Karlsruhe Institute of Technology

TBM Consortium of Associates

Basics of breeding blanket technology

Forschungszentrum Karlsruhe in der Helmholtz-Gemeinschaft

Universität Karlsruhe (TH) Research University • founded 1825

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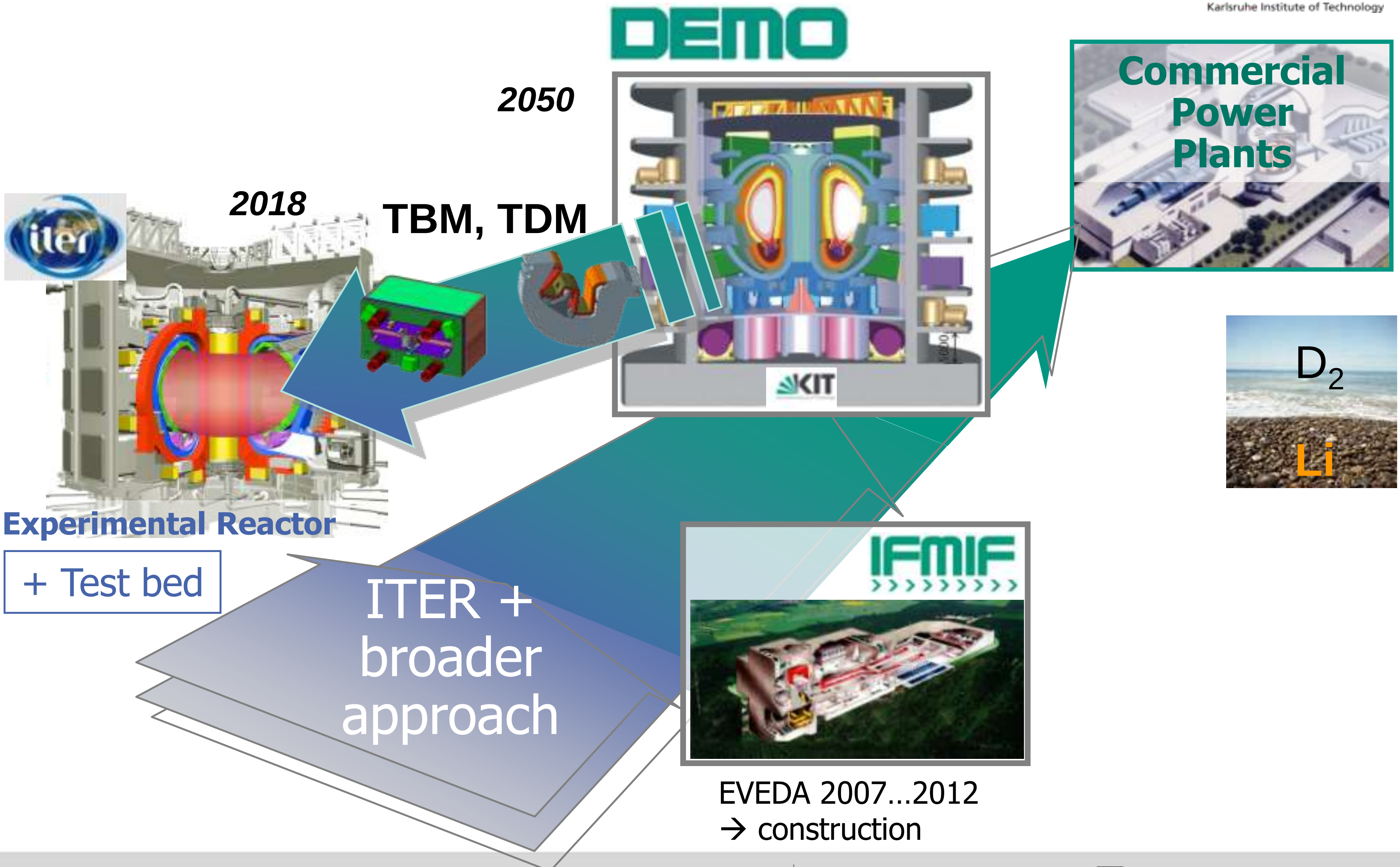
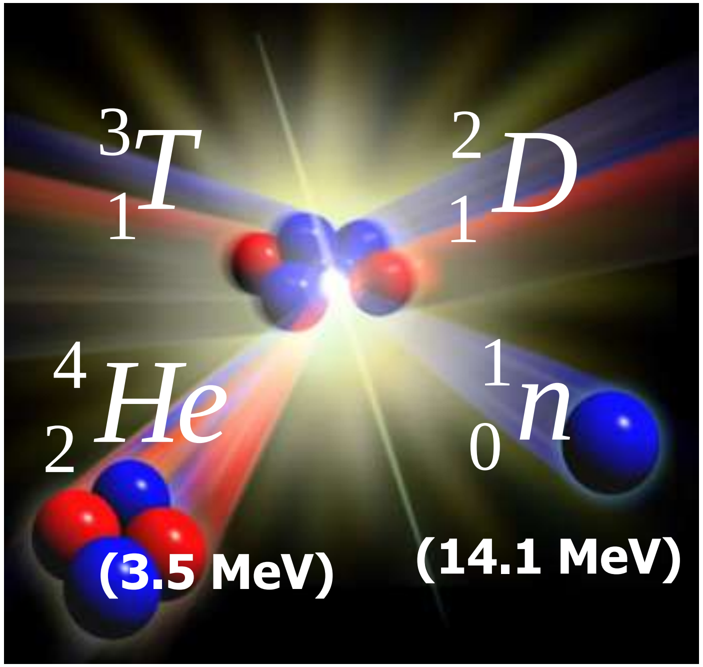
Development of Fusion power plants



Deuterium Tritium Fusion

- Kinetic energy of α-particles (^{4}He) and neutrons: 17.6 MeV
- α-particles and neutrons will have the **same impulse (m · v**)
- → neutron must be 4 times faster
- This means the kinetic energy (**½ m v²**) is distributed in the ratio 4/1, **80% neutron energy!**

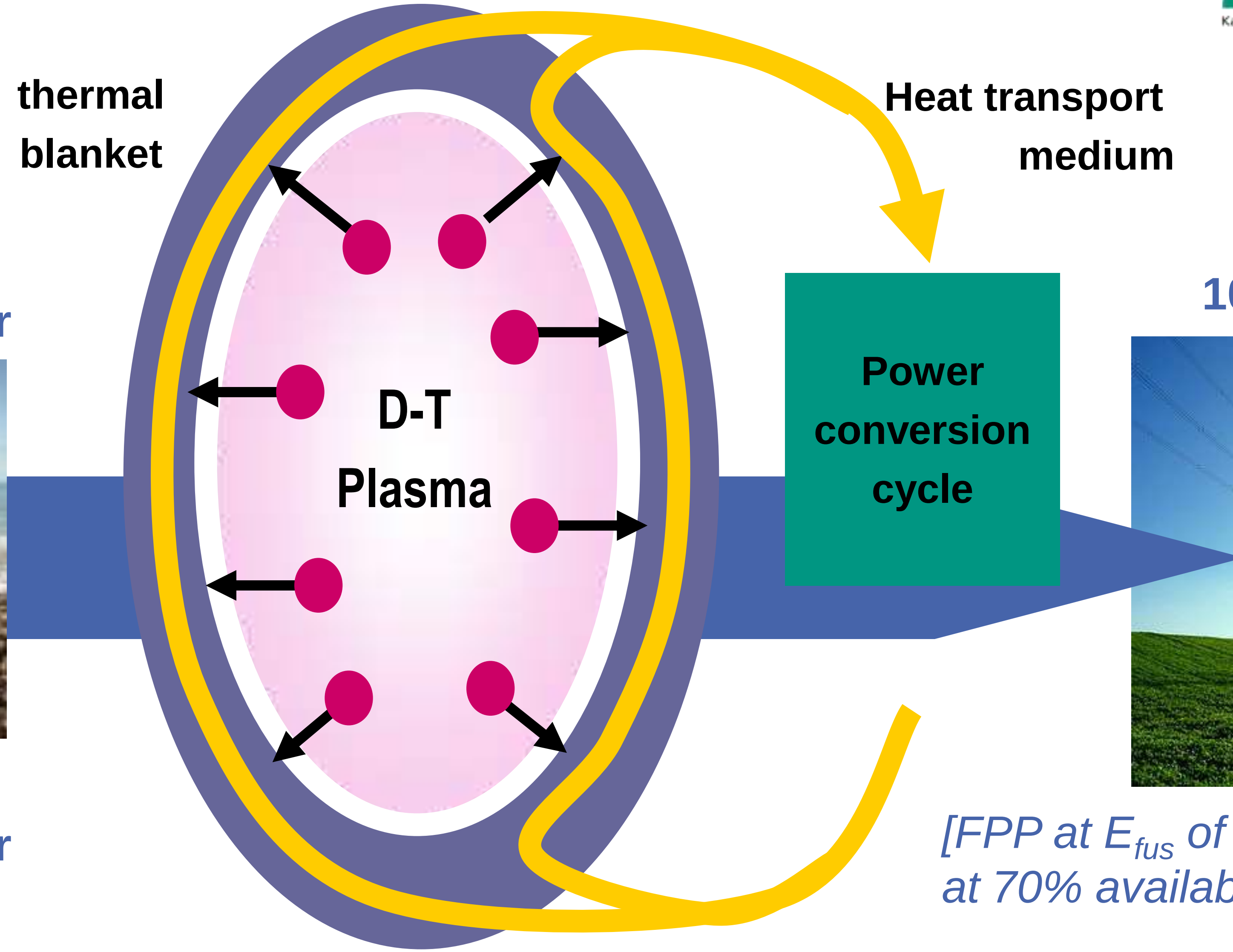


- **The neutrons will be decelerated in the thermal blanket placed around the fusion chamber**
- **The thermal power will be routed into a power conversion system.**

Principle of a nuclear fusion power plant

D_2:
100 kg/year

Lithium:
300 kg/year

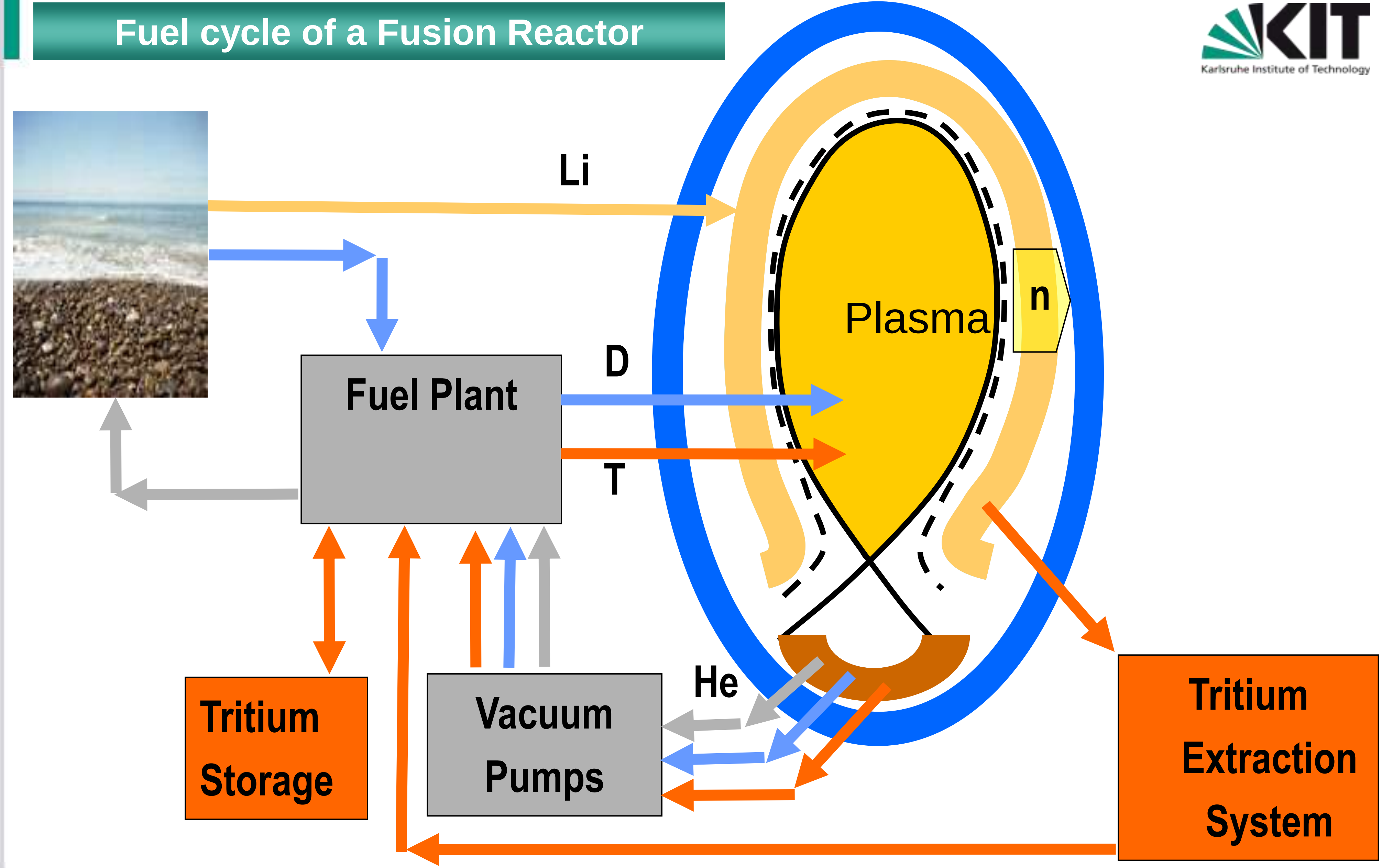


1000 MW_{el}

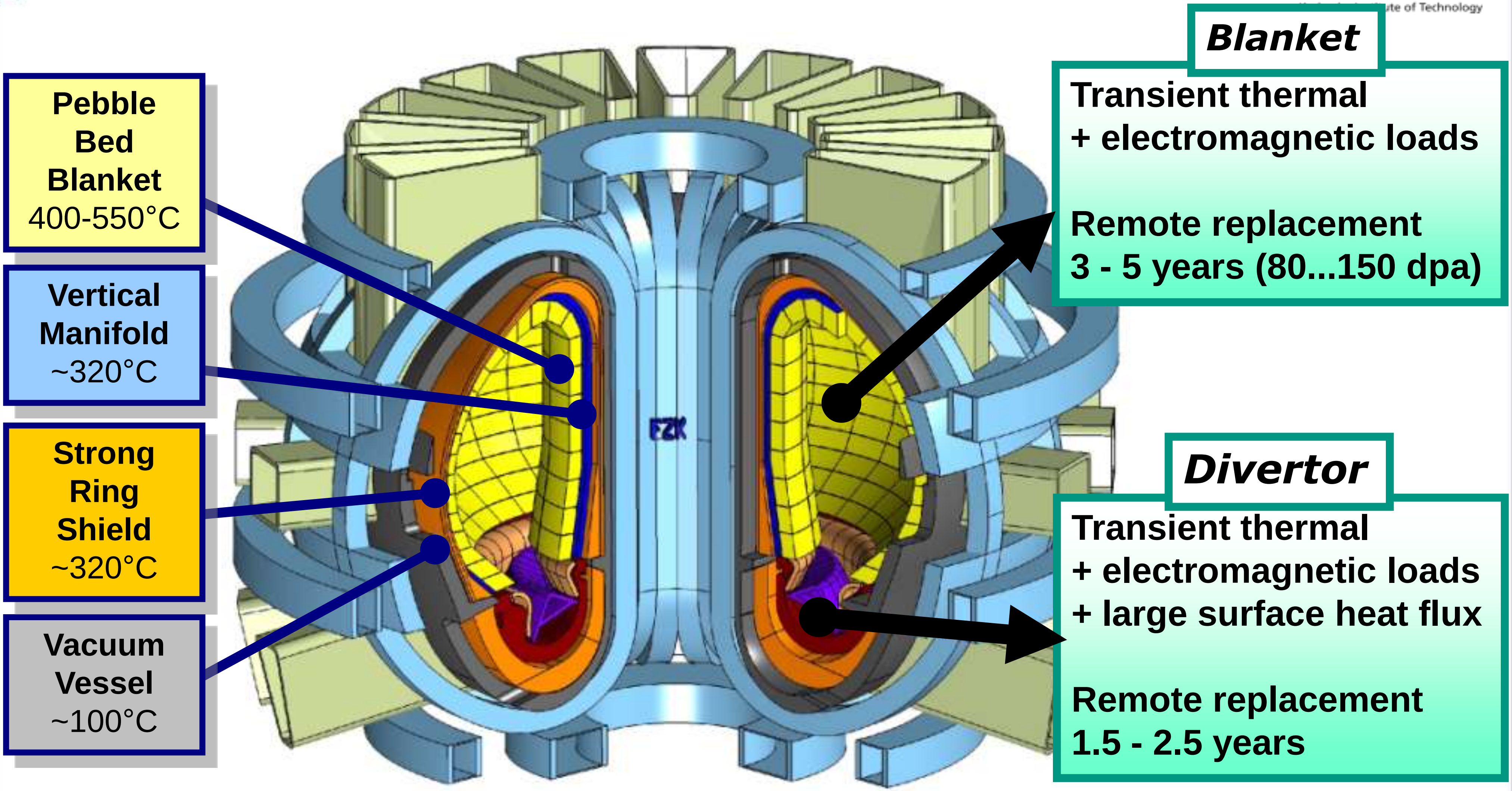
[FPP at E_{fus} of 2700 MW at 70% availability]

Energy option: Central power stations for many millions of years.

Fuel cycle of a Fusion Reactor



DEMO Fusion core (KIT)



DEMO = Demonstration Fusion Reactor Plant

Fusion core power distribution

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

2.82 10^{-12} Joule per Fusion

$^{2}D + {}^{3}T \rightarrow {}^{4}He + n + 17.6$ MeV

⊕ Proton
○ Neutron

20 % ^{4}He energy = 3.52 MeV

80 % neutron energy = 14.08 MeV

a) particles diffuse out of the plasma, b) heat conduction
50 %

α-particles are confined in the PLASMA → give energy to the plasma (α-heating)

Radiation of energy from the plasma
50%

Neutrons are not confined and have to be moderated in the blanket. With light atoms like lithium or beryllium the neutrons loose energy by elastic scattering.

$E_{particle+conduction}$ E_{rad} $E_{neutron}$

Blanket Load + Divertor Load

Fusion core power load distribution (example)

E_{rad}

8.5 % blanket

1.5 % divertor

Surface heat load on Blanket first wall and divertor target

E_{p+c}

2 % blanket

8 % divertor

Surface heat load on Divertor target and Blanket first wall

$E_{neutron}$

72 % blanket

8 % divertor

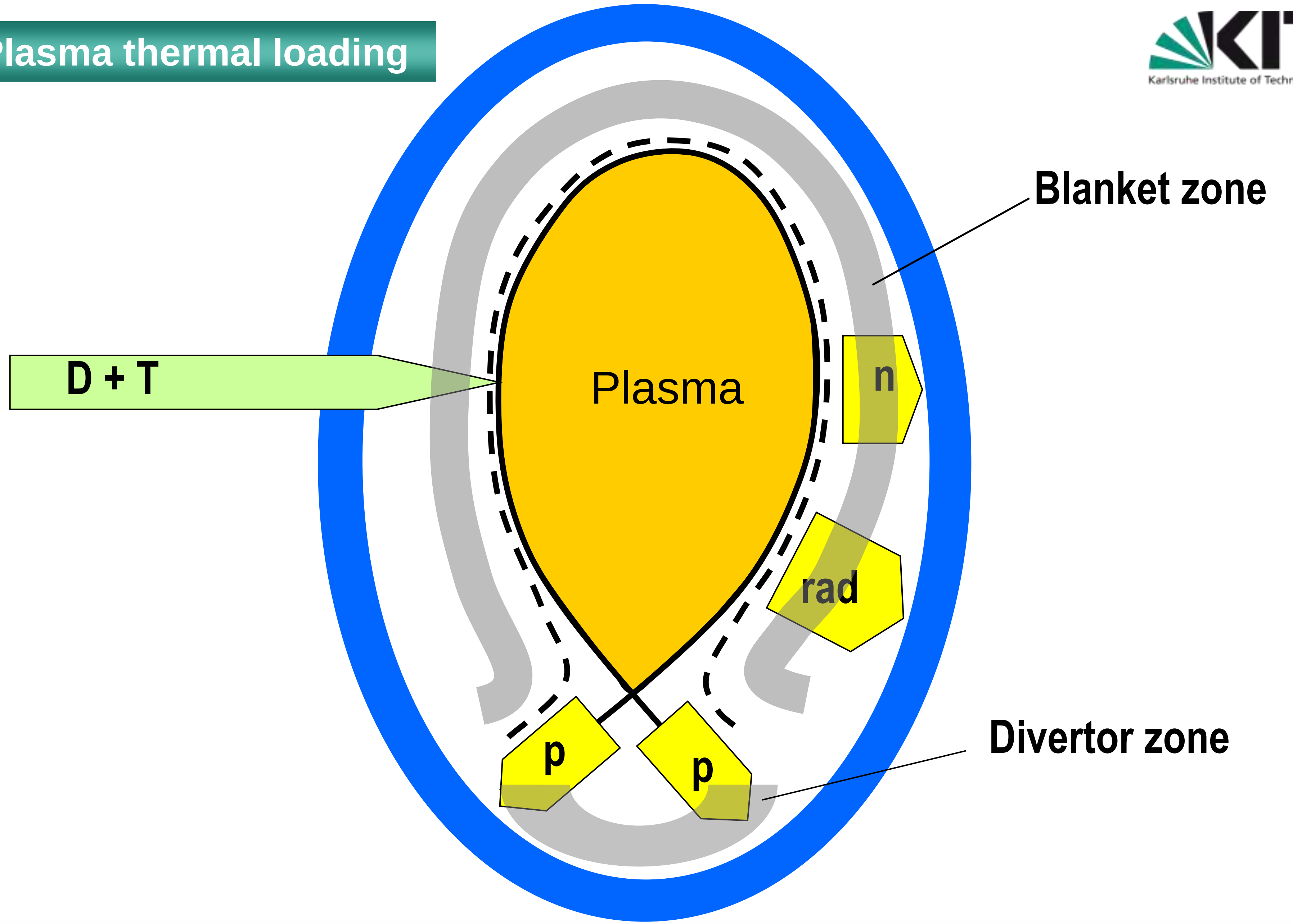
Most neutrons pass the first wall,

with light atoms like lithium or beryllium the neutrons loose energy by elastic scattering

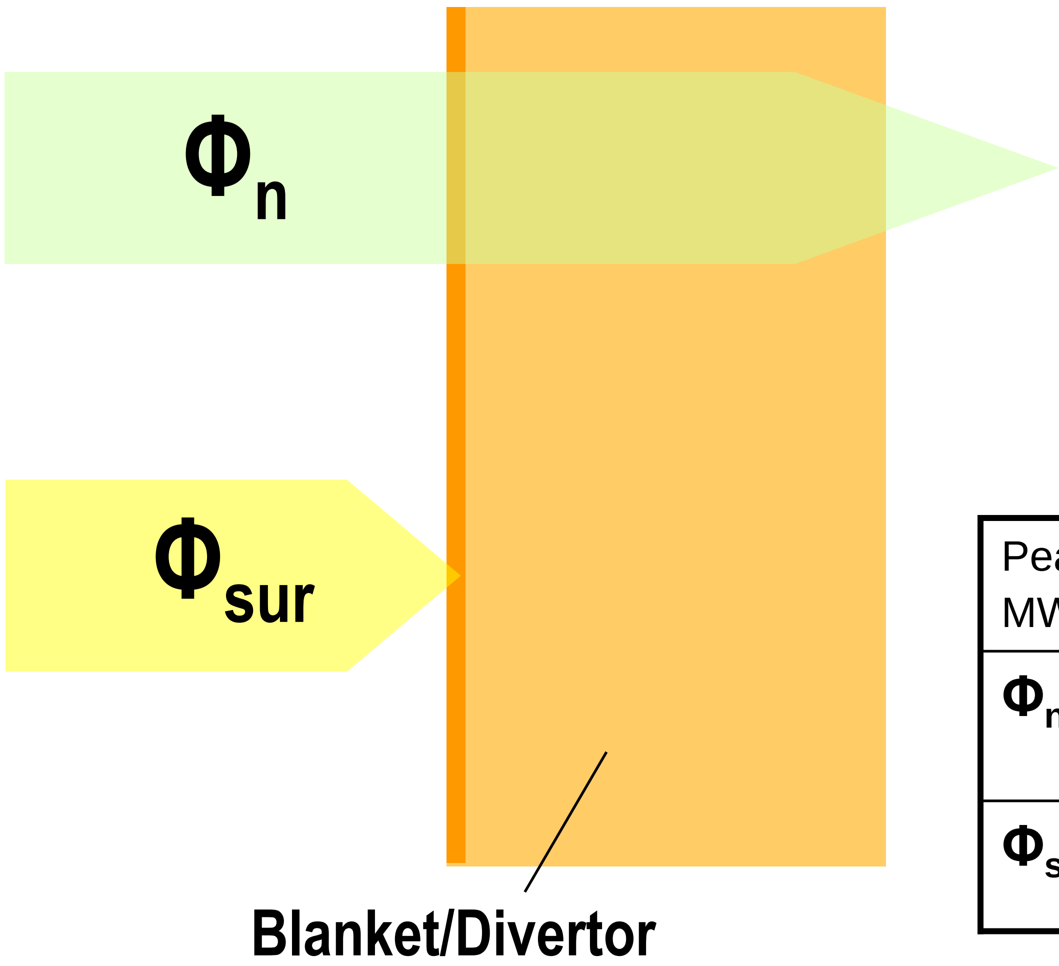
Additional neutron shields behind the blanket

γ-irradiation occurs where medium or heavy atoms are hit, but is converted into heat after few cm

Plasma thermal loading



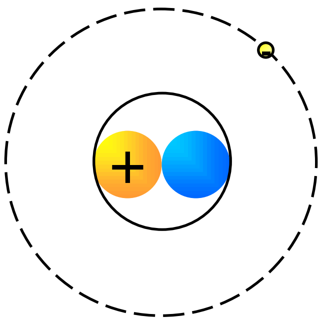
Energy distribution in Blanket and Divertor zones



	Blanket	Divertor
E [Ef %]	82.5 %	17.5%

Peak values in MW/m^2	Blanket	Divertor
Φ_n	2.4 - 3	~1-2
$\Phi_{sur} = \Phi_{rad+} \Phi_p$	~0.5	10-20

D: Deuterium



$^{2}_{1}H$

Property	D_2O (Heavy water)	H_2O (Light water)
Freezing point (°C)	3.82	0.0
Boiling point (°C)	101.4	100.0
Density at STP(g/mL)	1.1056	0.9982
Temp. of maximum density (°C)	11.6	4.0
Viscosity (at 20°C, mPa·s)	1.25	1.005
Surface tension (at 25°C, µJ)	7.193	7.197
Heat of fusion (cal/mol)	1,515	1,436
Heat of vaporisation (cal/mol)	10,864	10,515

Can be found: in ocean water at a H/D ratio of ~6500 (~150 ppm)

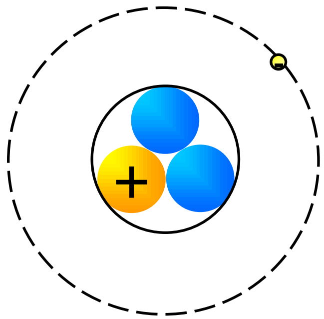
Used: in nuclear energy (e.g. D_2O in CANDU reactors)

Production methods (D_2O):
e.g. Girdler-Sulfid-Proces (isotopical exchange) + vacuum distillation

Extimated earth availability:
$5*10^{16}$ kg (in oceans)

Sufficient for several billion years !!

T: Tritium



$$^{3}_{1}H$$

Radioctive with a half life of 12.33y

$$T \rightarrow {}^{3}He + e^{-} + \ 18.6\ keV$$

Can be found in nature:
in neglegible amount as product of cosmical rays

$$^{14}N + n \rightarrow \ ^{12}C + {}^{3}T$$

Production as waste of nuclear D_2O reactors (e.g. CANDU):

$$D + n \rightarrow T \qquad \sim 2\ kg/year$$

No available production to support fusion reactors as external sources.

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

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

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

3.) Tritium mass flow = 3 * mass of proton (neutron) * frequency =
$3 * 1.67*10^{-27}$ kg * $9.57*10^{20}$ * 24 * 60 * 60 * 1/day = **0.41 kg/day**

Tritium T_3: ~ 0.41 kg/day ← **breeding in the reactor itself with Lithium – neutron reaction**

Deuterium D_2: ~ 0.27 kg/day ← **from sea water**

Current world production of Tritium: 2 kg/year (!)

Needed ressources for a D-T-Fusion Power Plant, ~1000 MW electrical :

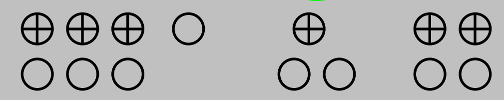
Deuterium D_2: ~ 100 kg/a → **in $5*10^{16}$ kg Oceans**

Sufficient for 30 billion years !!

Tritium T_3: ~ 150 kg/a

breeding with Lithium reaction →
Only 300 kg Li^6 needed per year

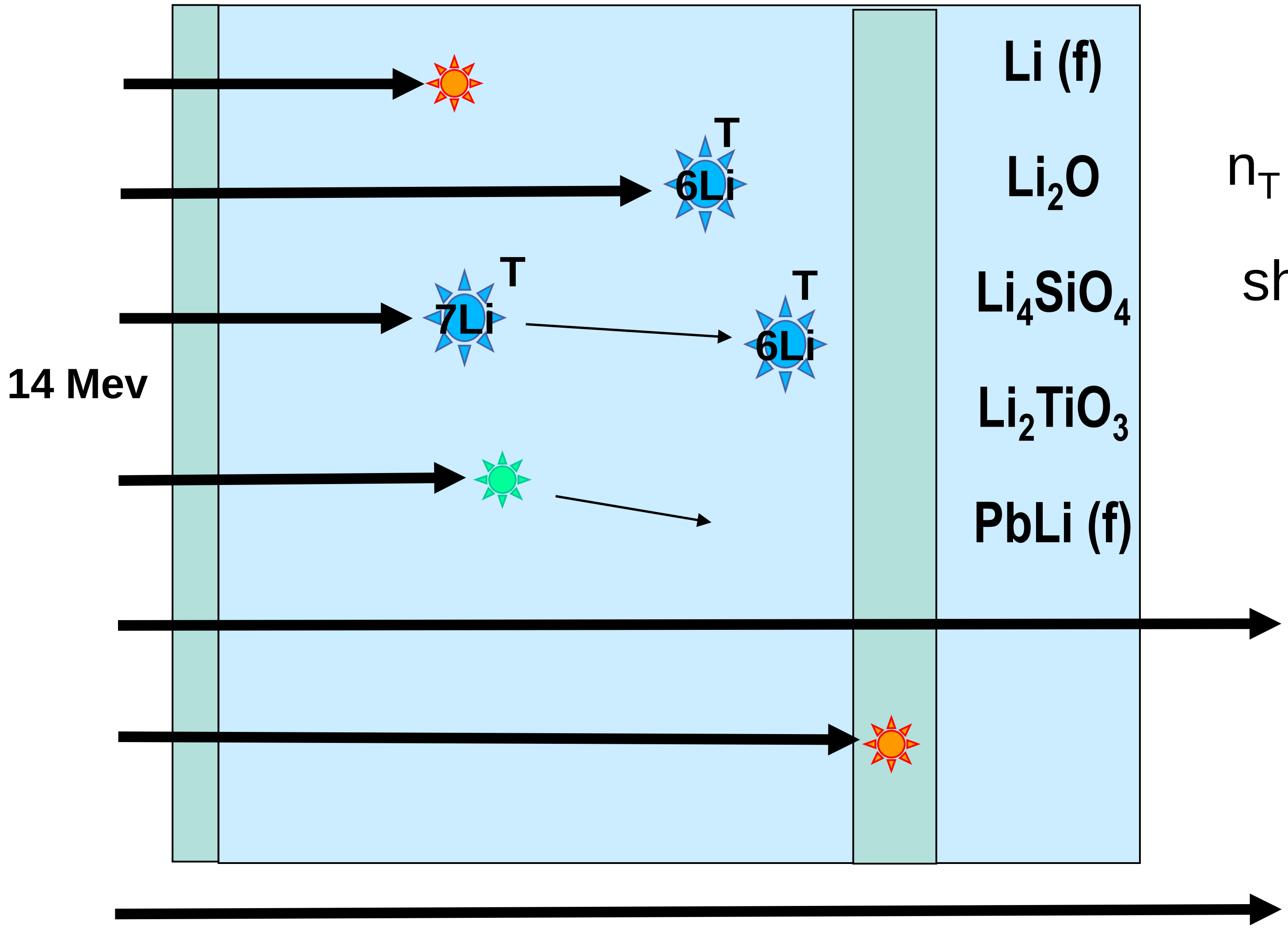
$$^{6}Li + n \rightarrow {}^{3}T + {}^{4}He + 4.8\ MeV$$



About 10^{11} kg Lithium in landmass
Sufficient for 30'000 years

About 10^{14} kg Lithium in oceans
Sufficient for 30 million years !!

Tritium breeding

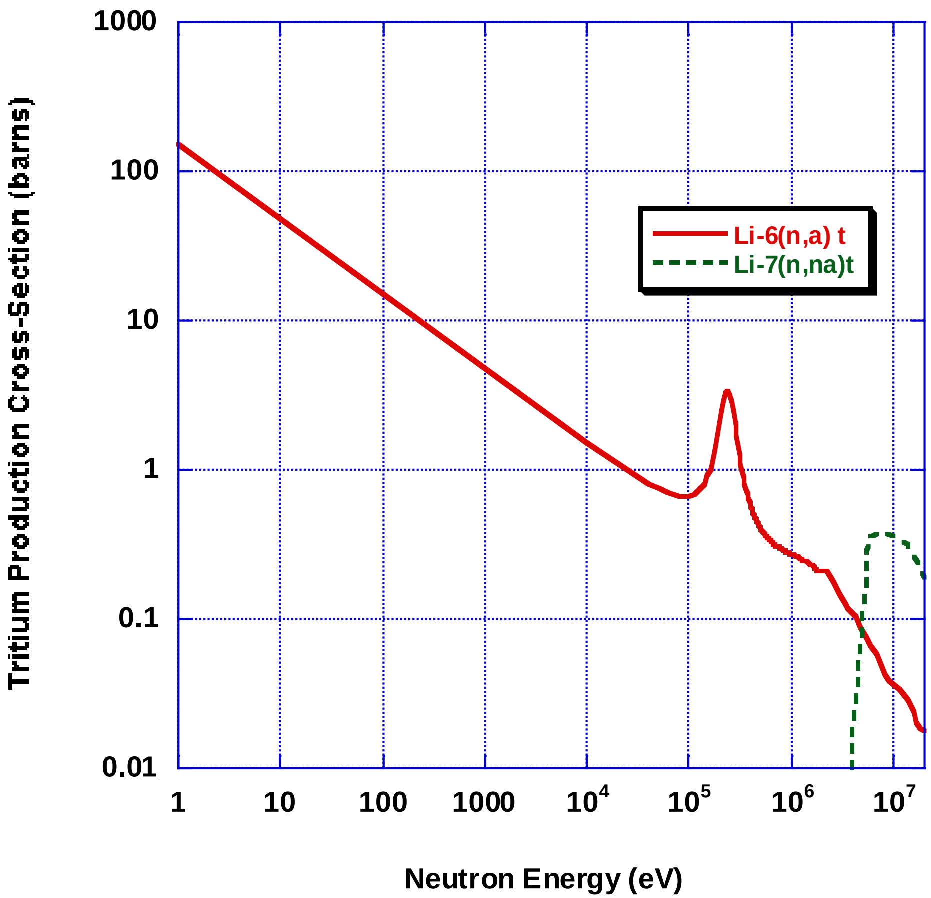


$$n_T = n_f * X_b * X_T * m$$

shall be $n_T / n_f > 1$

Tritium breeding

Li-6(n,alpha)t and Li-7(n,n,alpha)t Cross-Section



The ^{7}Li reaction works with the high energy neutrons

$$^7Li + n \rightarrow {}^3T + {}^4He + n - 2.8\ MeV$$

⊕⊕⊕ ○ ⊕ ⊕⊕ ○
○○○○ ○○ ○○

The decelerated neutron can still make a Tritium atom by the ^{6}Li reaction.
"Two Tritium atoms with one neutron"

$$^6Li + n \rightarrow {}^3T + {}^4He + 4.8\ MeV$$

⊕⊕⊕ ○ ⊕ ⊕⊕
○○○ ○○ ○○

⊕ Proton
○ Neutron

Natural mixture:
92.5 % ^{7}Li, only 7.5 % ^{6}Li

^{6}Li(n,α)T transmutation

Tritium generation rate G

$G = \int_V \int_E \varphi\ \rho\ \sigma$ **(e.g.** φ = 1.8*10^{23} neutrons/(day*A_{ges}), σ = 20 barns = 20 * 10^{-28} m^2, ρ = 0.5 g/cm^3 = 500 kg/m^3)

- $\varphi(E)$: neutron flux density;
- $\sigma(E)$: ^{6}Li cross section (decreasing with ~ $\sqrt{E}$);
- ρ : ^{6}Li density;

integrated over the neutron energy E and the space coordinates V

Energy Multiplication with 1 x ^{6}Li-T transmutation per n:

The energy of the neutrons from the plasma (14.1 MeV)

The energy of the ^{6}Li reaction (4.8 MeV)

→ Energy multiplication in blanket: (14.1 + 4.8)/14.1 = 1.36

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

Estimate for: Breeding zone full of Lithium

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):

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

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

= number of Neutrons per second; per day: 8.27 10^{25} 1/day; per day and m² : 8.27 10^{22} 1/(day m^2)

3.) Cross Section (Wirkungsquerschnitt) of Li^7 at 14MeV: σ = 0.2 barns (= 0.2 10^{-28} m^2)

Density of Lithium ρ ~ 500 kg/m^3, Tritium production rate 0.41 kg/ day,

Volume: 1000 m^2 * 0.7 (Blanketsurface, ratio of breeder space)

Needed radial build of breeding zone:

R = 0.41 kg/day / (1000 m² * 0.7 * 8.27 10^{22} 1/(day m²) * 0.9 * 0.2 10^{-28} m² * 500 kg/m³) = **0.77 m**

$$G = \int_V \int_E \varphi \, \rho \, \sigma$$

Why don't we just use liquid Lithium? (would allow for sufficient breeding)

1) Lithium is dangerous, it burns and ignites in air, strong reaction with water.

2) High solubility of Tritium → hard to extract

How else could we design Lithium blankets?

A) Increase the number of neutrons (using neutron multipliers)

B) Use Lithium 6 enrichment in combination with high number of slower neutrons

How can we use Lithium in blankets?

A) Ceramic materials (Oxides, used in solid state)
e.g. LiO_2, $LiAlO_2$, Li_2SiO_3, Li_4SiO_4, Li_8ZrO_6, Li_2TiO_3

→ Tritium is collected by a Helium purge gas

B) Eutectic alloy (liquid state use) $Li_{17}Pb_{83}$ (17 atom% Lithium)

→ Tritium is extracted from the liquid metal outside the vacuum vessel

Ceramic breeder Blanket: neutron multipliers

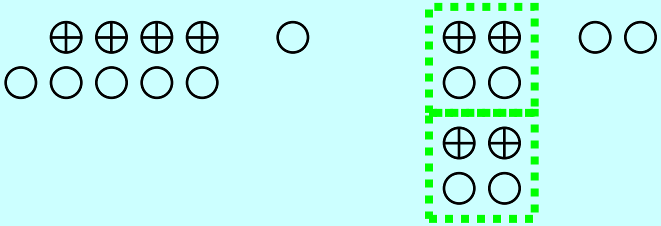
In materials like Li_4SiO_4 due to the presence of other materials the probability of neutrons hitting Lithium is strongly reduced.

→ What would you suggest?

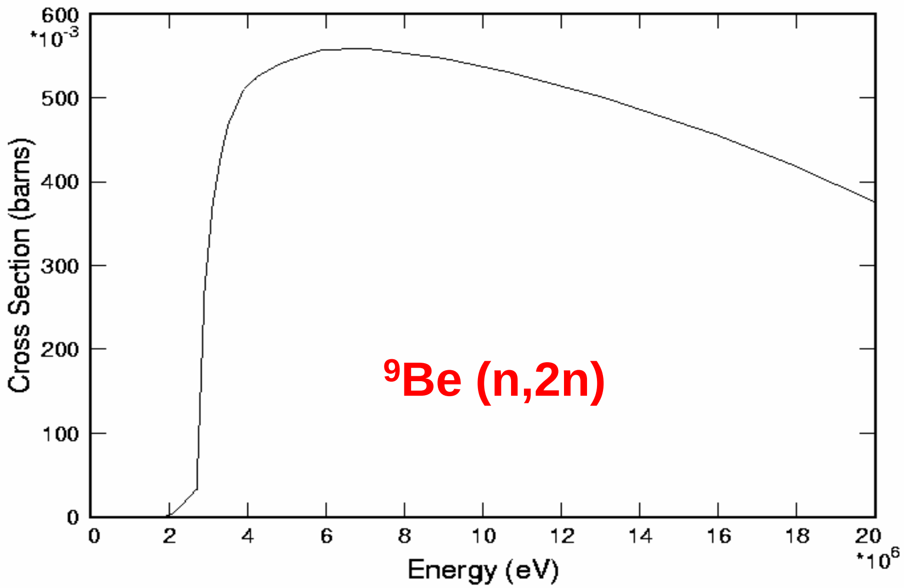
Use neutron multiplier materials:
Beryllium Be or Lead Pb

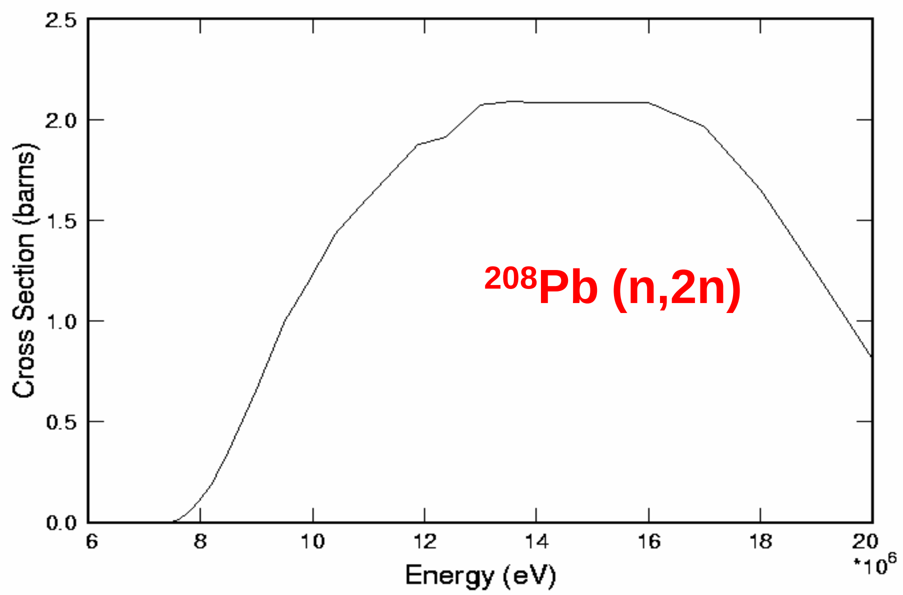
^{208}**Pb (n,2n) threshold 7.4 MeV**
^{9}**Be (n,2n) threshold 2.5 MeV**

$^{9}Be + n \rightarrow 2\ ^{4}He + 2n$



neutron multipliers





Be advantage:

+ needs no high energy neutrons,
+ larger number of impacts per neutron is possible

Be disadvantage:

1.) Small world resources of usable Be,
2.) Beryllium is toxic (dangerous if dust occurs)

Lead Pb:

- melts at 327°C
- suitable for liquid metal concept.
- Corrosion is an issue, especially in liquid state.

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

Estimation 2: Breeding zone with Be, Li^7, Li^6

Number of Neutrons from plasma per day and m² : $8.27\ 10^{22}$ 1/(day m²)
neutron multiplication ~ 2

Cross Section (Wirkungsquerschnitt) of Li^6 and Li^7 average:

σ = 2 barns (= $2\ 10^{-28}$ m²)

Density of Lithiumorthosilicate ρ ~ 2400 kg/m³, Tritium production rate 0.41 kg/ day,
Volume: 1000 m² * 0.7 * 0.64 * 0.2* 0.23
(Blanketsurface, ratio of breeder space, packing density,
amount of lithium in relation to beryllium, amount of Lithium in ceramic)

Needed radial build of breeding zone:

R = 0.41 kg/day / (1000 m² * 0.7 * 0.64 * 0.2 * 0.23 * 2 * $8.27\ 10^{22}$ 1/(day m²) * 0.9 * $2\ 10^{-28}$ m² * 2400 kg/m³) = **0.278 m**

$$G = \int_V \int_E \varphi\, \rho\, \sigma$$

Beryllium: neutron multiplier

$^{9}Be + n \rightarrow 2\,{}^{4}He + 2n$

2.5 MeV

$^{9}Be + n \rightarrow {}^{7}Li + {}^{3}T$

10.5 MeV

$^{7}Li + n \rightarrow {}^{3}T + {}^{4}He + n$

0.6 MeV

$^{9}Be + n \rightarrow {}^{6}He + {}^{4}He$

$^{6}He \rightarrow {}^{6}Li + e^{-}$

$^{6}Li + n \rightarrow {}^{3}T + {}^{4}He$

Helium and Tritium are produced in Beryllium !

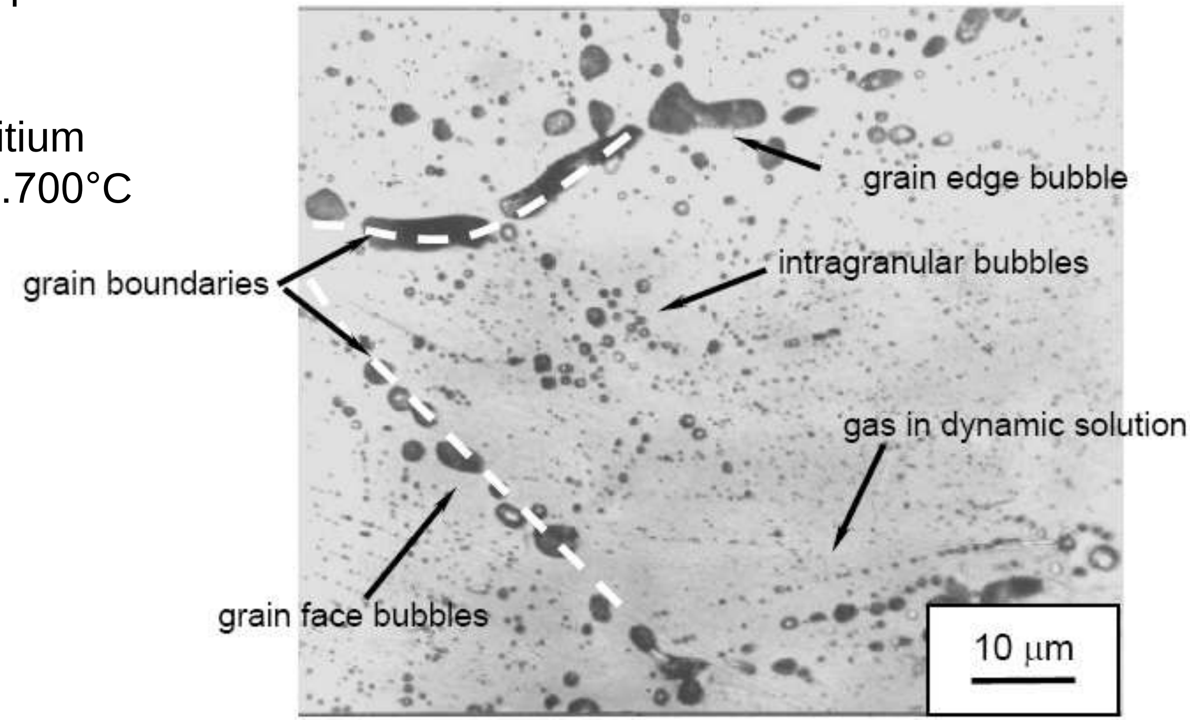
1. Tritium is safety issue if stored in the Be layer
2. Gas bubbles cause swelling (but thermal creep compensates)

Beryllium: typical operational conditions in blanket of power reactor

Note: *1eV = 1.602 10^{-19} Joule,*
*Fluence = power * time / area [Joules/m^2]*
Irradiation = power / area [W/m^2]

1. Lifetime: 40,000 h
2. Fluence (accumulated energy end of life): 3 x 10^{26} neutrons/m^2 (E_n > 1MeV)
3. Irradiation damage (end of life): 80 dpa
4. He production: 25’700 appm
5. Tritium production: 640 appm
6. Total production in blanket: 24 kg Tritium
7. Allowable Temperature range: 400…700°C

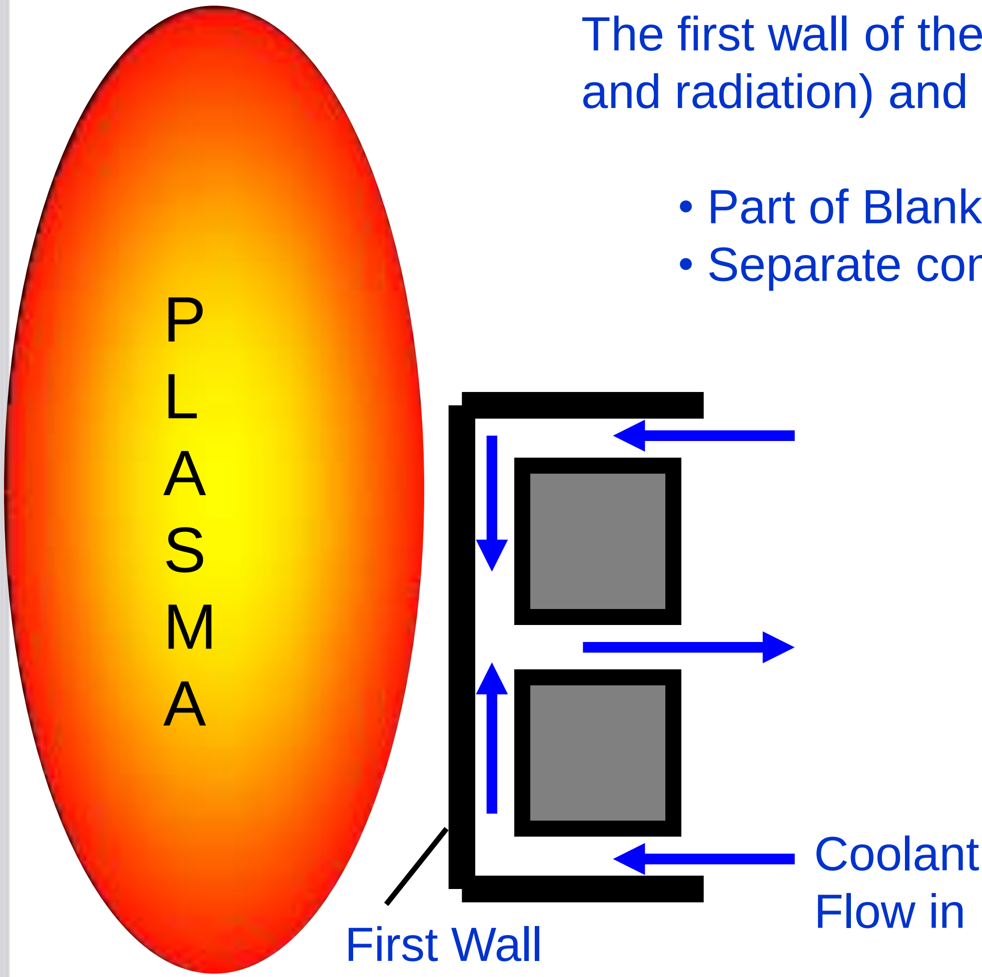
Bubbles in grain and
at grain Boundaries →
Embrittlement and Swelling !



First Wall

The first wall of the blanket is loaded with surface load (particles and radiation) and neutrons

- Part of Blanket (standard in European Designs) or
- Separate component (in some Japanese concepts)

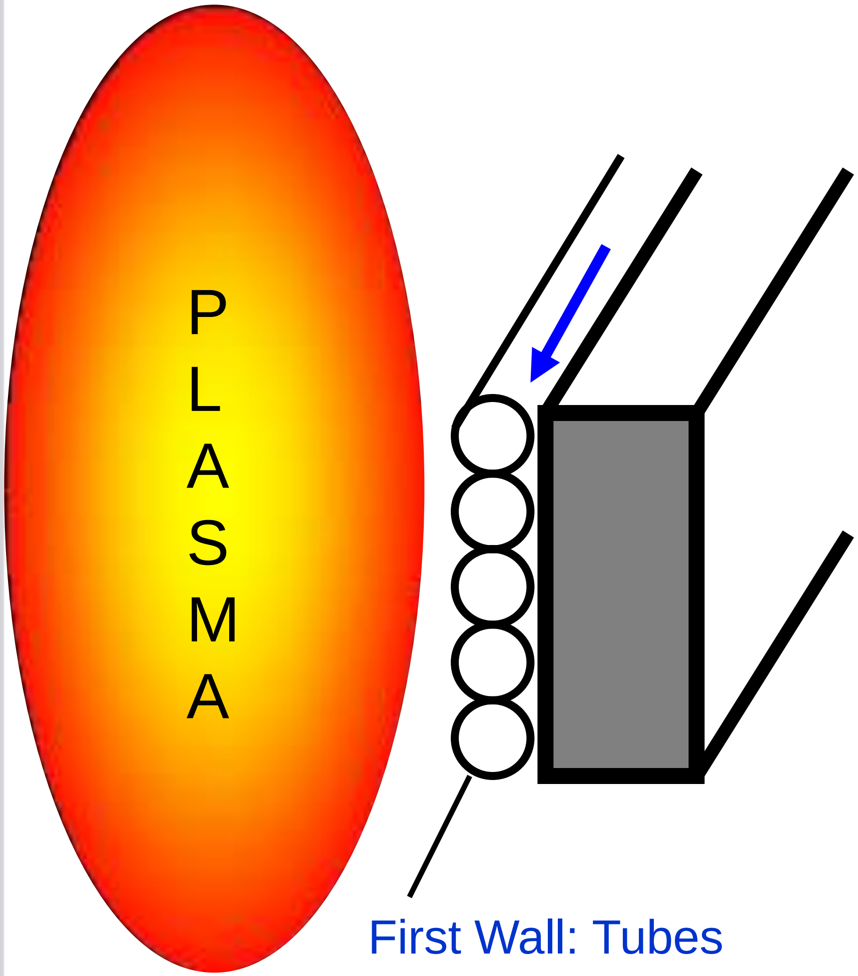


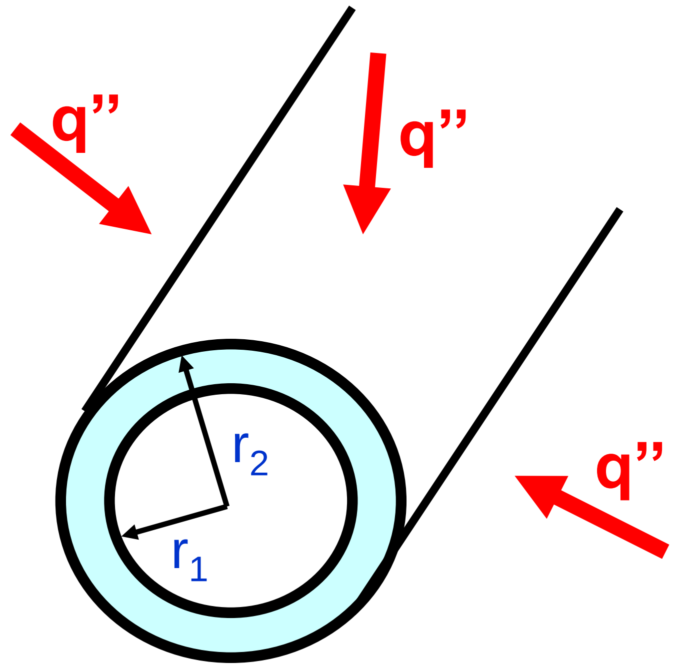
Engineering issues
- Stresses (Thermal, from EM)
- Erosion
- Nuclear (Radiation Damage, Nuclear Heating, Activation)

The first wall has to be cooled intensively

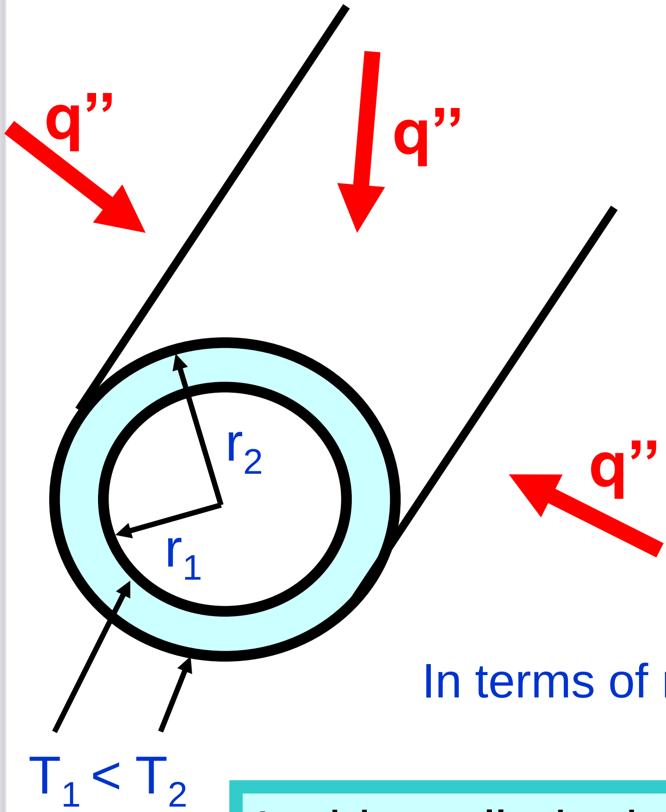
First Wall examples: tubes

Assumptions:
1. The heat flux is uniform around the tube
2. The neutron heating is neglected
3. The tube is unconstraint in axial direction





First Wall examples: tubes



Thermal Stress:
At r_2, T is highest and the fiber at this point wants to expand more than the inner material. The inner material constrains the outer fiber from full expansion

→ The outer fiber is compressed
→ The inner fiber is under tension

In terms of material failure (fracture), tensile stresses are more of concern:

In thin walled tubes:

$$\sigma(r_1) = \frac{\alpha \cdot E \cdot \Delta T}{2(1-\nu)} = \frac{\alpha \cdot E \cdot \dot{q} \cdot (r_2 - r_1)}{2(1-\nu) \cdot \lambda}$$

α – thermal expansion coefficient
E – modulus of elasticity
ν – Poisson's ratio
λ – thermal conductivity
q'' – surface heat flux

First Wall examples: tubes

In thin walled tubes:

$$\sigma(r_1) = \frac{\alpha \cdot E \cdot \Delta T}{2(1-\nu)} = \frac{\alpha \cdot E \cdot \dot{q} \cdot (r_2 - r_1)}{2(1-\nu) \cdot \lambda}$$

Example

$\alpha = 1.8\ 10^{-5}\ K^{-1}$
$E = 1.8\ 10^{11}\ Pa$
$\nu = 0.3$
$\lambda = 20\ W/mK$
$q'' = 0.5\ MW/m^2$
$r_2 - r_1 = 5\ mm$

$$\Rightarrow \sigma(r_1) \approx 290\ MPa$$

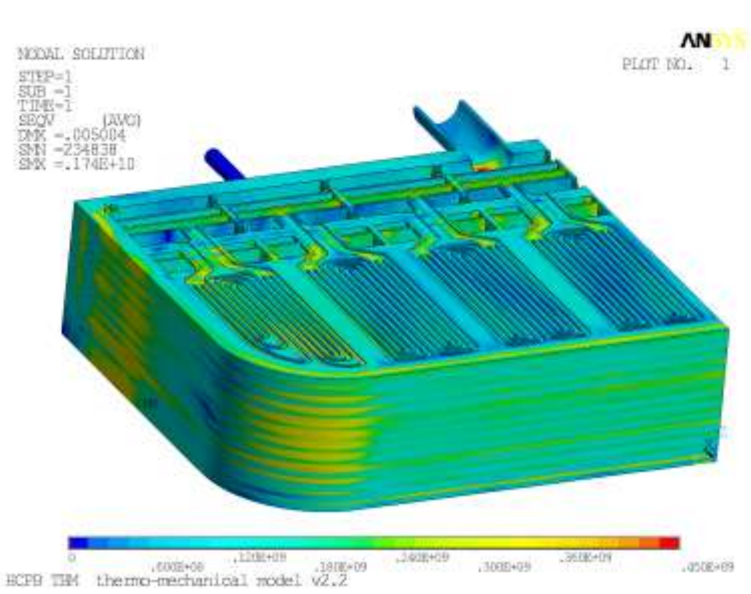
Acceptable?

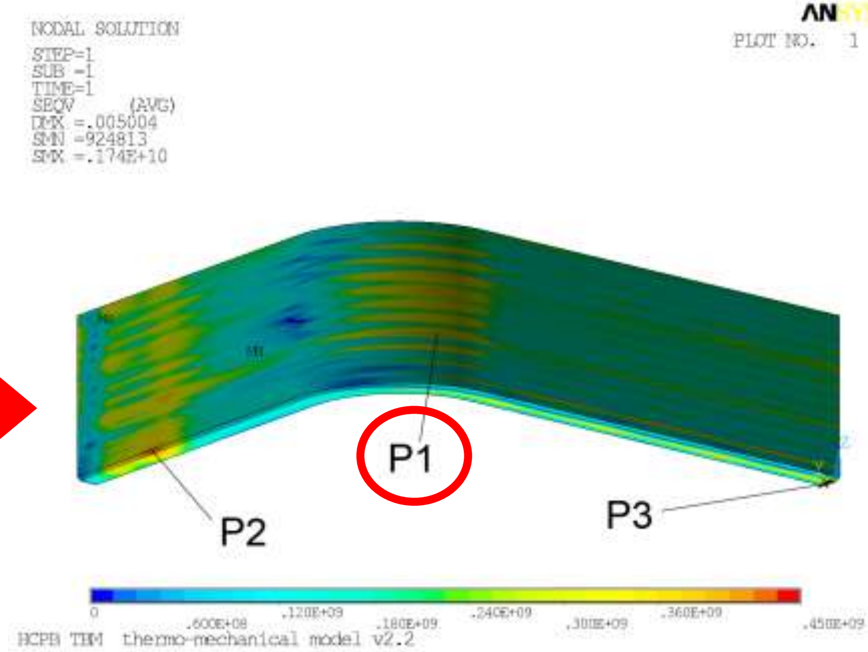
→ **Stress criteria: e.g. elastic stress criteria:**
a) The primary stress from internal pressure (membrane + bending)
b) The total stress (primary + secondary thermal stress)
have to be below material limits:

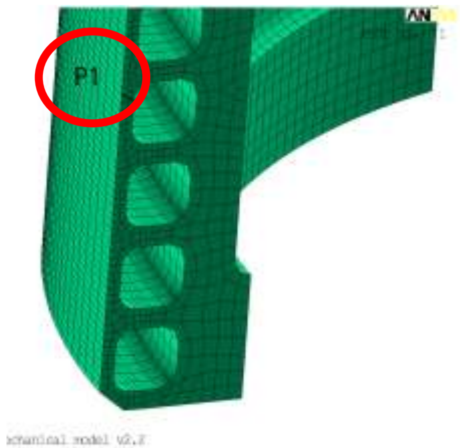
$$\sigma_{prim} \leq S_m$$
$$\sigma_{prim+sec} \leq 3 \cdot S_m$$

e.g. S_m = 132 MPa at 500°C for typical steel →
3Sm criteria: primary stress up to 100 MPa would be allowed

First Wall thermo-mechanical analyses: stress profiles







	Paths	P_L+Q_L [MPa]	T_m [°C]	$S_e(T_m)$ [Mpa]	$3S_m(T_m)$ [Mpa]	IPFL	PD
FW	**P1**	200,7	408,3	160	430,5	*not fulfilled*	fulfilled
	P2	381	360	195,8	481	*not fulfilled*	fulfilled
	P3	301,5	376,5	182,3	473	*not fulfilled*	fulfilled

Additional effects

→Some effects reduce the available structural material quality

a) Cyclic loads
b) Thermal creep
b) Displacement of lattice atoms through collisions (radiation damage) in dpa
c) Generation of gases (He, H_2) through transmutation reactions (e.g. (n,α)) in αppm/year

First wall of blankets at 3 MW/m^2 neutron wall load: **36 dpa/year** and **440 αppm/year**

S_m is function of time, temperature and irradiation history

Neutron heating

Neutron heating effects

a) Particle slowing down (~90 %)

Elastic and inelastic scattering → displaced atoms →
displaced atoms slow down (collide with lattice atoms) → heat up the lattice

b) Secondary gamma-ray production and absorption

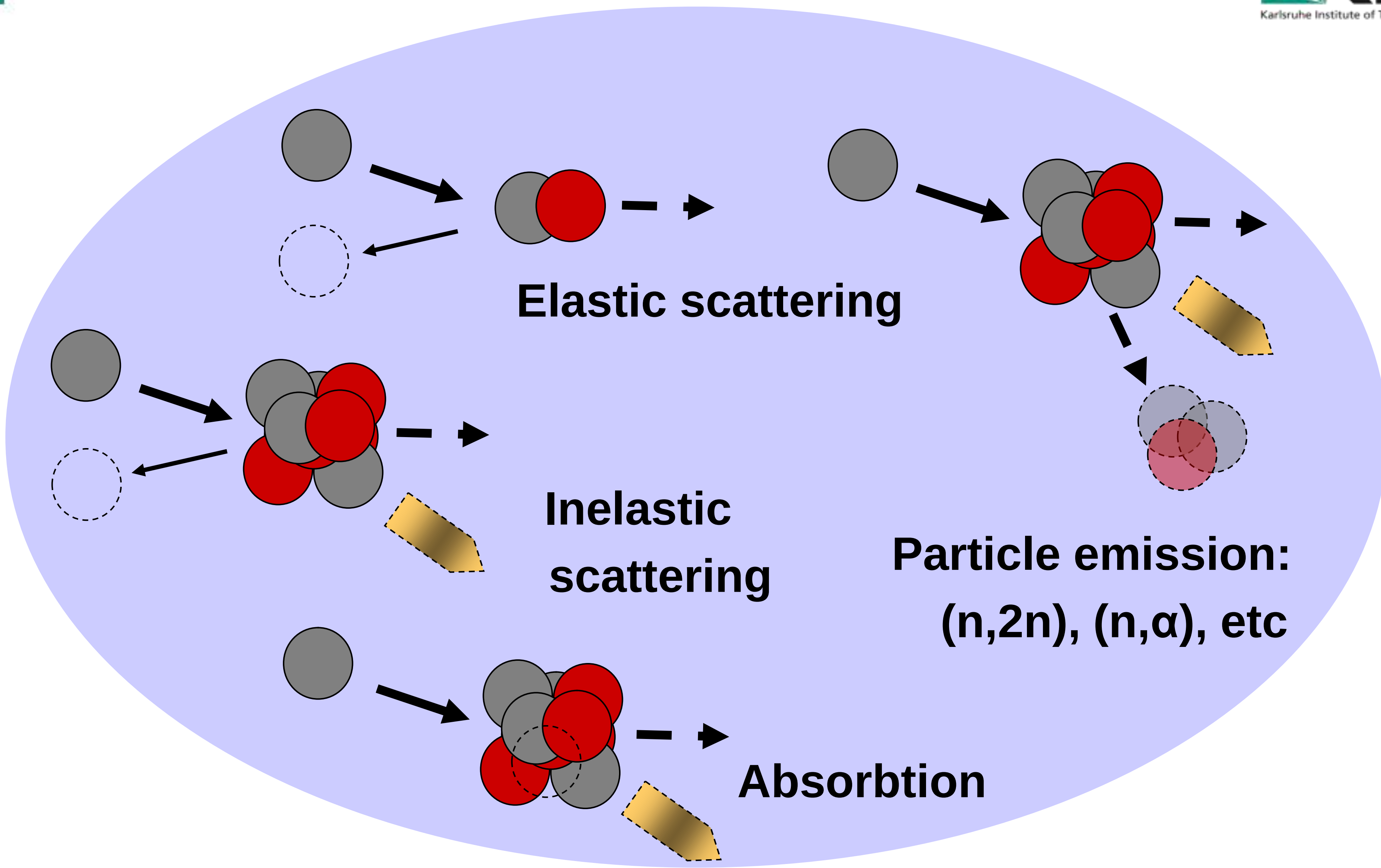
Example:
First wall of blankets at 3 MW/m² neutron wall load:
$q'''_{neutron}$ ~ 25 W/cm³
for wall thickness 2 mm →
$q''_{neutron}$ ~ 5 W/cm² = 0.05 MW/m² **< $q''_{surface}$ ~ 0.5 MW/m²**

Averaged blanket heating at 3 MW/m² neutron wall load:
$q'''_{neutron}$ ~ 3 MW/m³ for 1 m radial build

Surface Heating is critical for First Wall

Fission LWR Core: ~ 100 MW/m³

Neutron heating



Breeding Blanket functions

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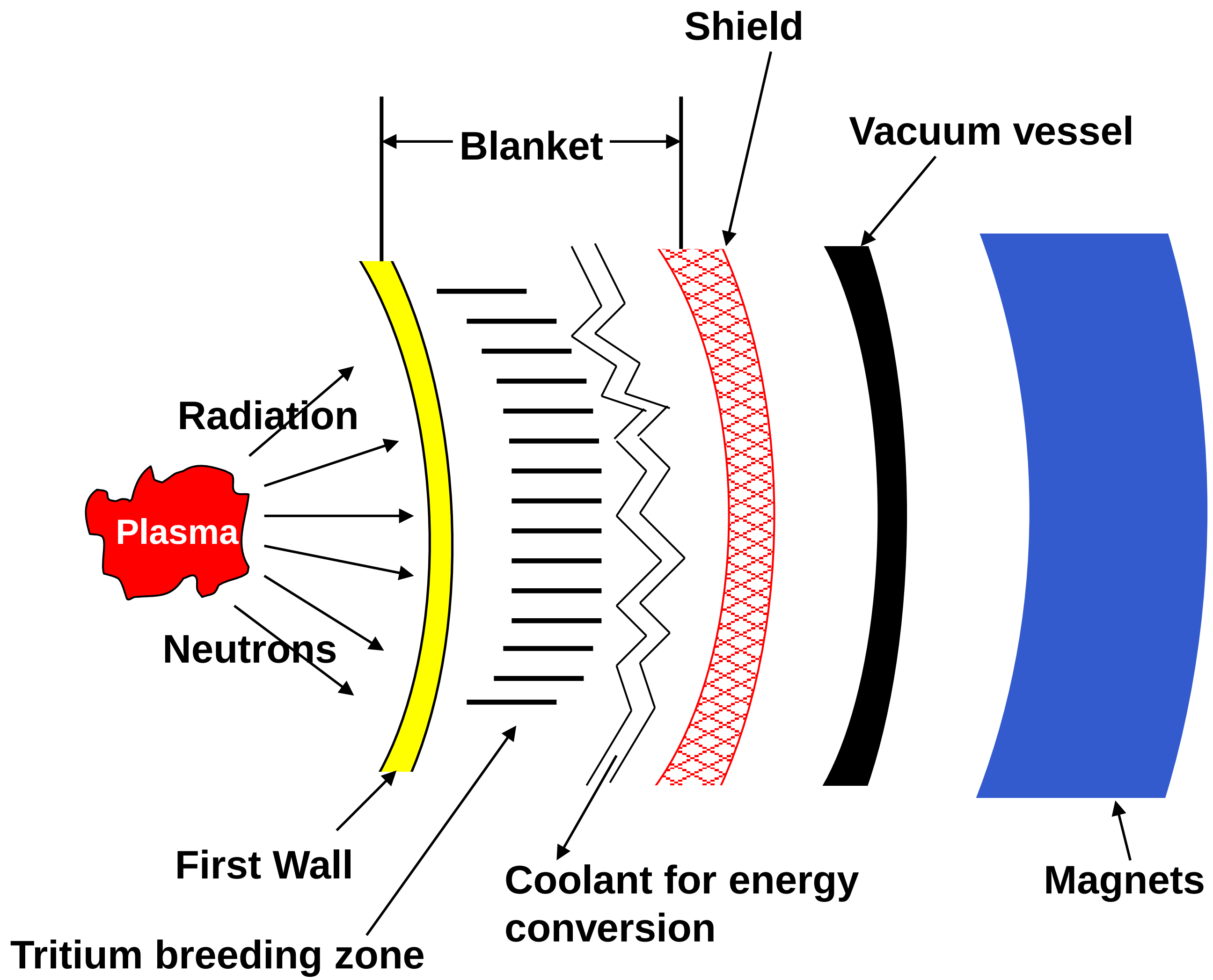
Main functions of the blanket:

1. Tritium production (breeding) and extraction (purging)
2. Transforming neutron power into heat and collection of the heat
3. Shielding of the Vacuum Vessel and Toroidal Field Coils

The breeder blanket is made of:

- Breeder (solid or liquid)
- Neutron multiplier (solid or liquid)
- Shielding (may be separate component)
- Structural material
- Coolant (He, Water, Liquid Metal, Molten Salts)

Breeding Blanket radial build



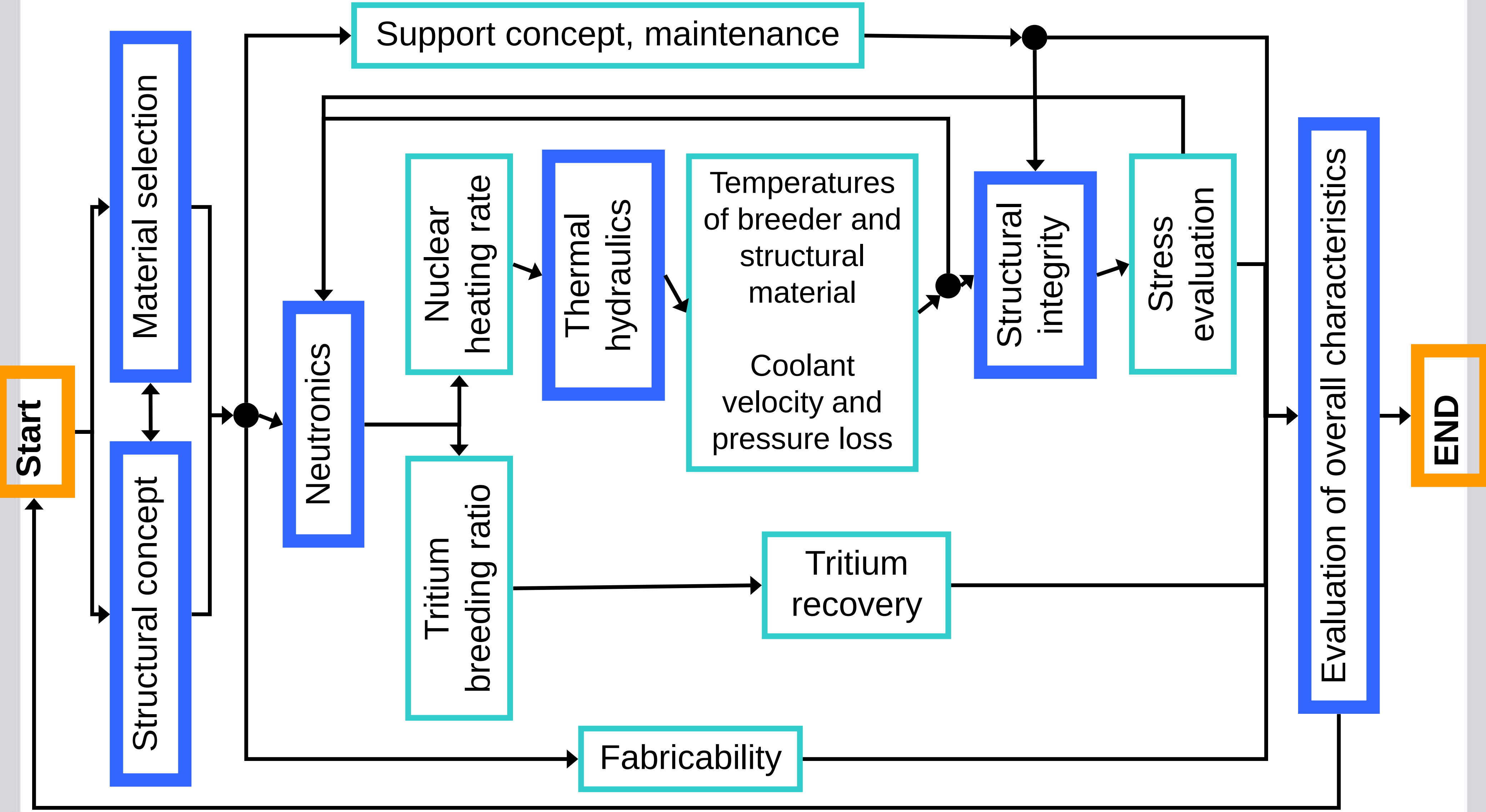
Breeding Blanket functions

The combination of the different components should be made on the basis of their compatibility from chemical, thermal and safety standpoints

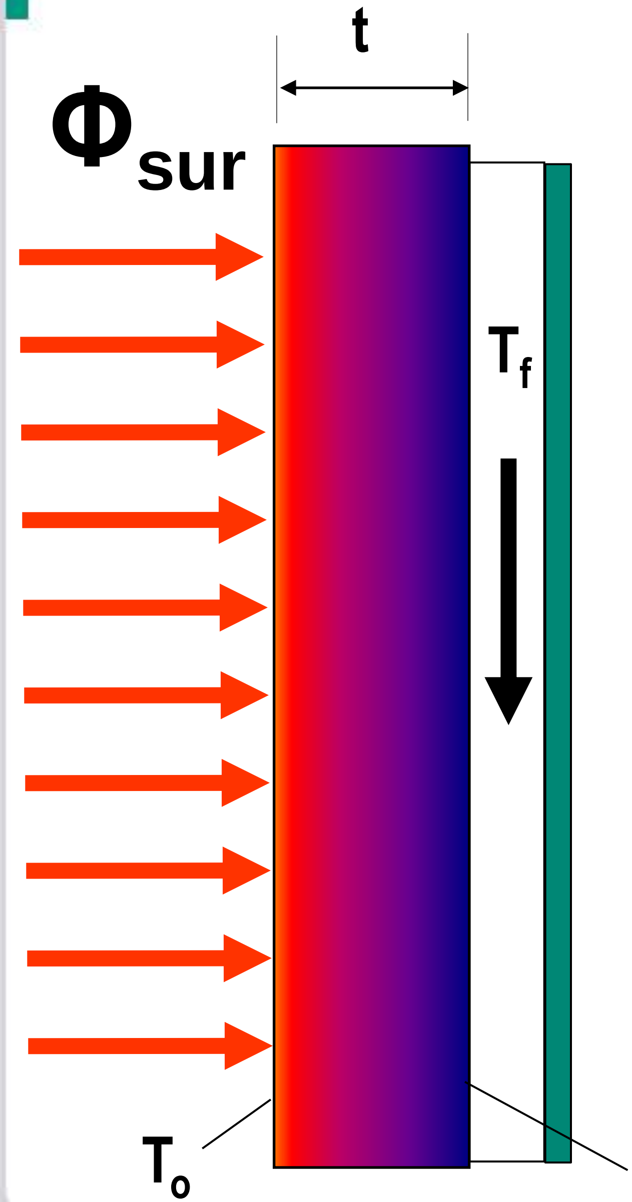
The design has to be featured in order to achieve:

1. Low maintenance time
2. Sufficiently long lifetime
3. High safety level and low environmental impact (including waste)
4. Reasonable direct cost including operation

Blanket development



First Wall examples: plate



$$T_i = T_f + \frac{\Phi_{sur}}{h} \qquad T_o = T_i + \frac{\Phi_{sur} \cdot t}{\lambda}$$

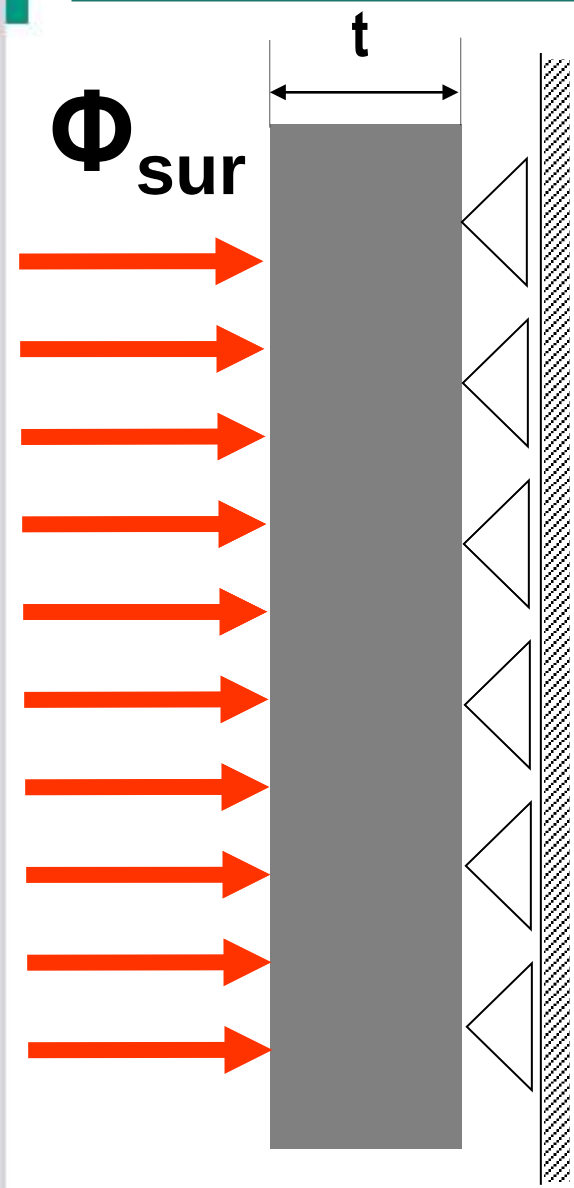
Example of helium cooling of a steel plate:

λ	= 20 W/mK	thermal conductivity
Φ_{sur}	= 0.5 MW/m²	surface heat flux
h	= 8000 W/m²K	heat transfer coeff. (He @~80 m/s)
T_f	= 300°C	coolant bulk temperature
t	= 5 mm	thickness

$T_i = T_f + \Phi_{sur} / h$ {= 300 + 0.5 10^6 / 8000} = 362.5°C

$T_o = T_i + \Phi_{sur} \cdot t / \lambda$ {= 362.5 + 0.5 $10^6 \cdot$ 0.005 / 20 = 362.5 + 125 } = 487.5 °C

First Wall examples: plate



In thin plate:

$$\sigma_{x,y,\max} = \frac{\alpha \cdot E \cdot (T_o - T_i)}{2(1-\nu)} = \frac{\alpha \cdot E \cdot \Phi_{sur} \cdot t}{2(1-\nu) \cdot \lambda}$$

Example:

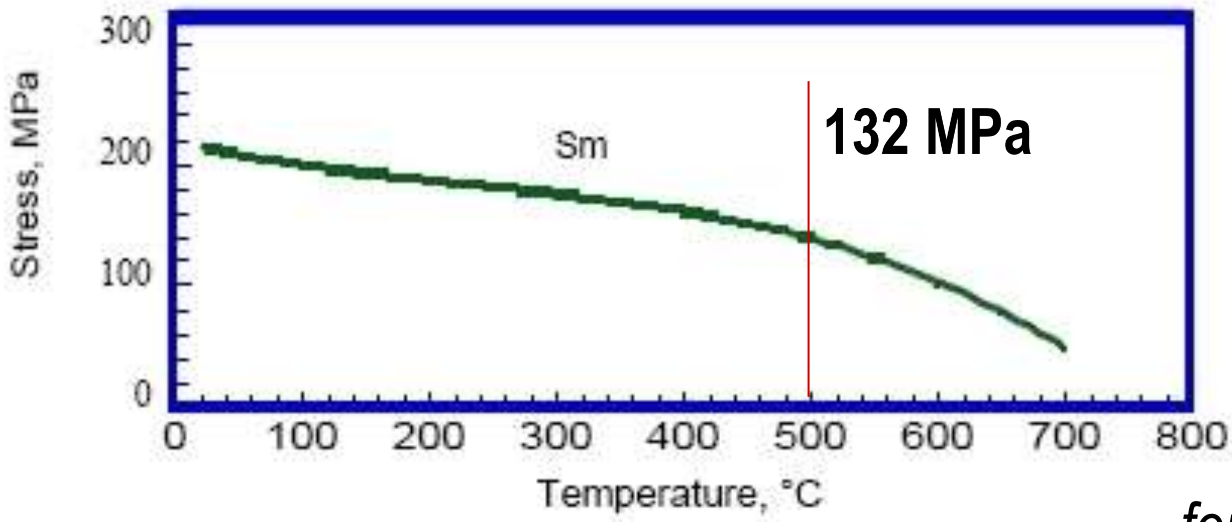
$\alpha = 1.8\ 10^{-5}\ K^{-1}$ thermal expansion coefficient

$E = 1.8\ 10^{11}$ Pa modulus of elasticity

$\nu = 0.3$ Poisson's ratio

$$\sigma_{x,y,\max} \cong 290 MPa$$

First Wall examples: plate



for EUROFER steel

Acceptable?

→ <u>Stress criteria: e.g. elastic stress criteria:</u>

a) The primary stress from internal pressure (membrane+bending)

b) The total stress (primary + secondary thermal stress

have to be below material limits:

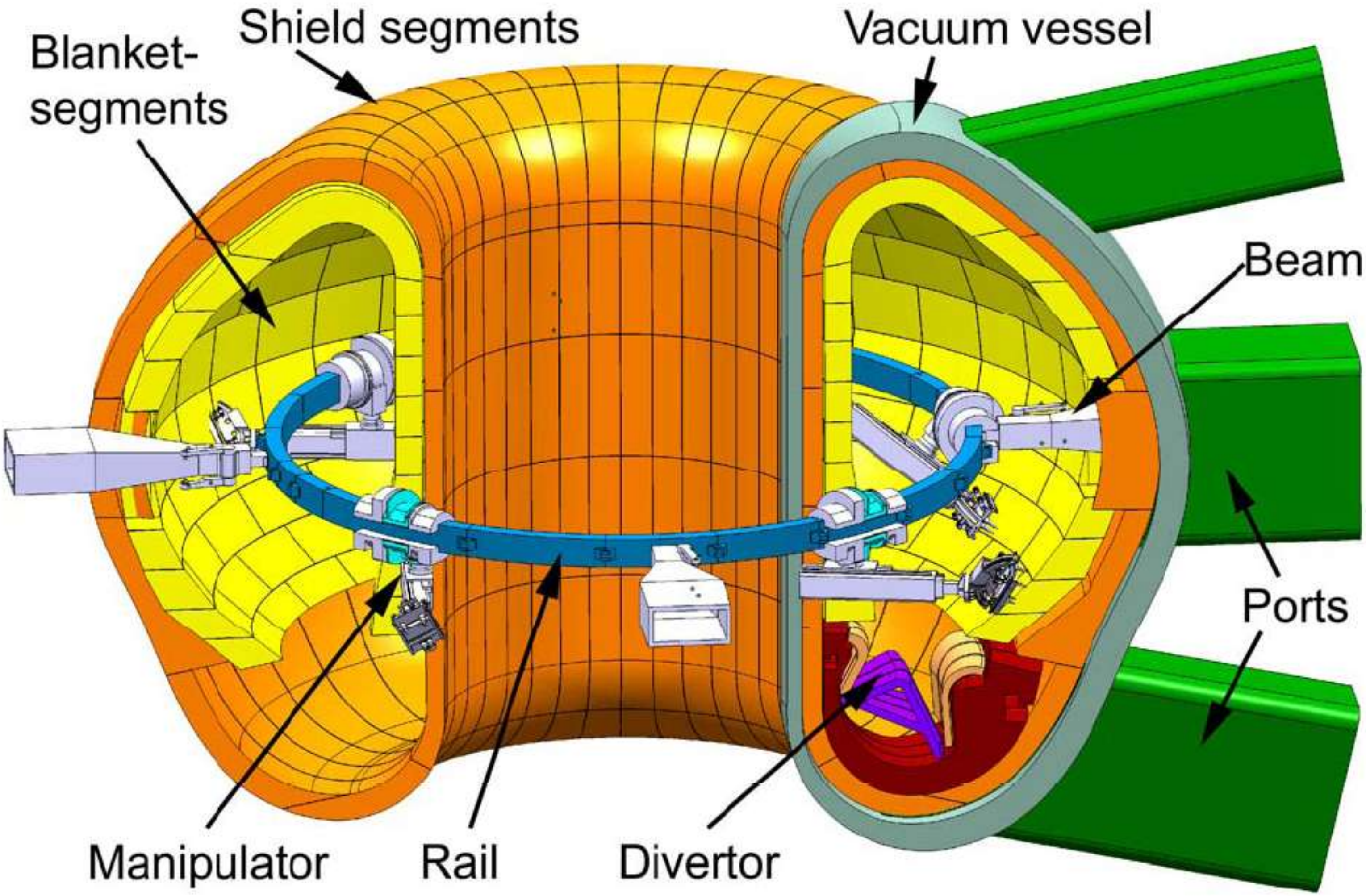
$$\sigma_{prim} \leq S_m$$

$$\sigma_{prim+sec} \leq 3 \cdot S_m$$

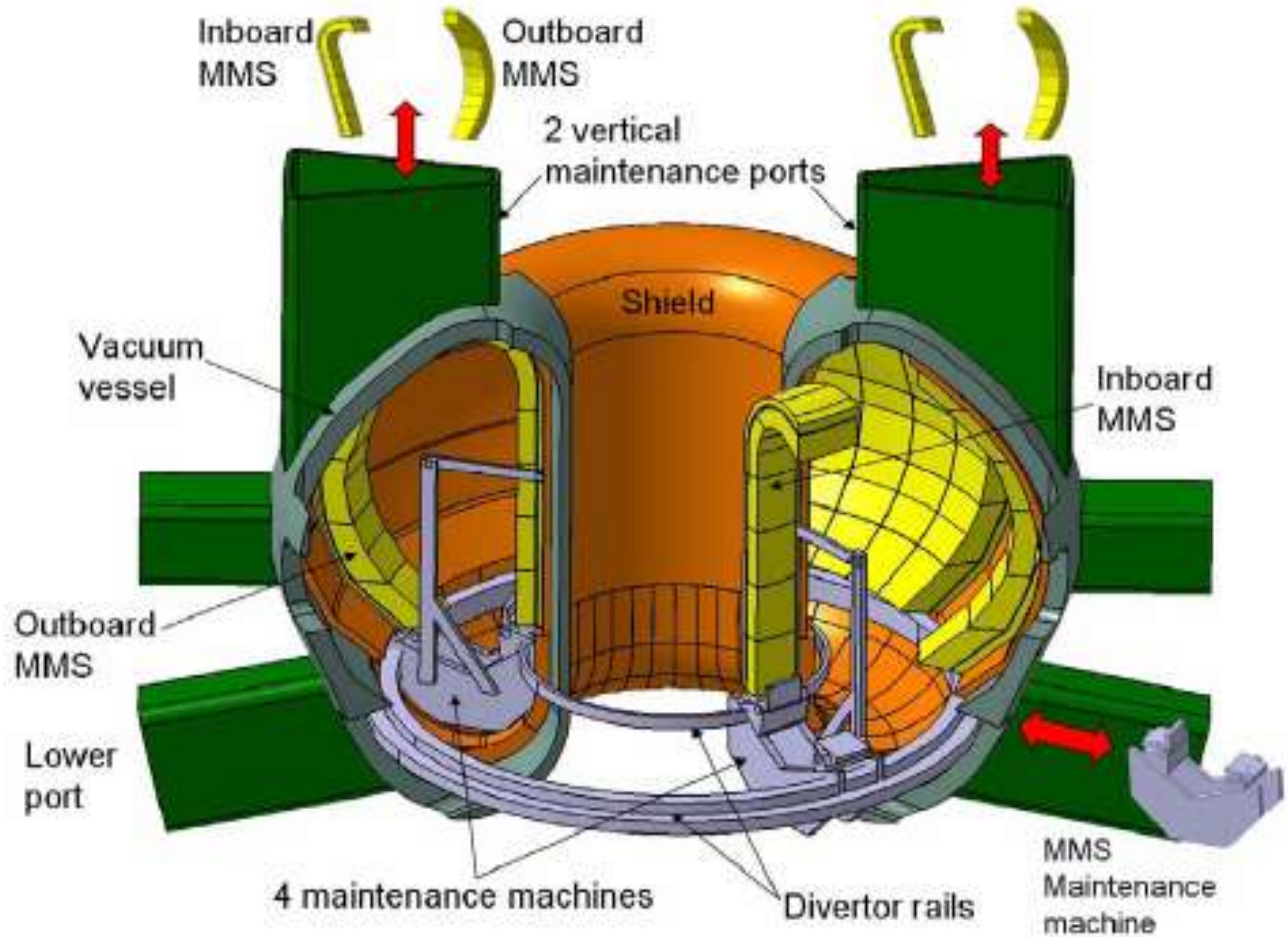
e.g. S_m = 132 MPa at 500°C for typical steel →

3Sm criteria: primary stress up to 100 MPa would be allowed

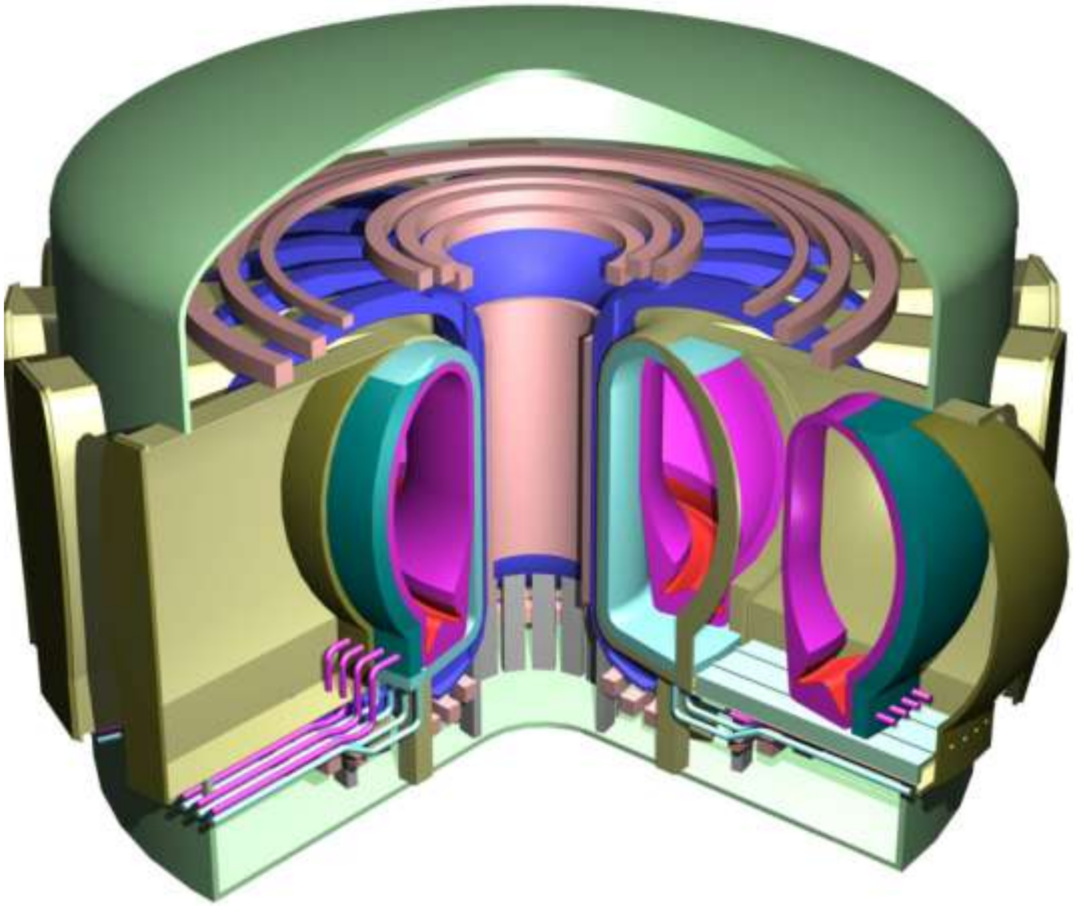
Maintenance system: ITER configuration

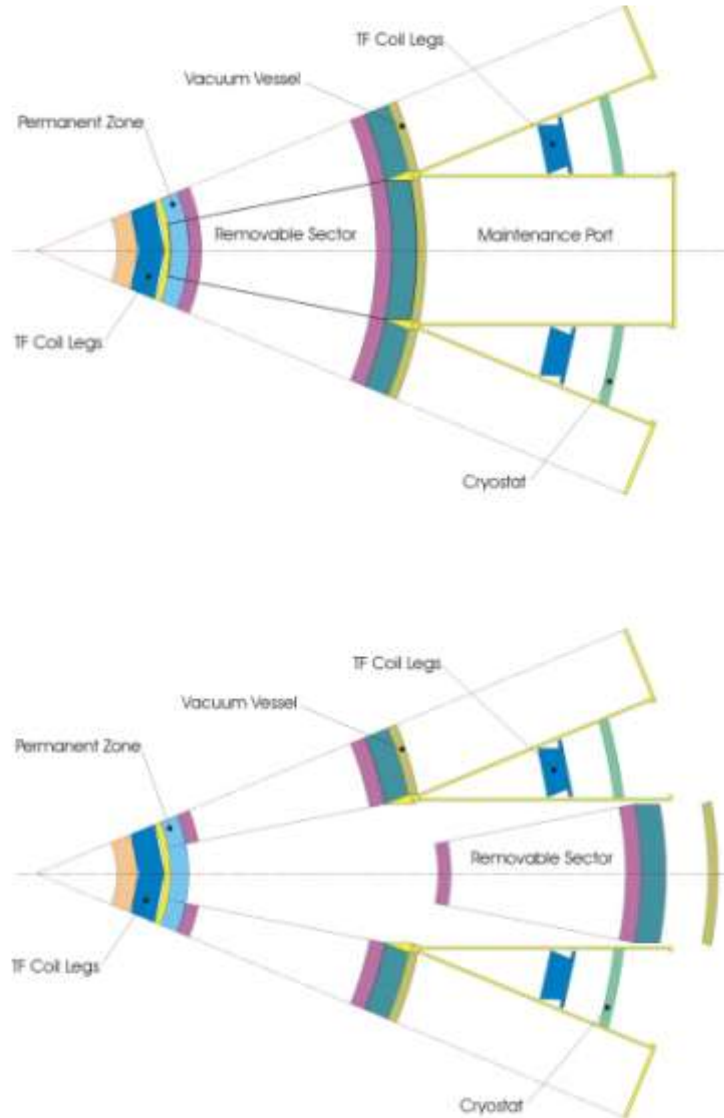


Maintenance system: vertical ports



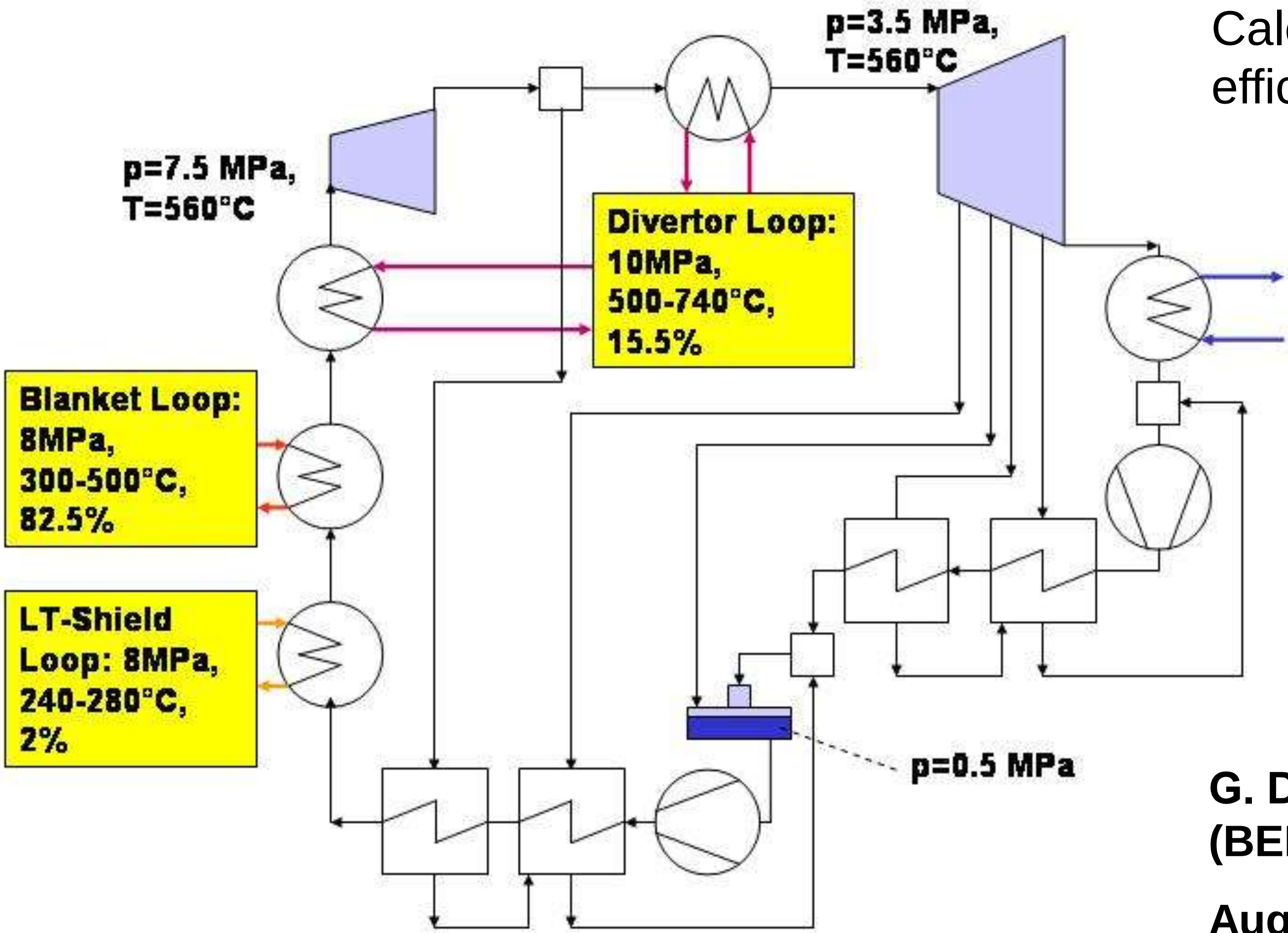
Maintenance system: large sector concept





Aries Studies, US

Power generation system: Rankine



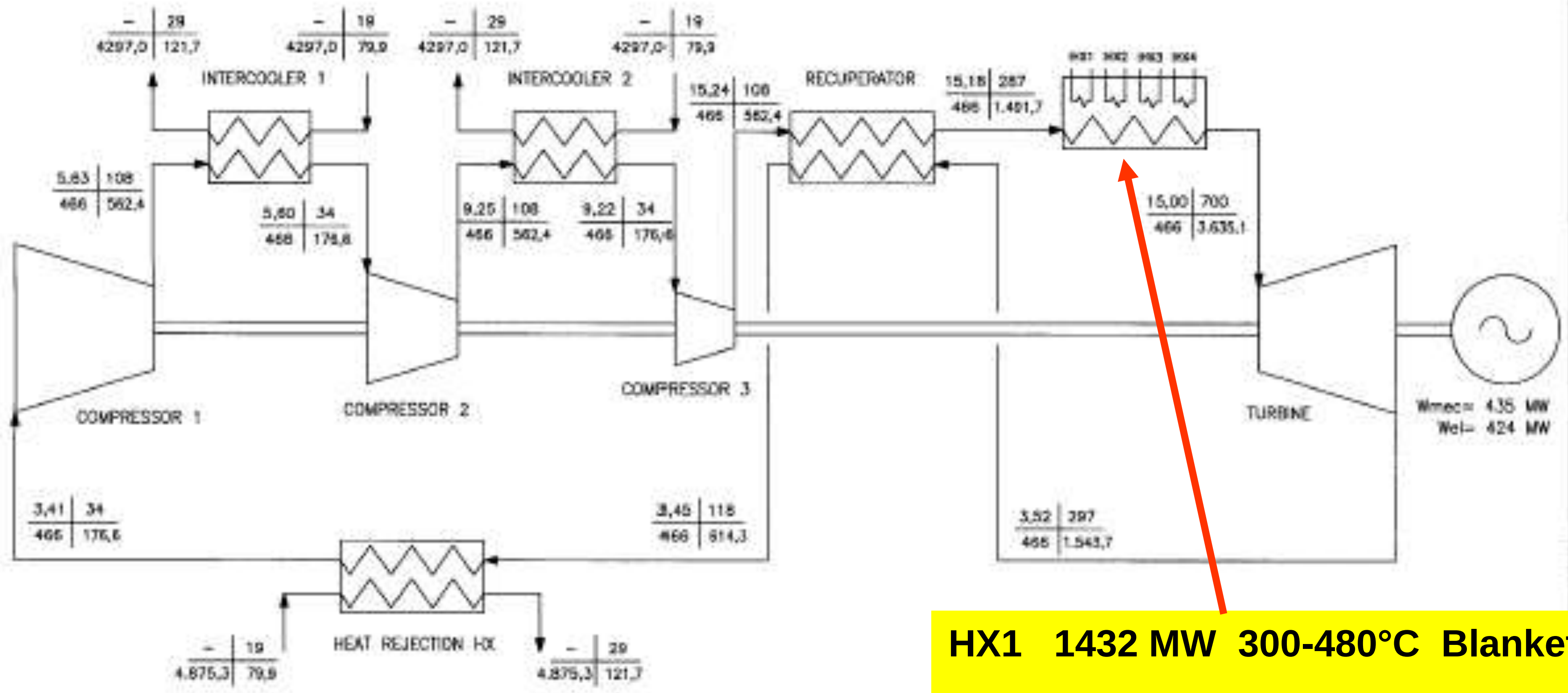
Calculated net cycle efficiency: 41.46%

G. Du Bois d'Enghien (BELGATOM-EFET)

August 2002

Power generation system: Brayton

Karlsruhe Institute of Technology



HX1	**1432 MW**	**300-480°C**	**Blanket (He)**
HX2	**335 MW**	**480-615°C**	**Divertor**
HX3	**1976 MW**	**480-700°C**	**Blanket (PbL)i**
HX4	**248 MW**	**700-800°C**	**Divertor**

Plasma magnetic confinement: plasma limit

The plasma ends where a flux surface is interrupted by a solid surface (Limiter). The interrupted flux surfaces are "open".

The closed flux area can alternatively be defined by an intersection of the flux surfaces (X-point). In this case the open flux surfaces end on divertor targets.