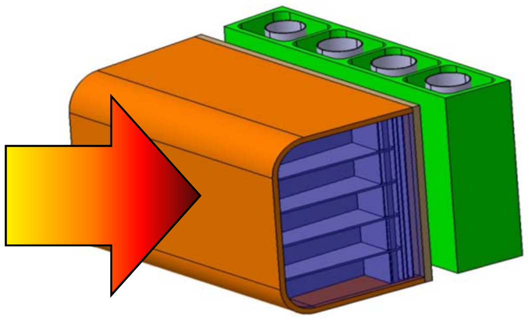
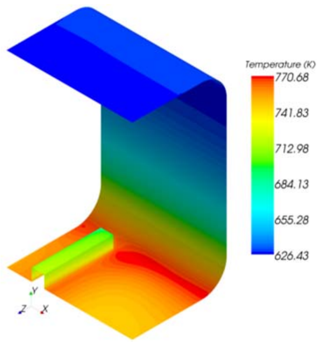
Karlsruher Institut für Technologie

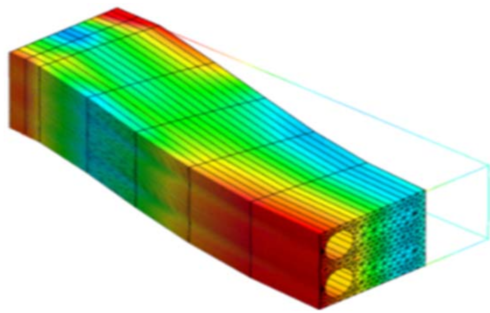
Limits of First Wall and limiter PFCs in DEMO

*Frederik Arbeiter (KIT), Julien Aubert (CEA), Tom Barrett (CCFE), Phani Kumar Domalapally (CV-Řež), Furkan Özkan (KIT) - **02.12.2014**, EFPW, Split.*

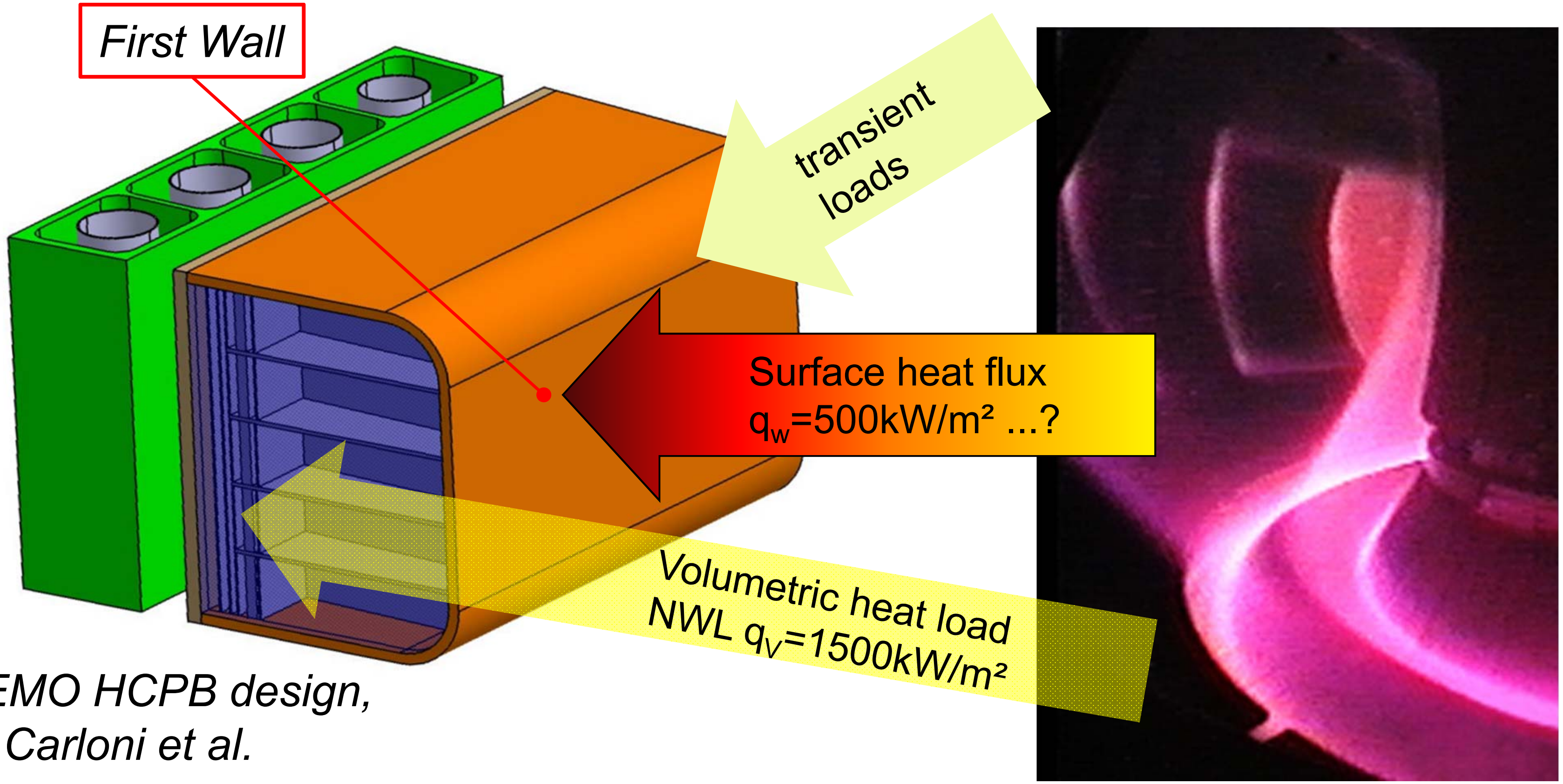
Institut für Neutronenphysik und Reaktortechnik,
Gruppe Messtechnik und experimentelle Methodik (INR-MET)







Heat loads on the First Wall (FW)

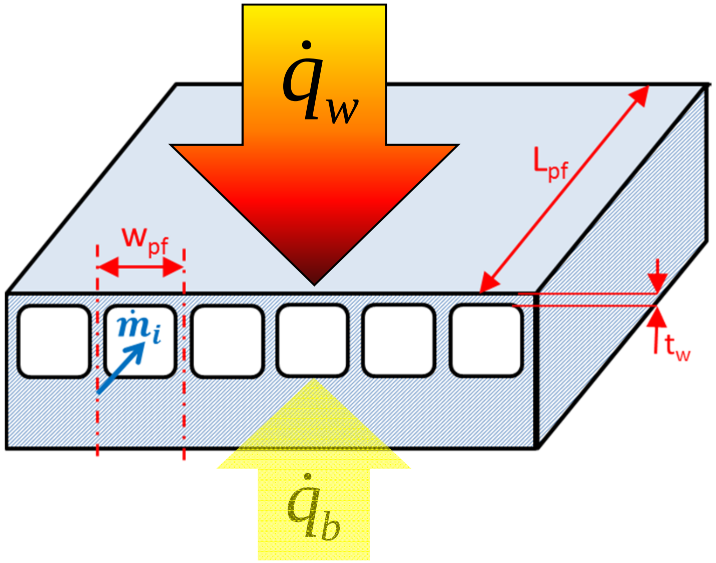


DEMO HCPB design,
D. Carloni et al.

Plasma (in AUG)

Simple maths on FW cooling / thermohydraulic

Simplified 1D, steady state



Maximum (outlet) coolant temperature

$$T_{mf,2} = T_{mf,1} + \frac{(\dot{q}_w + \dot{q}_b)\cdot(L_{pf} \cdot w_{pf})}{\dot{m}_i \cdot \overline{c}_p}$$

Maximum plasma-facing wall temperature

$$T_{w,p,\max} = T_{mf,2} + \underbrace{\frac{\dot{q}_w}{h_{wf}}}_{\text{heat transfer fluid - wall}} + \underbrace{\frac{\dot{q}_w}{\lambda_w / t_w}}_{\text{heat conduction inside wall}}$$

heat transfer fluid - wall; heat conduction inside wall

$$h_{wf} \propto \dot{m}_i^{0.8}$$

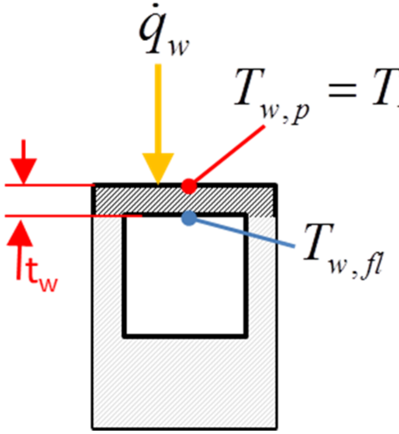
Necessary pumping power – substracts from net output !

$$P_{pump} \approx \frac{\dot{V}_{fl} \cdot \Delta p}{\eta_{pump}} \approx \frac{\dot{m}_i^3 \cdot L_{pf} \cdot f}{\rho_{fl}^2 \cdot 2 d_h A_c^2 \cdot \eta_{pump}}$$

$\dot{m}_i$	Mass flow rate in single channel
$T_{mf,1/2}$	Bulk fluid temperature at inlet / outlet
λ_w	Heat conductivityof wall material

Simple maths on FW mechanics

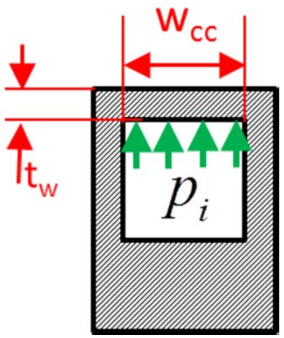
- Temperature gradient induced bending stress



$$\sigma_{b,DT} = \frac{1}{2} \cdot CTE \cdot E \cdot \frac{\Delta T}{1-\nu} = \frac{1}{2} \cdot CTE \cdot E \cdot \frac{\dot{q}_w \cdot t_w}{(1-\nu) \cdot \lambda_w}$$

CTE Coefficient of thermal expansion
E Young's modulus
ν Poisson ratio
λ_w Heat conductivity

- Pressure induced bending stress (rect. channel)



$$\sigma_{b,IP} = \frac{\beta_1 \cdot {w_{cc}}^2 \cdot p_i}{{t_w}^2} \quad , \beta_1 = 0.5$$

Both stresses act aligned at the channel sides:

- *compression near plasma,*
- *tension near cooled face*

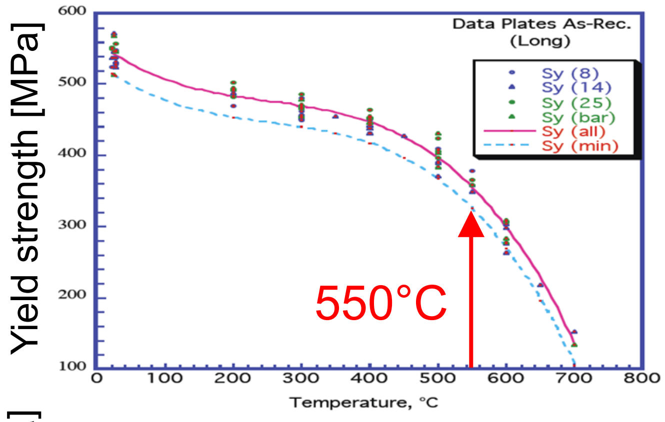
Range of real material data

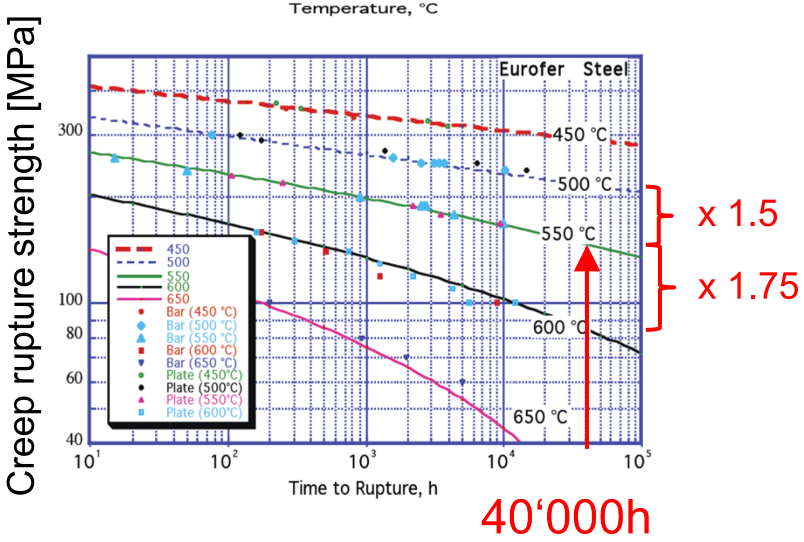
(Data at 400°C)	9%Cr RAFM (Eurofer, F82H)	Tungsten (Plansee)	Copper alloys (CuCrZr-IG)
Thermal conductivity	29 .. 33 W/m/K	135 W/m/K	352 W/m/K * * dep. on grade
Heat capacity ρc	5.12 J/K/cm³	2.70 J/K/cm³	~3.3 J/K/cm³
Coeff. of therm. expansion	11.7 µm/m/K	4.3 µm/m/K	18.2 µm/m/K
Young Modulus E	197 GPa	380 GPa	109 GPa
Poisson ratio ν	0.3	0.28	0.34
Yield stress $S_{y,min}$	416 MPa	420 MPa 100 (after recryst.)	189 MPa
S_m	154 MPa		80 MPa
Temperature window w/ irrad.	> 300-350°C < 550°C	> 600-800°C < 1150-1300°C	> 250-285°C < 300-350°C

Other candidates: Vanadium, SiC/SiC_f, CuNiBe, TZM, W-Cu composites …

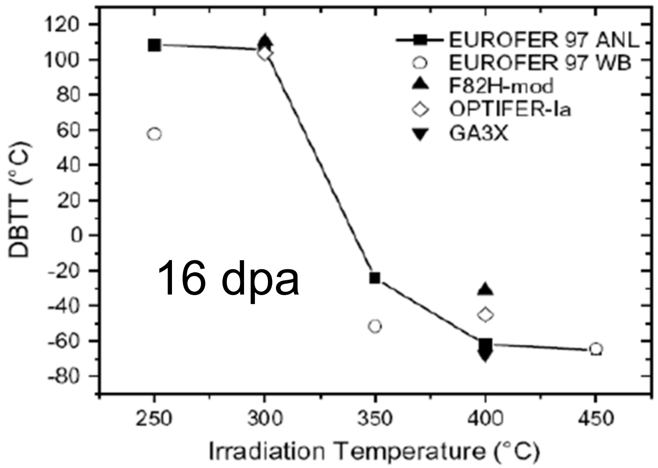
Material temperature window (Example: Eurofer)

Eurofer, DEMO-ISDC





Gaganidze et al. 2007

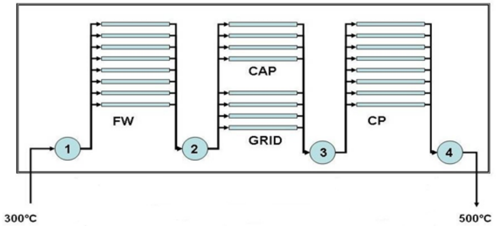


Materials have a temperature **window**:

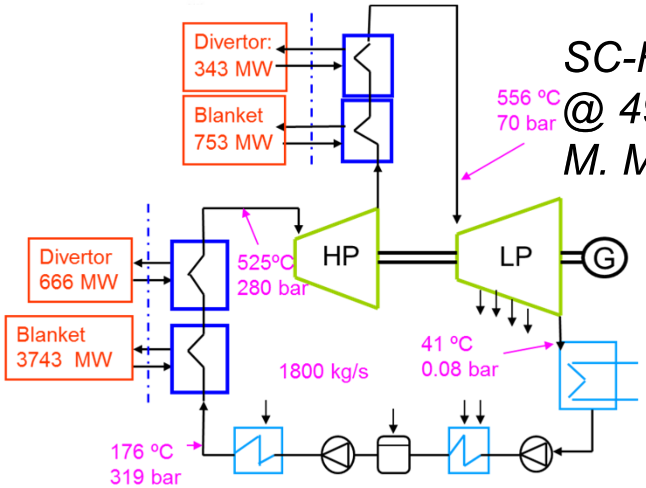
- lower limit defined by DBTT (shift by irrad.)
- upper limit : Strength (S_y, S_r)

... even more constraints

- The FW cooling has to integrate with other component (Breeder zone, Divertor) cooling systems and finally BoP, which needs high temperature sources for high efficiency (See more details EPFW-Talk by L.V. Boccaccini)
- The FW materials should not perform too bad concerning decay heat and activation (Effect on remote handling and disposal)

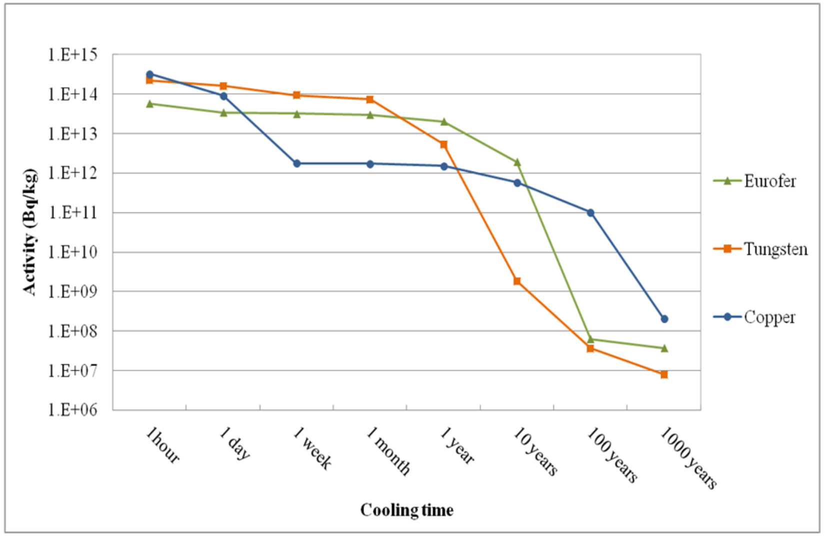


DEMO HCPB cooling topology D. Carloni et al.



SC-Rankine cycle @ 49.88% M. Medrano, 2006

Activation of divertor materials, Pereslavtsev et al. 2013



Example analyses

Thermal analysis examples:

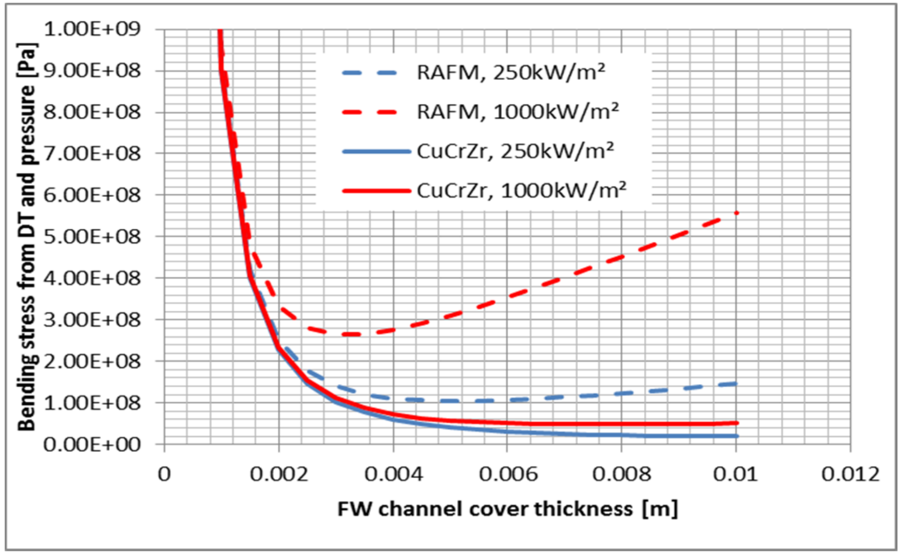
Base-case values:
He @ 80bar, 500kW/m²
h(50g/s) = 4858 W/m²/K
L_{pf} = 1000mm w_{pf}=20mm
„EF“ : Eurofer, „Cu“ : CuCrZr-IG

Case	T_{m1} [°C]	T_{m2} [°C]	ΔT_{wf} [K]	ΔT_{w} [K]	T_{wmax} [°C]
50g/s, 3mm EF	300	345	103	48	495
100g/s, 3mm EF	300	322	59	48	429
150g/s, 3mm EF	300	315	43	48	405
100g/s, 3mm Cu	300	322	59	4	385

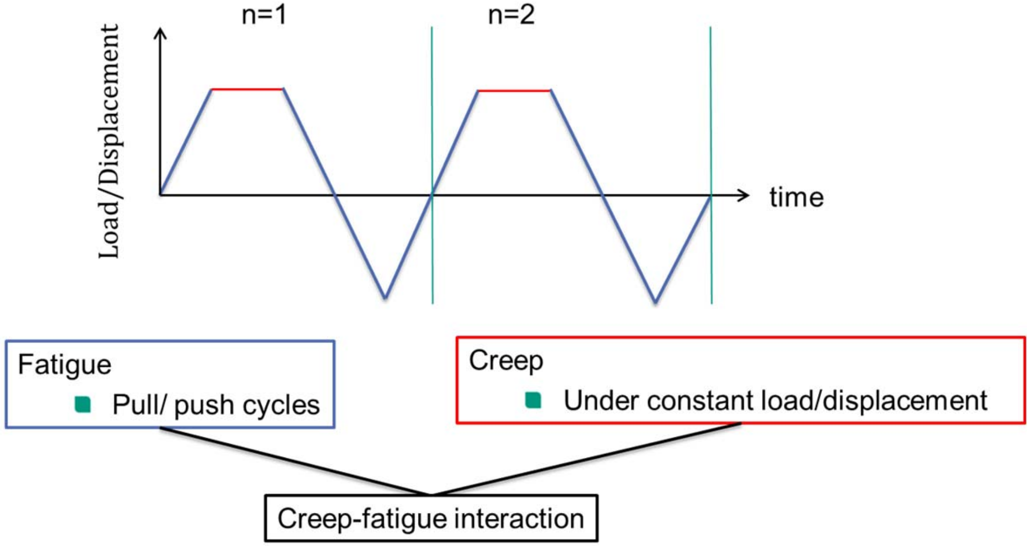
Stress analysis examples:

Summative stresses from internalpressure and thermal gradient are evaluated:

Optimum for cover wall thickness exists.



Creep-Fatigue failure



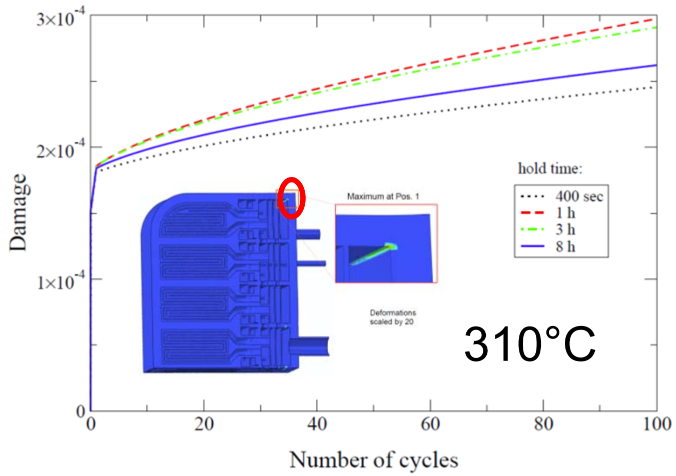
Blanket and divertor components work under high thermo-mechanical loading. Creep-fatigue is one of the main failure modes.

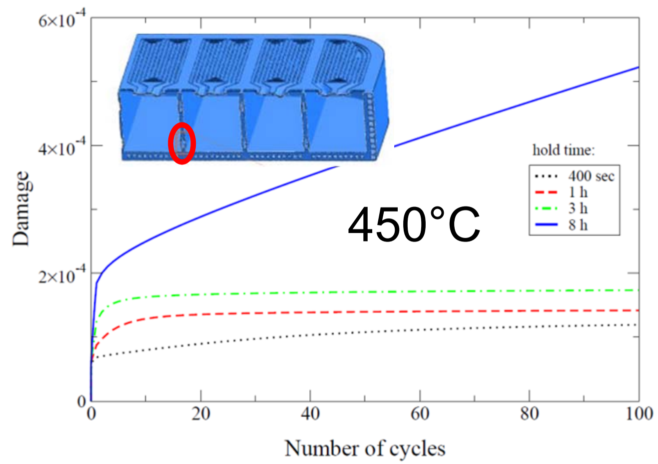
Creep-fatigue damage criteria	**TBM**	**DEMO**
Pulse number	30’000	20’000 (2nd blanket)
Pulse length	400 s	2h
Coolant pressure	80 bar	80 bar
FW design and temperature	comparable	

Creep fatigue assessment (Aktaa et. al)

Assessment Criteria	Conservatism	Mat. Properties for Eurofer	
		TBM	DEMO
ASME – elastic rules	Very high	available	Not available
ASME – inelastic rules	High	available	Not available
Aktaa – UMat Model	**Normal**	**available**	**Available but to be verified by experimental results**

Application of UMat model in TBM: Influence of hold time on damage



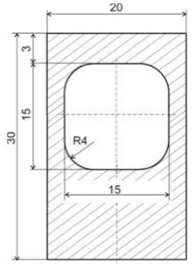


In addition to simple $3S_m$ rules creep-fatigue assessment should be considered for DEMO and TBM design determining allowable number of cycles.

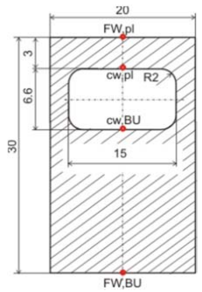
Design example A :
Helium cooled FW (HCPB or HCLL, KIT/CEA)

Karlsruher Institut für Technologie

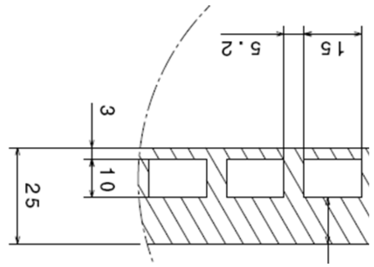
HCPB TBM v2.1
Ilić et al. 2013



DEMO HCPB
Carloni et al. 2013



DEMO HCLL
Aiello et al. 2013



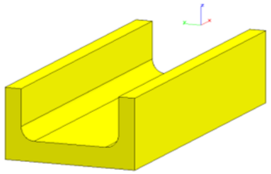
	HCPB-TBM v2.1	HCPB 2013	HCLL 2013
Flow rate	110.8g/s, 84.6m/s	49g/s, 80m/s	73.9g/s, 80m/s
heat flux density	500kW/m²	500 kW/m²	500 kW/m²
PF length x width	2x 1290mm x 20mm	1006mm x 20mm	1512mm x 20.2mm
Tmf1, Tmf2	300°C → 360°C	300°C → 330-340°C	300°C → 372°C
heat transfer coeff.	6129 W/m/K @Rz20µm	5950 W/m²/K	5569 W/m²/K
pressure drop (*)	0.16 MPa	0.04 MPa	0.15 MPa
peak temperature (*)	539°C	488°C	521°C

(*) different calculation approaches / definitions may have been used

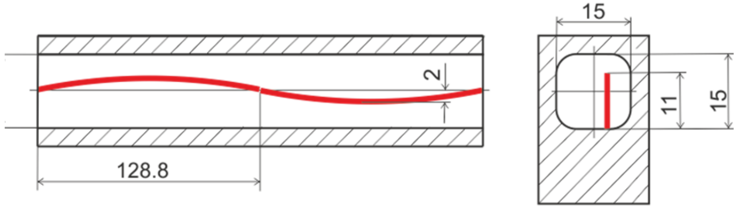
Study 2013 : Increase HTC

➔ Effect of rib roughness or mixing devices was assessed by CFD

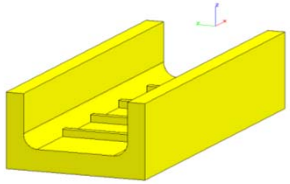
„G0“ : smooth



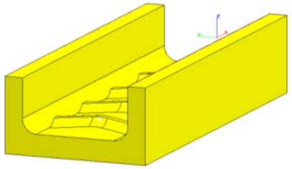
„G7“ : waved ridge

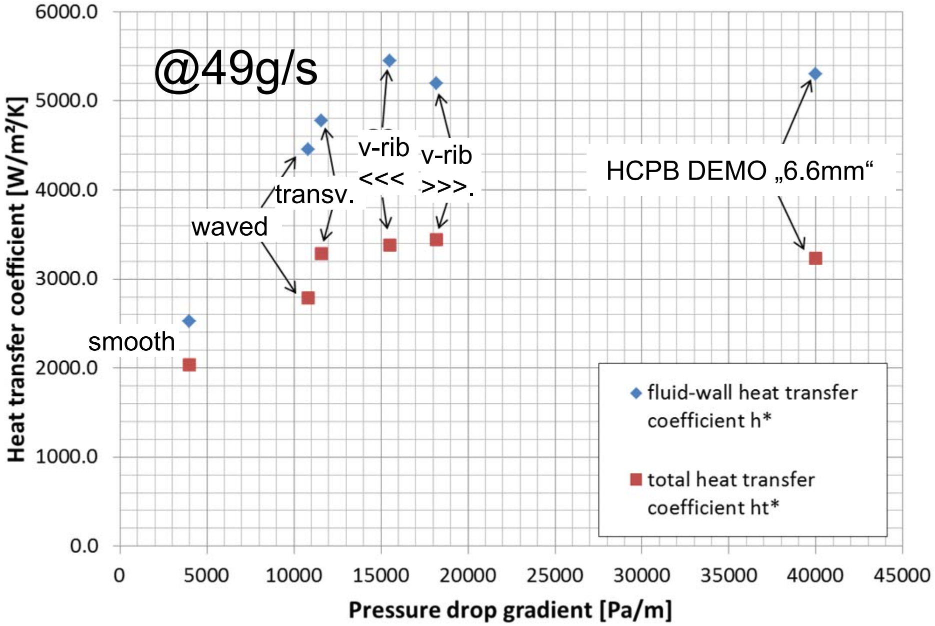


„G5“ : transv. rib



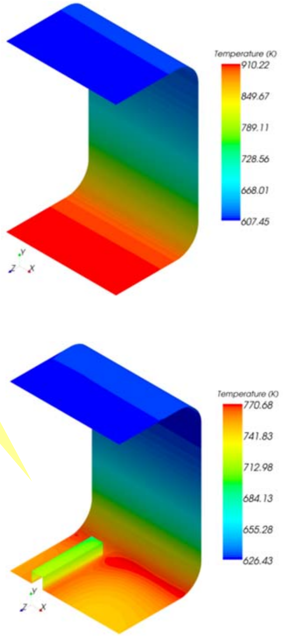
„G2“ : V-shape rib





Example
@49g/s,
750kW/m²:

ΔT=-139K !



Extrapolated heat flux limit

Smooth surface, 3mm EF cover, T_2=360°C, T_{max}=550°C:

Heat Flux	0.5 MW/m²	0.75 MW/m²	1.0 MW/m²
Coolant flow rate	74 g/s	154 g/s	293 g/s
Pressure drop gradient	0.09 bar/m	0.4 bar/m	1.43 bar/m
pumping / removed heat	0.96 %	6.0 %	32 %

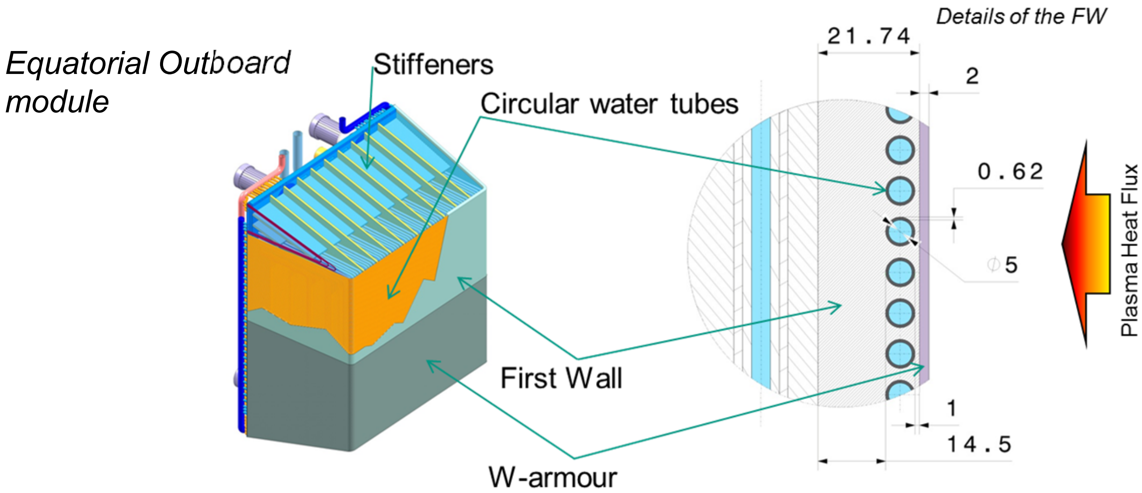
Ribbed surface, 3mm EF cover, T_2=360°C, T_{max}=550°C:

Heat Flux [MW/m²]	0.5 MW/m²	0.75 MW/m²	1.0 MW/m²
Coolant flow rate	33 g/s	70 g/s	132 g/s
Pressure drop gradient	0.05 bar/m	0.23 bar/m	0.84 bar/m
pumping / removed heat	0.25 %	1.5 %	8.5 %

Ribbed surface, 1.5mm EF cover, T_2=360°C, T_{max}=550°C:

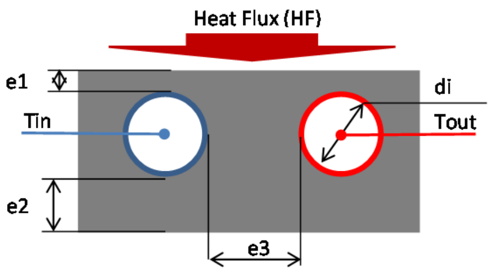
Heat Flux [MW/m²]	0.5 MW/m²	0.75 MW/m²	1.0 MW/m²
Coolant flow rate	28 g/s	50 g/s	80 g/s
Pressure drop gradient	0.038 bar/m	0.12 bar/m	0.31 bar/m
pumping / removed heat	0.15 %	0.6 %	1.9 %

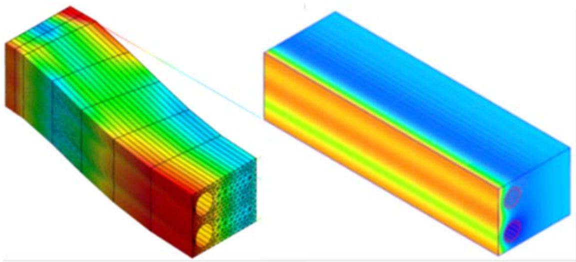
Design example B:
Water cooled FW (J. Aubert et al., CEA)

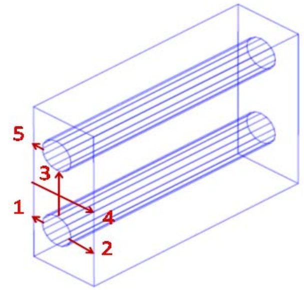


- **<u>Eurofer</u>** as heat sink structural material.
- **Two separate cooling systems** per module (FW/BZ): For safety and coolant regulation.
- **<u>PWR conditions</u>** :
  Tin / Tout = **285°C / 325°C** ; P = 155 bar.
  For efficient power conversion cycle
- Toroidal **counter current flow**.
- **<u>Double Walled</u>**.
  For reliability considerations from industrial feedback data base. To explore if needed or not !
- Water **velocity < 8m/s** and diameter of pipes > 5mm
  To prevent excessive pumping power (and corrosion ?)
- Total thickness < 22 mm.
  To optimize TBR.
- **2 mm <u>W-armour</u>** (not taken into account in calculations)

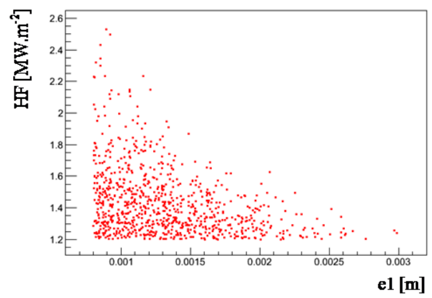
WCLL FW parametric study

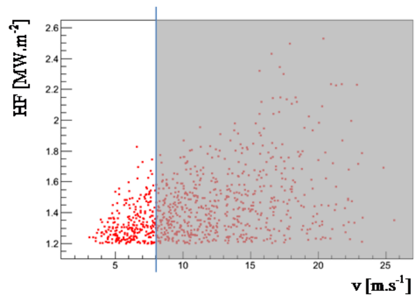






- Parametric generation of model
- 3D simulation of temperature and stress fields (Cast3M) for 2 load cases:
  - LC1 : normal condition :
    - Heat Flux, power deposition, 155 bar inside the tubes, 5 bar from the PbLi pool, end loads.
  - LC2 : faulted condition (pressurization of the box) :
    - 155 bar from the pbLi pool, end loads.
- Decision OK/fail:
  - Stress assessment acc. to RCC-MRx, Pm<Sm, Pm+Pb<1.5Sm, Pm+Pb+Q<3Sm
  - Eurofer max. temperature 550°C
  - Creep and irradiation neglected for this study





WCLL FW Conclusions

Heat Flux [MW/m²]	0.5	1	1.5
Coolant Velocity [m/s]	2.8	4.9	7
Power removed by the FW / Total power in the blanket [%]	33	48	57
Ratio pumping power / Removed heat [%]	0.1	0.12	0.17

(The FW removes 100% of the Heat Flux + ~12% of the neutron deposition)

- Excellent capability for high heat fluxes.
- Low pumping power, but PWR conditions limit potential for high therm. efficiency
- Possible problem of corrosion and tritiation of water.
- Outlook: Include Creep, Fatigue and Irradiated matl. prop. in analyses.

⚠ **Corrosion of Eurofer with water !**

A. Kanai et al. "Corrosion behavior of F82H exposed to high temperature pressurized water with rotating apparatus". (2013)

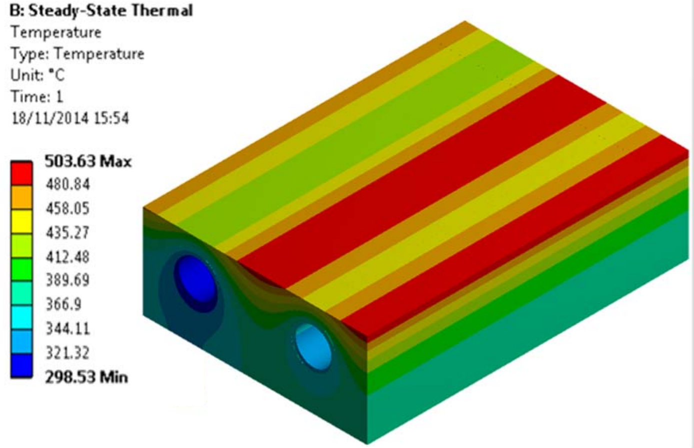
➢ loss of 1µm of steel with v = 2,3 m/s during 100 h. Should increase with velocity and time.

\+ Effect of tritiated water ?

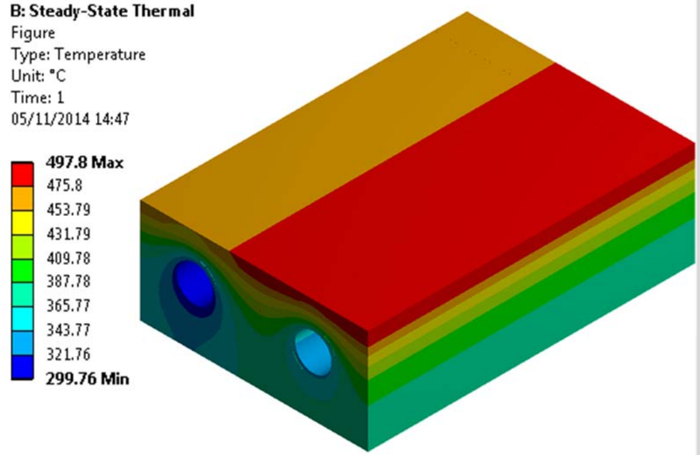
= 1mm thickness in front of the plasma may be to thin > increase thickness > <u>decrease Max HF ?!</u>

Effect of Tungsten armour on FW structural integrity T. Barrett et al., CCFE)

- **By FEA modelling, we can see that the presence of W Armour has a significant effect on FW structural stress**
- We compare two thermal-structural models
  1. Baseline WCLL EUROFER FW
  2. WCLL EUROFER FW + 2mm W armour
- Looked at the change in thermal and structural response of EUROFER
- We find the W layer beneficially re-distributes some heat (peak temperature lower by ~5°C)
- Primary (pressure) stress is slightly improved by W armour
- Secondary (thermal) stress – **3Sm reserve factor reduced by 20-70% *** by presence of W armour
- Armour castellations and a compliant interlayer will help lower this stress, but clearly **this effect must be considered in design studies**



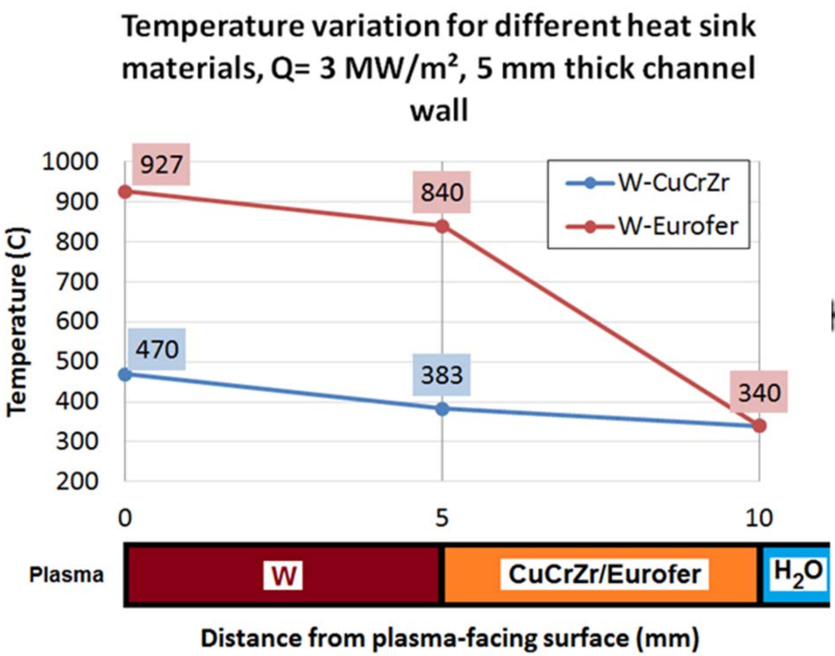
FW model – no W armour

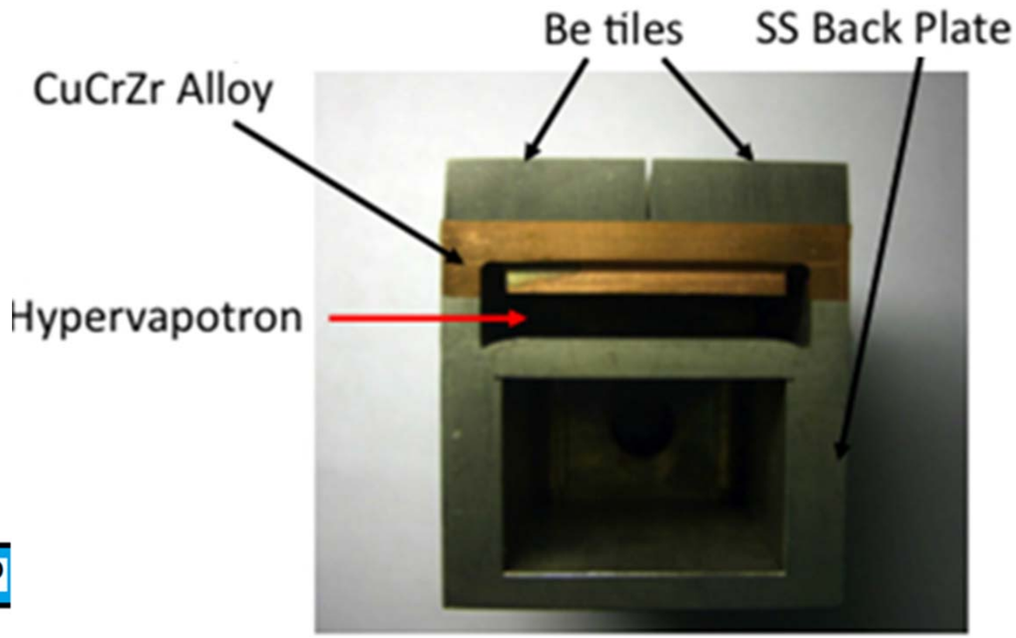


FW model – with 2mm W armour

Design example C: hypervapotron FW/limiter (CV-Řež)

- In ITER hypervapotrons are foreseen in the FW.
- In the ITER FW CuCrZr is being used with low temperature coolant with a specified irradiation damage limit of 5.5 dpa.
- → Very high heat transfer coefficients
- → Using Eurofer as heat sink instead of CuCrZr will cause the same difficulties as in the case of the FW.





Hypervapotron technology for FW/limiter

- Hypervapotrons might be considered for plasma limiter PFCs
- Using Eurofer as heat sink instead of CuCrZr will reduce the heat flux performance to 1-2 MW/m² (not attractive)
- An attractive hypervapotron design seems difficult to realize when using Eurofer in PWR condition

	ITER FW	DEMO limiter
Neutron damage	<5.5 dpa	~15 dpa/fpy
Technology	Steel / CuCrZr structure with Be-tiles, water-cooled	Steel **or** CuCrZr structure with castellated tungsten-armour, water-cooled
Operating pressure	3 – 4 MPa [ITER PDD 2009]	5-8 MPa (CuCrZr) 15.5 MPa (Eurofer)
Coolant temperature	70-100 °C [ITER PDD 2009]	~220°C (as in DEMO Cu-alloy divertor) ~300°C (Eurofer)
Heat flux performance	4.7 MW/m²	**~5 MW/m² (CuCrZr)** **1-2 MW/m² (Eurofer)**

Conclusions

- High Heatflux FW/limiter designs *can* be produced
  - 5MW/m² hypervaporton (water) cooled / Copper
  - 1.5-2.5 MW/m² water cooled / Eurofer
  - 0.5-1.0 MW/m² helium cooled / Eurofer
- Uncertainty on wall heat flux must be limited
  - necessary safety factors evoke unattractive designs:
    (1) too much pumping power
    (2) too low outlet temperature for efficient electricity generation BoP
- Integrated optimization approach for FW must be followed
  - Material temperature windows
  - *Complete* stress assessment
  - Integration with BoP
  - ... also TBR, manufacturing, and other issues!