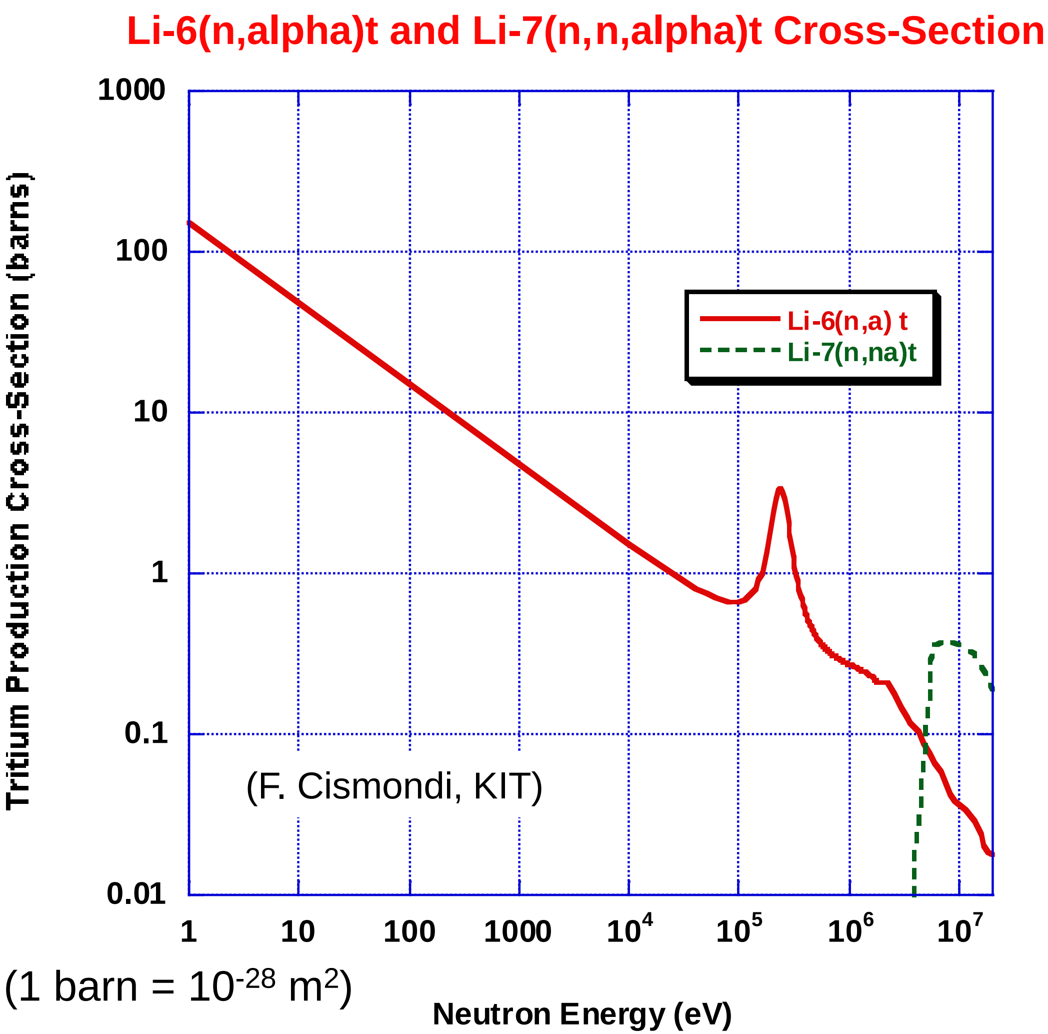
$$B_0 = B_{max}\left(1 - \frac{a+b}{R_0}\right)$$

(F. Cismondi,
L. V. Boccaccini,
KIT,
PPCS Studie)

Fusion power plant: distance between plasma edge and TF coil casing **b ~ 1.8 m**.
This number does not scale with reactor size → consequence for reactor size

Tritium breeding blanket

Tritium ($t_{1/2}$ = 12.32 years) is only scarcely available (from fission reactors) and hence it has to be produced in the fusion reactor („breeding“).



(1 barn = 10^{-28} m^2)

Natural Lithium consists of 7.42% ^{6}Li and 92.58% ^{7}Li.

Possible breeding reactions:

$$^6Li + n \rightarrow T + \alpha + 4.78 MeV$$

$$^7Li + n \rightarrow T + \alpha + n - 2.47 MeV$$

The ^{7}Li(n;n'α)t reaction is endothermic with an energy threshold of 2.8 MeV.

In steady state operation, a fusion reactor should reach a tritium breeding ratio ((TBR) > 1.

Abschätzung der notwendigen Blanket-Dicke

Freie Weglänge (1/e) für die Abbremsung der Neutronen (after: J. Freidberg)

$$\lambda_{SD} = \frac{1}{n_{Li}\sigma_{SD}} \approx 0.055m$$

(Stoß-Querschnitt Neutronen-Kühlung $\sigma_{SD} = 10^{-28}$ m²)

Daraus folgt für die Energie der Neutronen folgender räumlicher Verlauf:

$$\frac{dE}{dx} = -\frac{E}{\lambda_{SD}}, \quad \Rightarrow E = E_n e^{-\frac{x}{\lambda_{SD}}}$$

Wie dick muss der Li-Moderator sein, damit die Neutronen von der Anfangsenergie E_n = 14.1 MeV auf thermische Energien (E_{th} = 0.025 eV) abgebremst werden?

Antwort:

$$\lambda_{SD} = \frac{1}{n_{Li}\sigma_{SD}} \approx 55\,mm, \quad \frac{E_n}{E_{th}} = \frac{14.1MeV}{25\,meV} = 5.63\times 10^8 \Rightarrow x = \ln\left(5.63\times 10^8\right)\lambda_{SD}$$

→ Es werden etwa 20 Abfall-Längen λ_{SD} benötigt, d.h. x = 1.1 m

Berücksichtigt man zusätzlich die Brutreaktion, genügt eine Blanket-Dicke von etwa 0.7 … 0.9 m

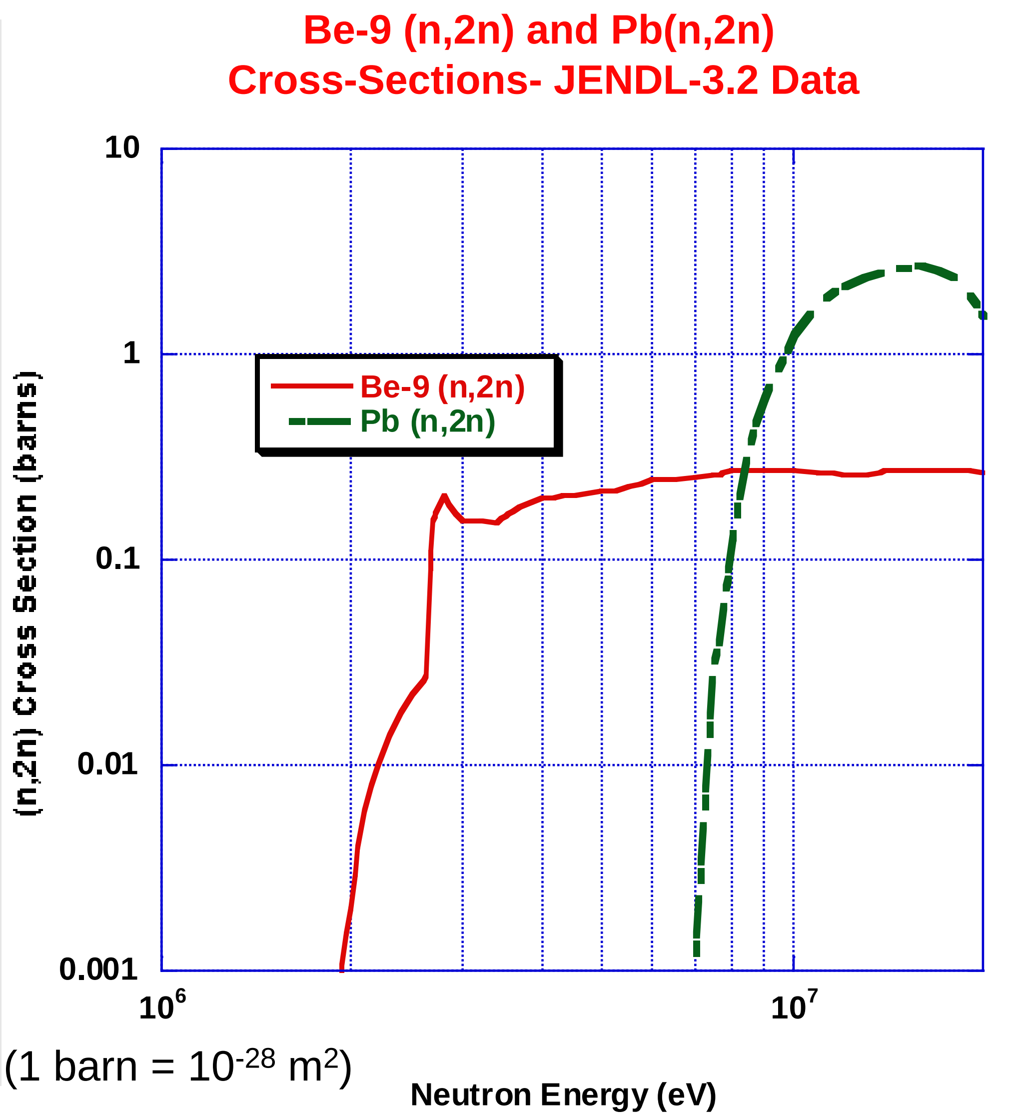
Neutron multiplication

A pure Lithium blanket cannot reach TBR > 1 due to unavoidable neutron losses:

- absorption in structural materials
- Geometric losses through divertor (no breeding blanket there)
- voids in the blanket needed for heating and diagnostic access

Endothermic reactions with Be or Pb are suited for neutron mulitiplication in the blanket → TBR > 1

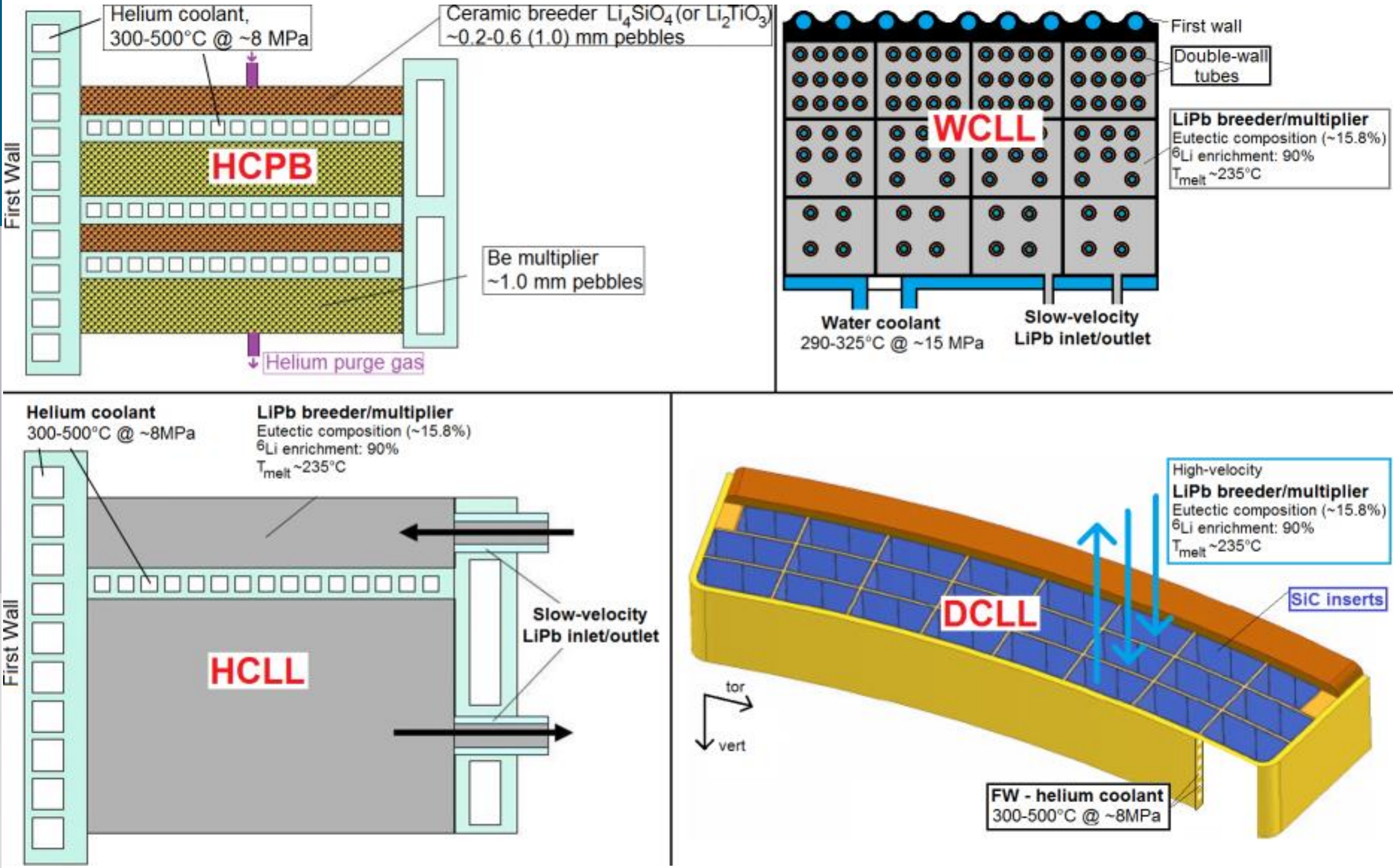
In total, the blanket is producing extra energy due to the exothermic ^{6}Li reaction. The typical total energy yield per primary fusion reaction is about 20 MeV.



(1 barn = 10^{-28} m^2)

Overview: European blanket concepts for DEMO

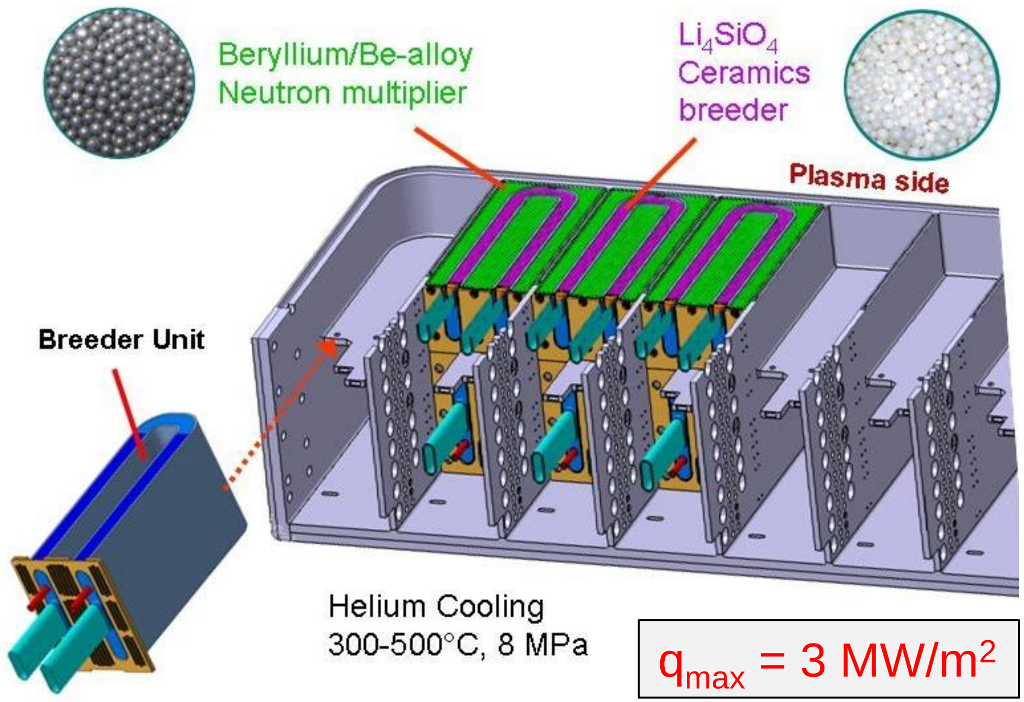
(L. Boccaccini, KIT)



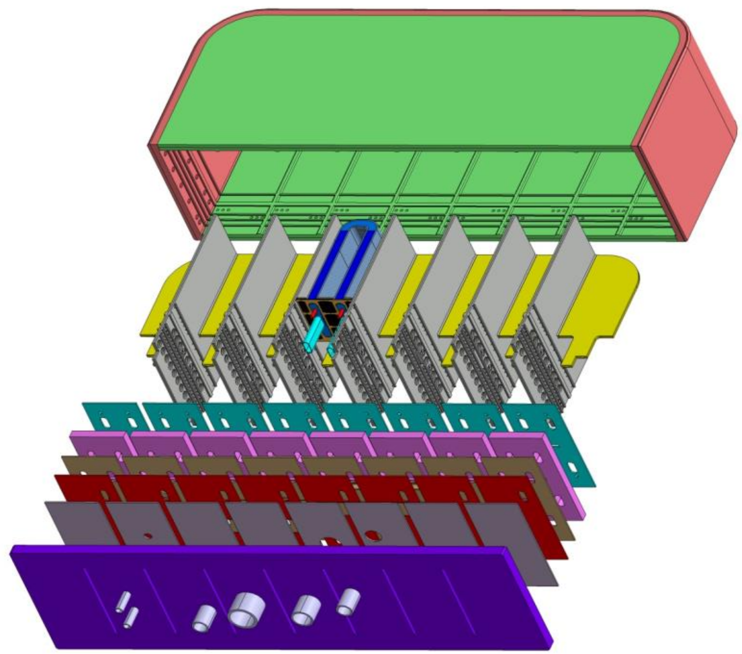
Helium-gekühltes „Pebble-Bed"-Blanket

HCPB Konzept (KIT):

- Keramische Kugel-Schüttungen mit Li und Be; Verbrauch ca. 1 cm/Jahr
- Helium-Kühlung (hohe Abgangstemperatur; Sicherheit)
- Komplett-Austausch von Blanket + erster Wand nach einigen Jahren



$q_{max} = 3\ MW/m^2$

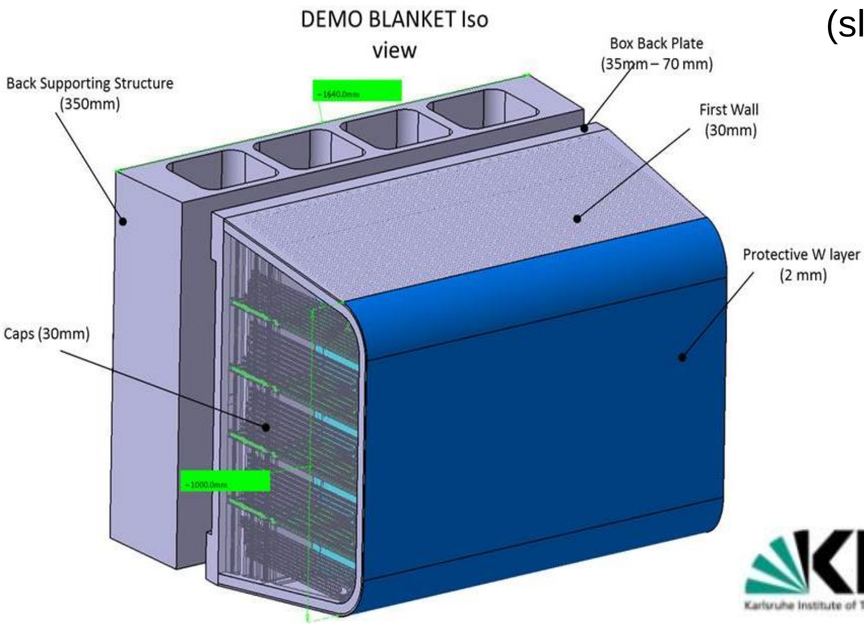


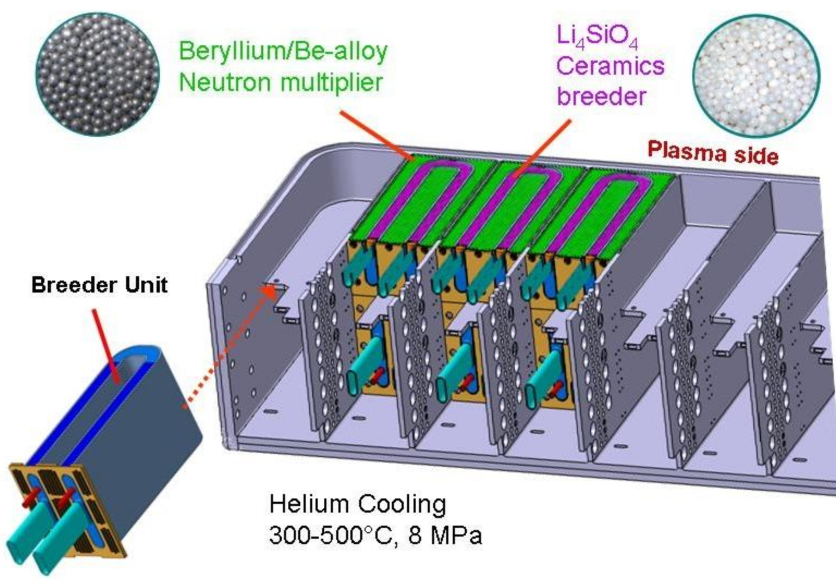
(F. Cismondi, KIT, 2008)

- benötigt sehr hohe Pumpleistungen
- T-Inventar in den Li_4SiO_4 Kugeln (Ausgasrate ist temperaturabhängig)
- Versprödung der keramischen Kugeln

HCPB Blanket (Helium Cooled Pebble Bed)

(slide after L. Boccaccini, KIT / Eurofusion)





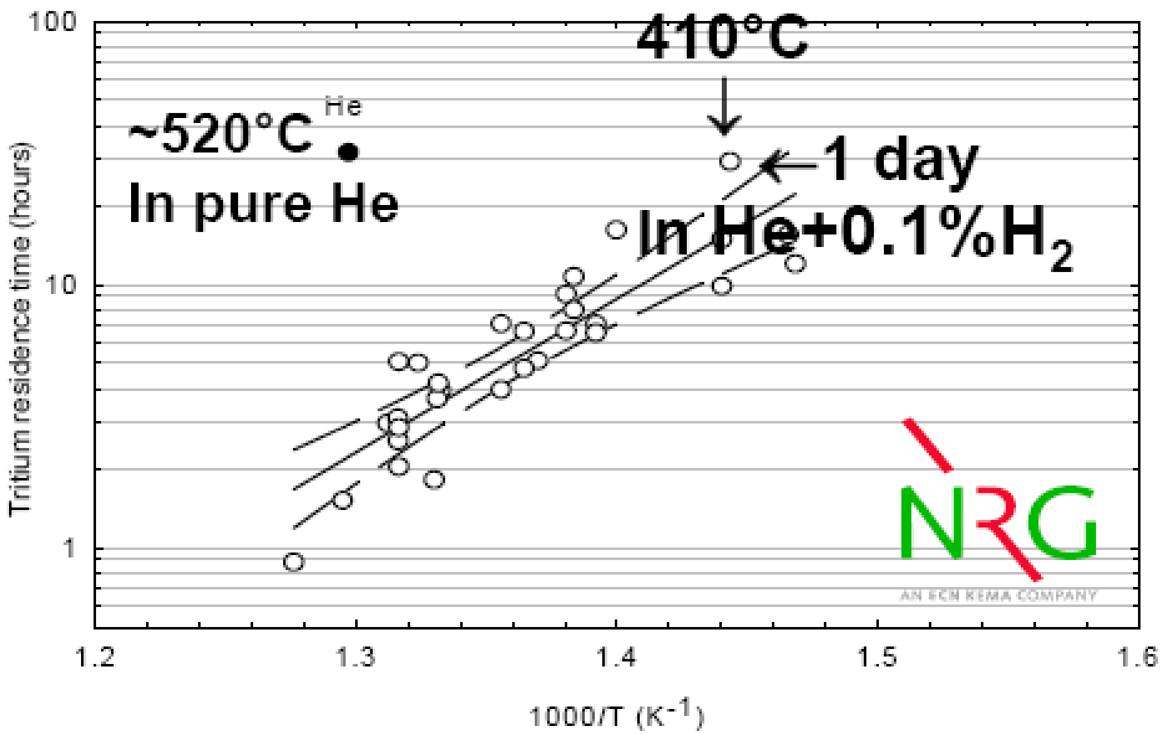
Main features

- Large modules (up to 1 m x 2 m)
- EUROFER as structural material; protective tungsten layer at the front side
- He at 8MPa, Tinl/Tout = 300/500 °C coolant
- Ceramic Breeder (CB): Li_4SiO_4 in form of pebble bed at 50% 6Li. Li2TiO3 is an alternative candidate.
- Beryllium as multiplier in form of a pebble bed
- T extraction (Be and CB) through low pressure purge He (few bars)

Operational conditions in a ceramic type blanket

High temperature operation needed

1. to ensure that the Tritium can outgas from the ceramic pebbles fast enough,
2. to allow for a high thermodynamic efficiency of electrical power generation

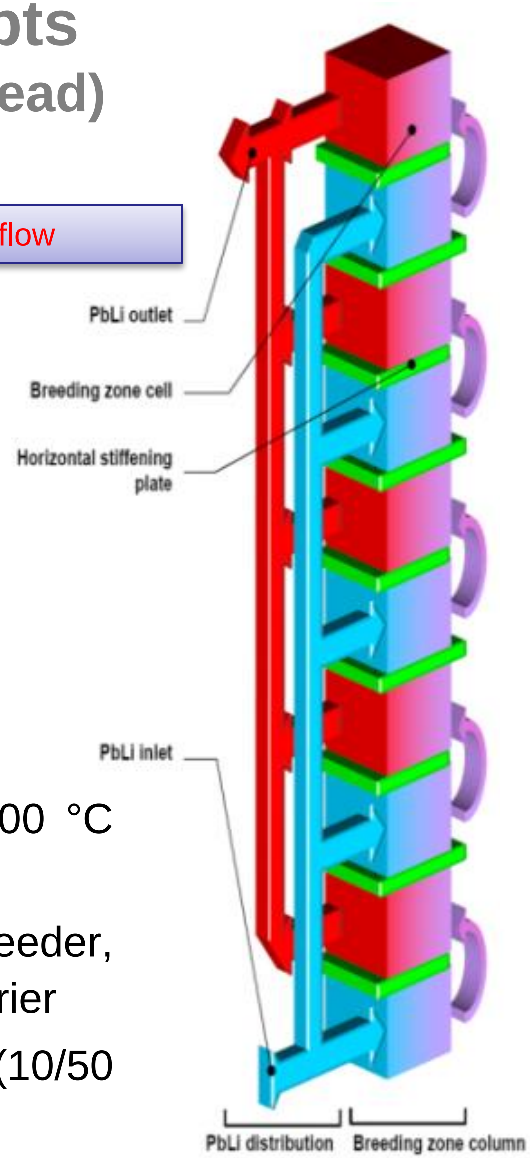


Note that high temperature operation is demanding for the materials requirements.

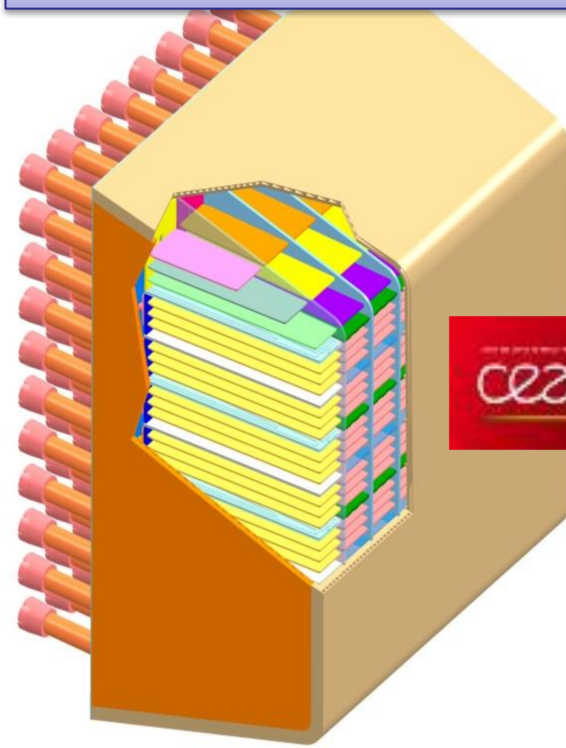
(slide after L. Boccaccini, KIT / Eurofusion)

HCLL Blanket Concepts
(Helium Cooled Lithium Lead)

LiPb flow



HCLL equatorial outboard module



Main features

- Large modules (~ 2 m x 1.5 m)
- EUROFER as structural material
- He at 8MPa, Tinl/Tout = 300/500 °C coolant
- Pb-Li (Li at 90% in 6Li) breeder, neutron multiplier and tritium carrier
- PbLi slowly re-circulating (10/50 rec/day)
- T extraction from Pb-Li outside the blanket

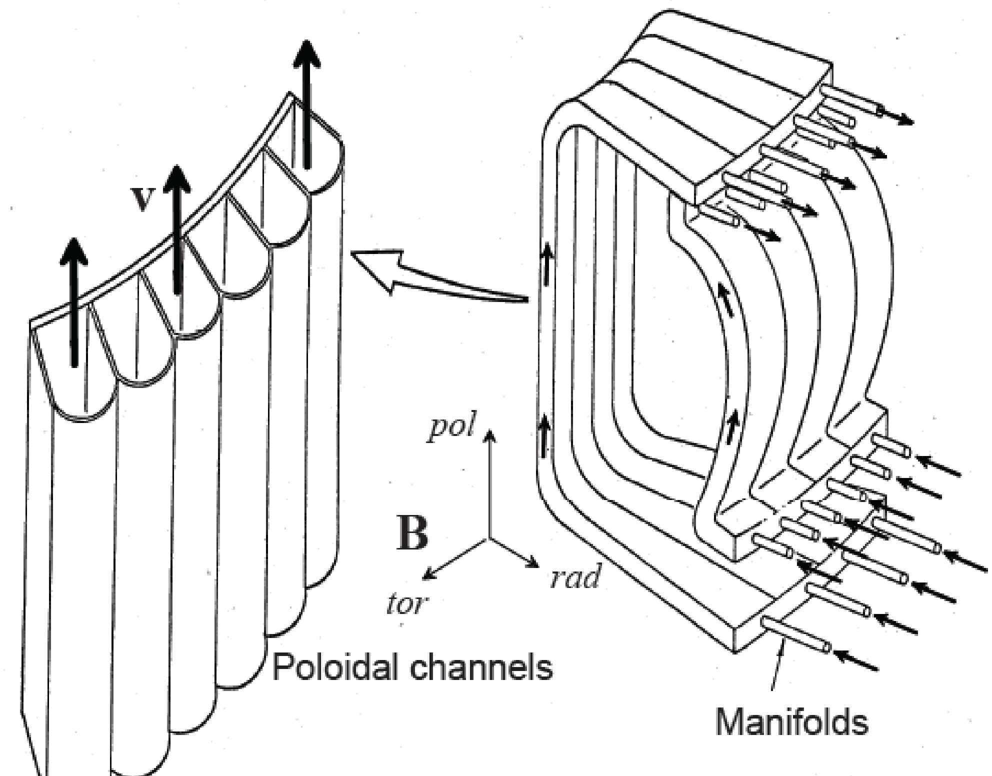
G. Aiello et al. Development of the Helium Cooled Lithium Lead Blanket for DEMO, ISFNT-11

Flüssig-PbLi Blanketprinzip

Self-cooled PbLi blankets

Poloidal flow concept
PbLi as breeder **and** coolant

Advantages:
- only one fluid
- simple design



a) Blanket cross section   b) Reactor sector

Schwierigkeiten:
- Strömung eines elektrisch leitfähigen Mediums senkrecht zum Magnetfeld, daher hoher Druckabfall
- Korrosion in den Leitungswegen

The ARIES-RS Blanket and Shield are Segmented to maximize Component Lifetime

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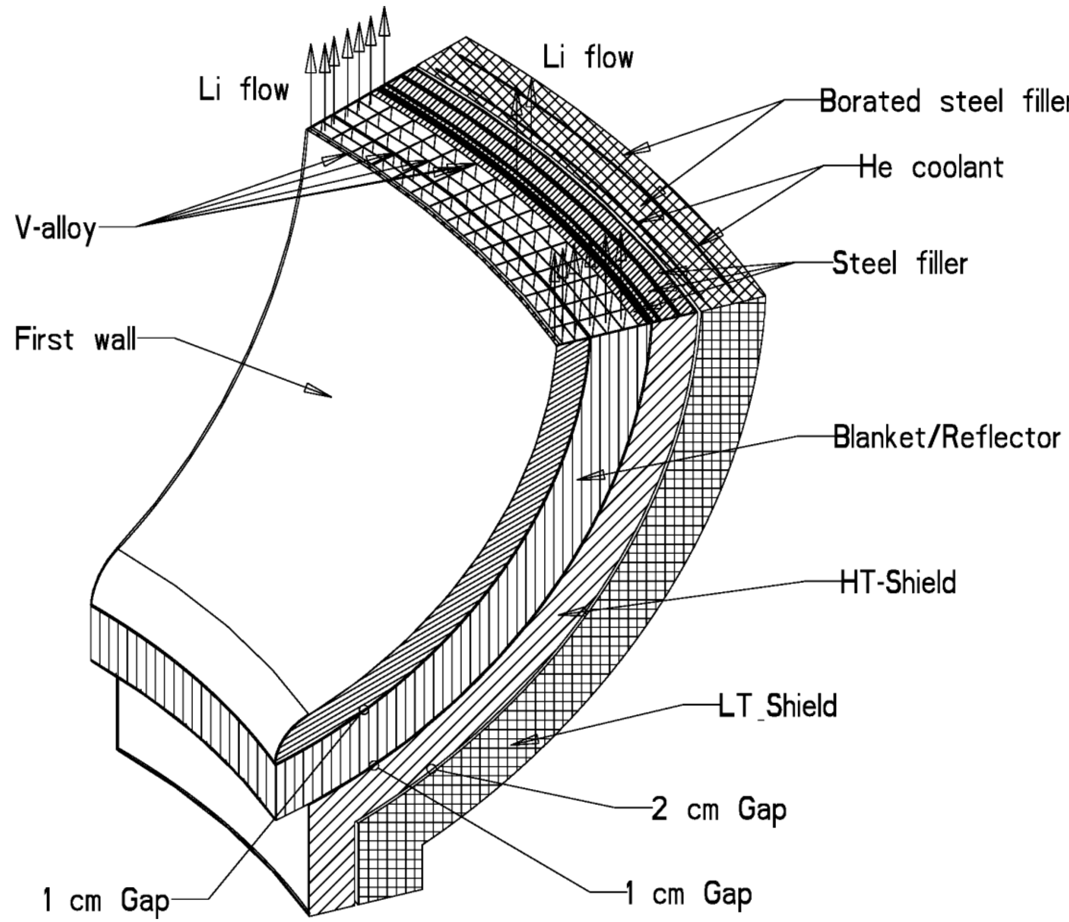
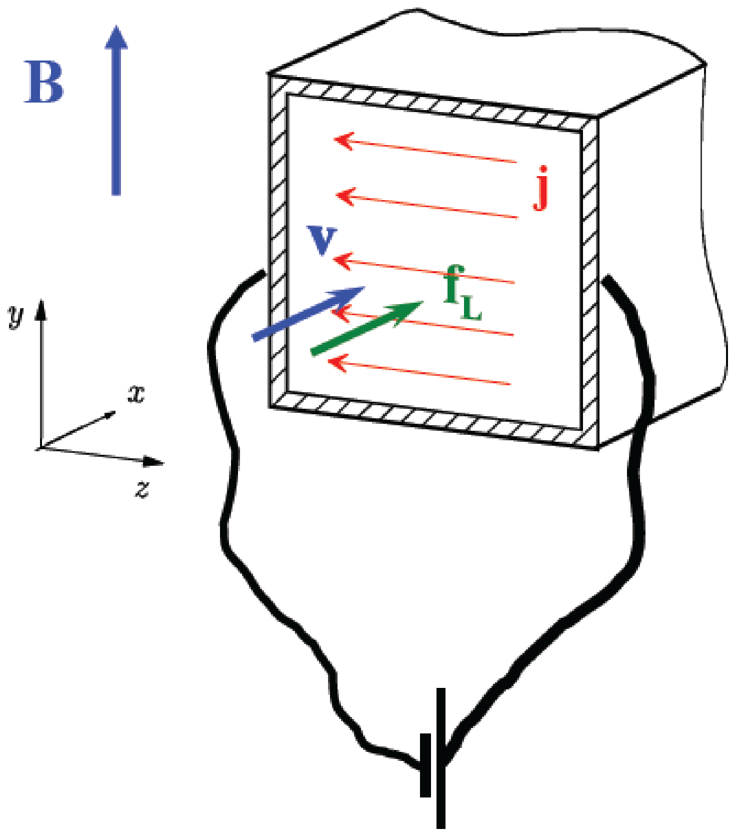
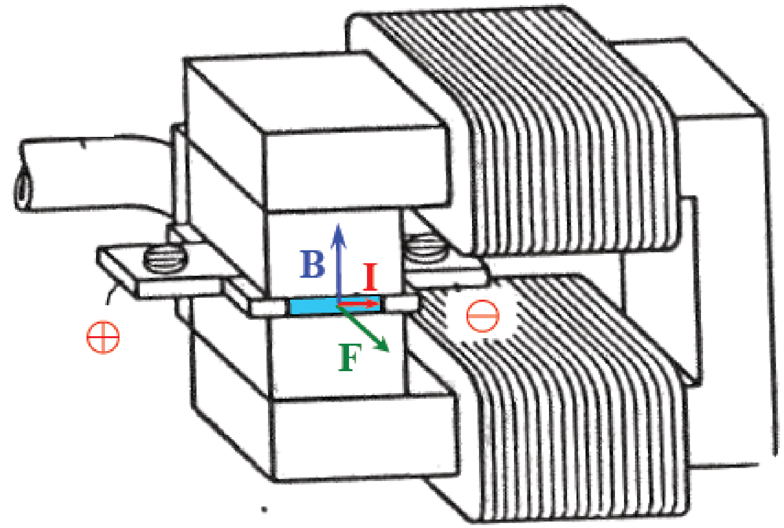
Outer blanket detail

- Blanket and shield consists of 4 radial segments.
- First wall segment, attached to the structural ring, is replaced every 2.5 FPY.
- Blanket/reflector segment is replaced after 7.5 FPY.
- Both shield segments are lifetime components:
  * High-grade heat is extracted from the high-temperature shield;
  * Ferritic steel is used selectively as structure and shield filler material.



Pumping liquid metals





J. Hartmann 1918

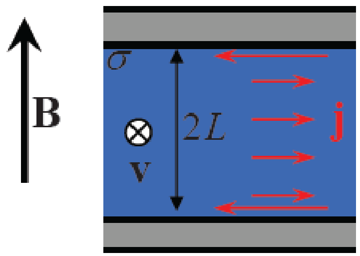
Current source $U[V]$

MHD DC pump

(after L. Bühler, KIT)

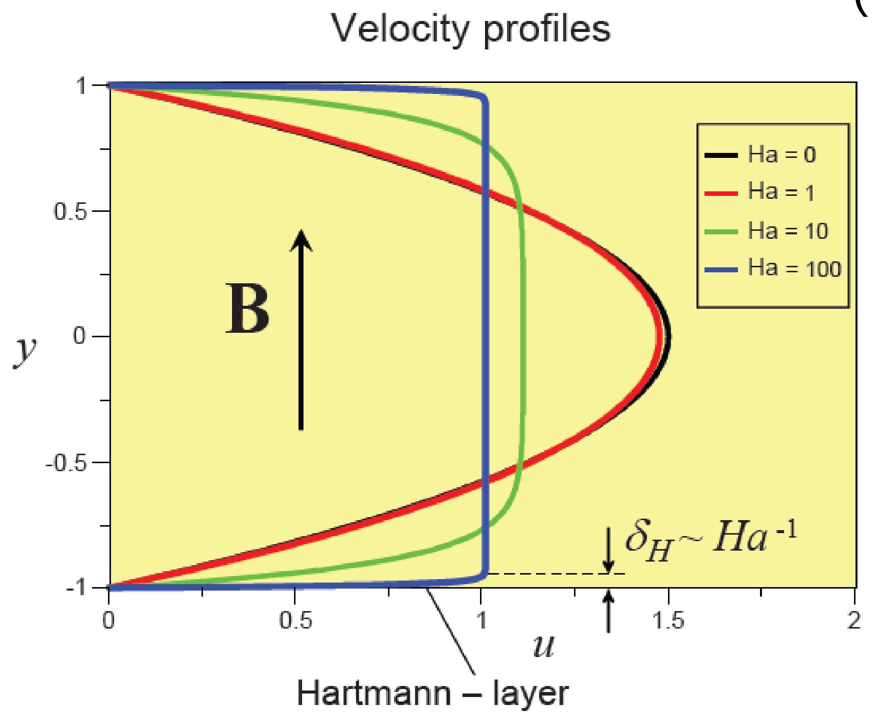
Poiseuille – Hartmann flow

(L. Bühler, KIT)



Exact solution

$$u = U\left(1 - \frac{\cosh Ha\, y}{\cosh Ha}\right)$$



Hydrodynamic flow for $Ha < 1$

Plug flow for $Ha >> 1$

Formation of thin boundary layers

Balance between pressure and Lorentz force

$$Ha = LB\sqrt{\frac{\sigma}{\rho\nu}}$$

σ = electr. conductivity
ρ = mass density
ν = kinematic viscosity
L = tube radius
B = magnetic field

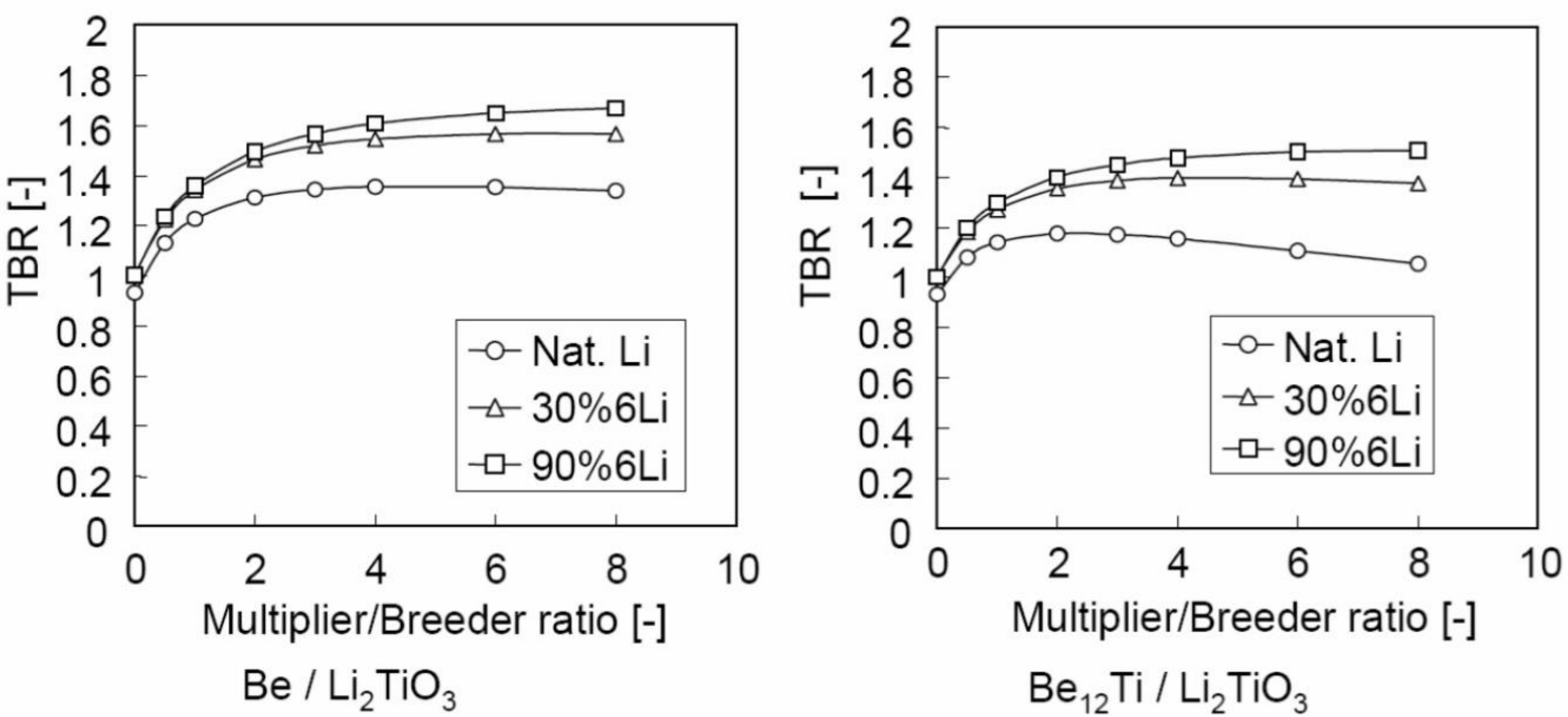
For applications in fusion blankets: $Ha > 10^4, \ \delta << 1$

Optimisation of Tritium breeding ratio (TBR)

Optimisation of TBR is possible via

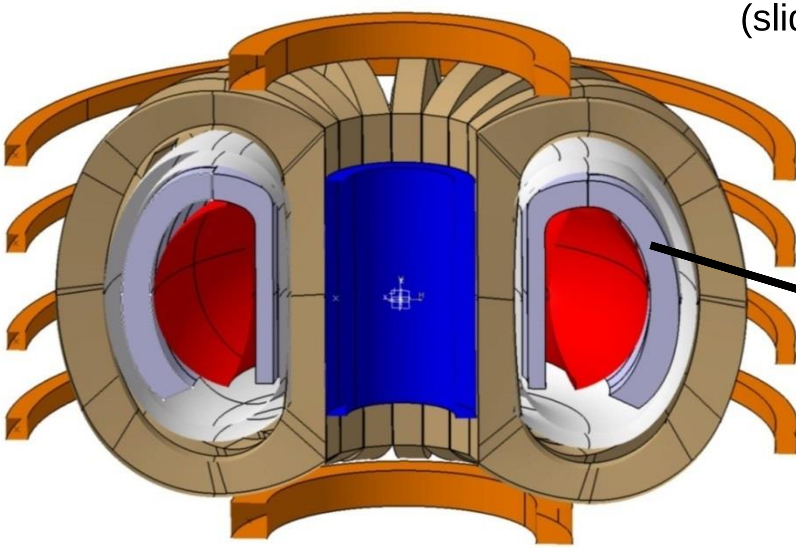
1. enrichment of ^6Li
2. mass ratio between neutron multiplier and breeding materials

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

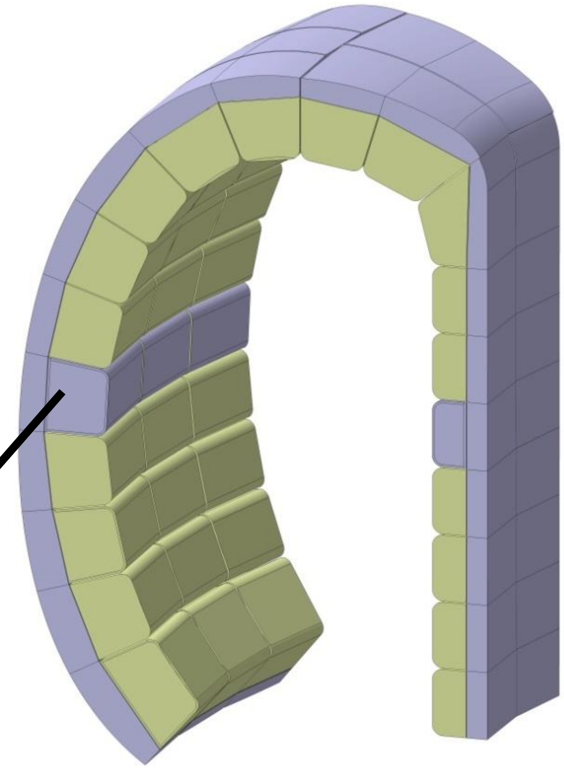


The Blanket systems: segmented design

(slide from L. Boccaccini, KIT / Eurofusion)

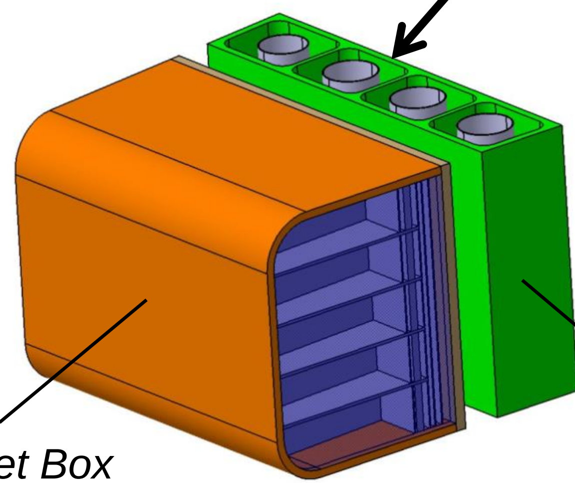


16 TF -> 16 Blanket Sectors



3 OB + 2 IB Blanket Segments

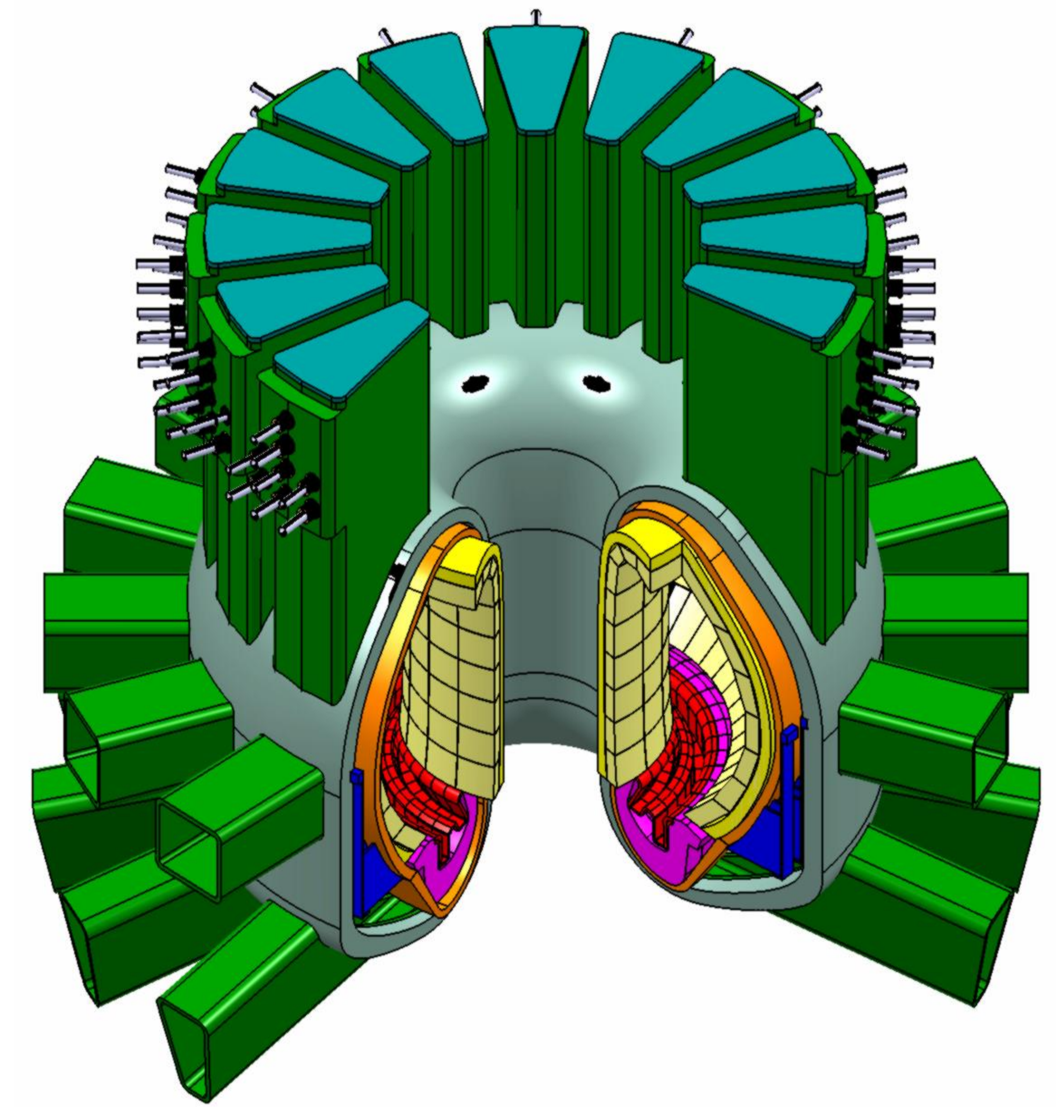
- Blanket replacement concept based on the Vertical Maintenance Concept
- Design of the blanket segment based on the Multi Module Design



Blanket Box

Back Supporting Structure

Fusionsreaktor: Gefäß-Komponenten und deren Integration



D. Filsinger, L. V. Boccaccini, et al. (KIT)

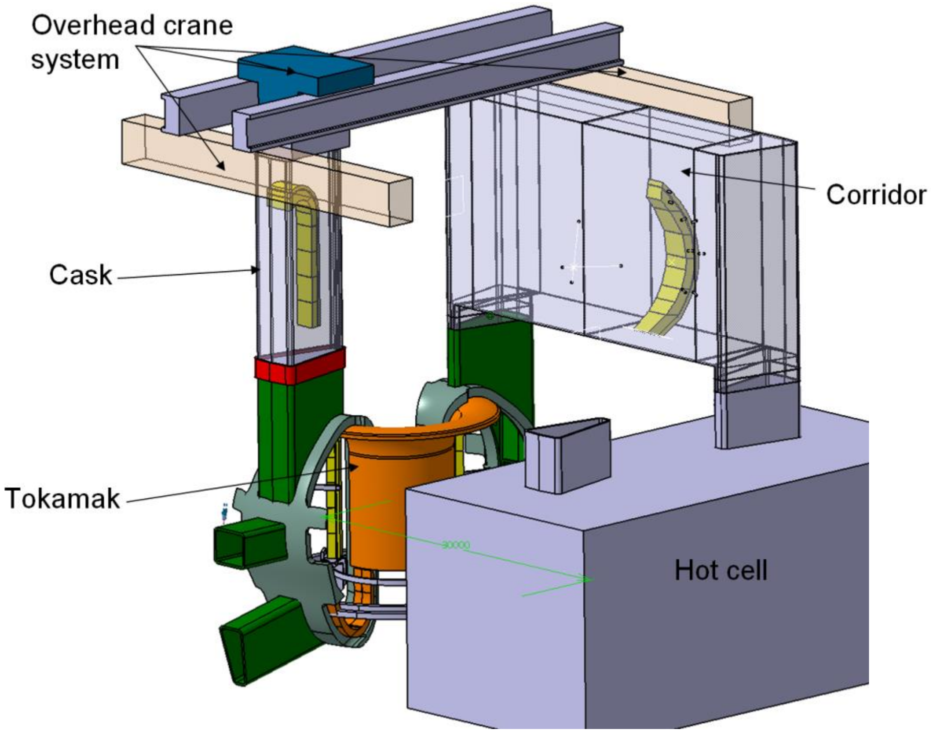
Reaktor-Komponenten:

- Vakuum-Gefäß + Ports
- Blanket
- Divertor
- Magnetsystem
- Anschlüsse und Rohre
- Abschirmung, Isolation

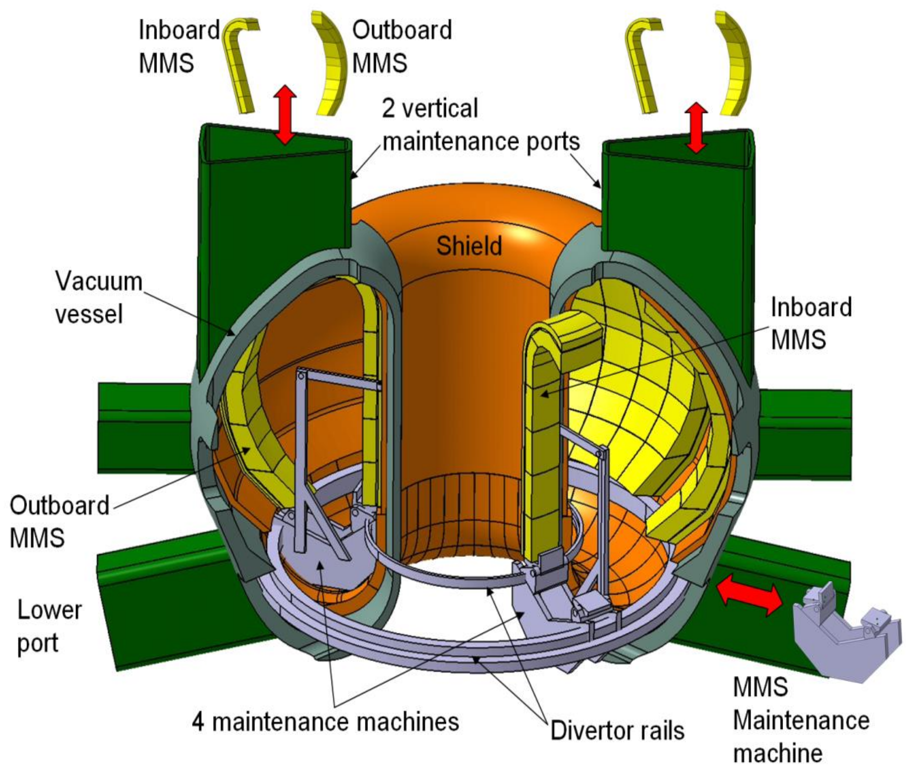
Wichtige Reaktor-Systeme:

- Kühlsystem
- Stromerzeugung
- Tritium-Erzeugung und Auskopplung
- Komponenten-Austausch-System
- Plasma-Heizung und Stromtrieb
- Plasma-Kontrolle

Konzept für Wartung und Austausch von Komponenten (Vertikaler Port)



Regelmäßiger Austausch von Wand-Komponenten und Blanket ca. alle 2 - 4 Jahre



D. Filsinger, L. V. Boccaccini, et al. (KIT)

Test blanket modules for ITER

Blanket Name	IP	Coolant	Breeder materials	Additional features
Helium Cooled Lithium Lead (HCLL)	EU	helium	PbLi	
Helium Cooled Pebble Bed (HCPB)	EU	helium	Ceramic Breeder + Be	
Water Cooled Ceramic Breeder (WCCB)	JA	water	Ceramic Breeder + Be	T-permeation barrier should be tested
Helium Cooled Ceramic Reflector (HCCR)	KO	helium	Ceramic Breeder + Be	Reflector of graphite pebbles coated with SiC.
Helium Cooled Ceramic Breeder (HCCB)	CHI	helium	Ceramic Breeder + Be	Be as binary bed and T Permeation barriers.
Lithium Lead Ceramic Breeder (LLCB)	IN(RF)	helium / PbLi	Ceramic Breeder + PbLi	Electrical insulating coatings for PbLi flow
[Dual Coolant Lithium Lead (DCLL)]	US	Helium / PbLi	PbLi	SiC_f/SiC inserts as electrical insulator for PbLi flow

All the Blankets use a RAFM stell as structural material (in EU the steel is EUROFER-97)

Port#16	Port#18	Port#2	none

Blanket concepts for a DEMO reactor

Label	Class of concept	Structure	Coolant	Breeder	Multiplier	Tritium removal
WCSB (JA)	Water Cooled Solid Breeder	RAFM	Water @ 285-325°C, 15.5 MPa Opt: @ 280/510°C, 25 MPa,	Li_2TiO_3	Be BeTi	Separated Tritium / Heat removal loops
WCLL (EU)	Water Cooled Lithium Lead	RAFM	Water @ 285-325°C, 15.5 MPa	PbLi	PbLi	Separated Tritium / Heat removal loops
HCPB (EU) **HCCB (CHI)** **HCCR (KO)**	Helium Cooled Solid Breeder	RAFM	Helium @ 300-500°C, 8 MPa	Li_4SiO_4 (Li_2TiO_3)	Be (Be12Ti)	Separated Tritium / Heat removal loops
HCLL (EU)	Helium Cooled Lithium Lead	RAFM	Helium @ 300-500°C, 8 MPa	PbLi	PbLi	Separated Tritium / Heat removal loops
DCLL (US, EU,CHI)	Dual Coolant Lithium Lead	RAFM	Helium @ 300-500°C, 8 MPa PbLi @ 500-700°C)	PbLi	PbLi	Combined Tritium / Heat removal loops
FFHR (JA)	FLiBe Self Coolant	RAF V (alloy)	FLiBe @ 450-550°C	FLiBe	FLiBe + Be	Combined Tritium / Heat removal loops
Li/V-SC (US)	Li/V Self Coolant	V (alloy)	Li @ 650-700°C	Li	(Be)	Combined Tritium / Heat removal loops
AHCPB (KIT-EU)	Advanced HCPB	SiC_f/SiC	Helium@ 350-750°C, 8 MPa	Li_4SiO_4	Be	Separated Tritium / Heat removal loops
SCLL (US, EU) TAURUS (CEA-EU)	Self Coolant Lithium Lead	SiC_f/SiC	PbLi @ 700-1100°C	PbLi	PbLi	Combined Tritium / Heat removal loops
Dream (JA)	High temperature Solid Breeder	SiC_f/SiC	Helium @ 600-900°C, 10MPa	Li_2TiO_3	Be	Combined Tritium / Heat removal loops
EVOLVE (US)	Evaporating Li	W (alloy)	Li @ 1200°C (boiling)	Li	none	Combined Tritium / Heat removal loops

Zusammenfassung zur Blanket-Auslegung für einen Fusions-Reaktor

- In der **Brutzone** laufen die Prozesse von Moderation der Neutronen, Tritium-Brüten und Neutronenvervielfachung parallel ab; einschließlich Strukturmaterial und Kühlung ist eine **Dicke von etwa 1 m** notwendig.
- Falls wir einen zu häufigen Austausch des Blankets vermeiden wollen, dann muss entsprechend eine **„Verbrauchsschicht"** zugegeben werden, hierfür genügen etwa + **10 cm (> 10 Jahre)**
- Eine Feinabstimmung der Brutrate (TBR) oder geringe Reduzierung der Blanketdicke kann durch Anreicherung von ^{6}Li erfolgen
- Die Magnetfeldspulen benötigen eine Abschirmung gegenüber der verbleibenden ionisierenden Strahlung sowie eine thermische Abschirmung **(+ 30 .. 40 cm)**.
- Ein doppelwandiges Vakuumgefäß ist für den sicheren Einschluss des Tritium-Inventars nötig **(+ 30 .. 40 cm).**
- Insgesamt ergibt sich auf der Innenseite des Torus ein Mindestabstand zwischen Plasmarand und TF-Spulen von **b = 1.8 … 2.0 m**