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Divertor of the European DEMO:

Overview of DEMO Divertor Architecture Design options(2014-2022)

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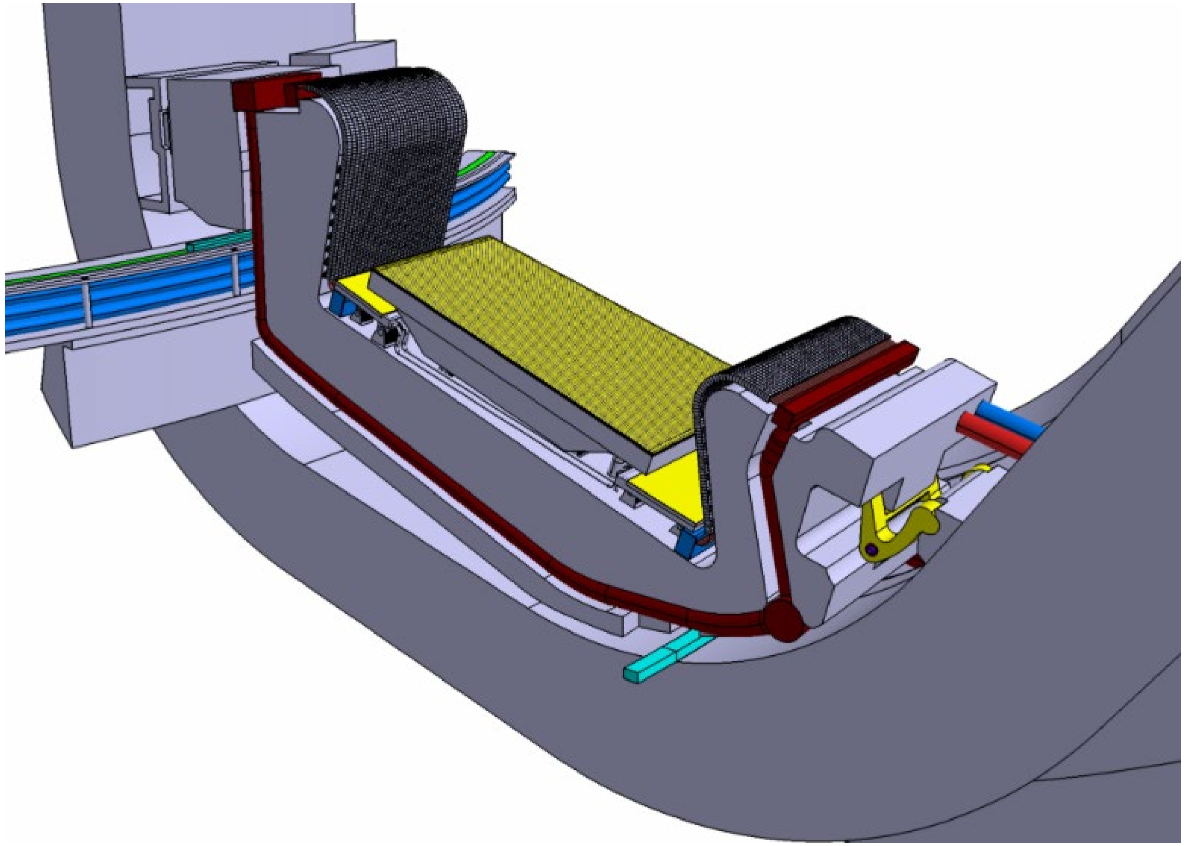
Contents

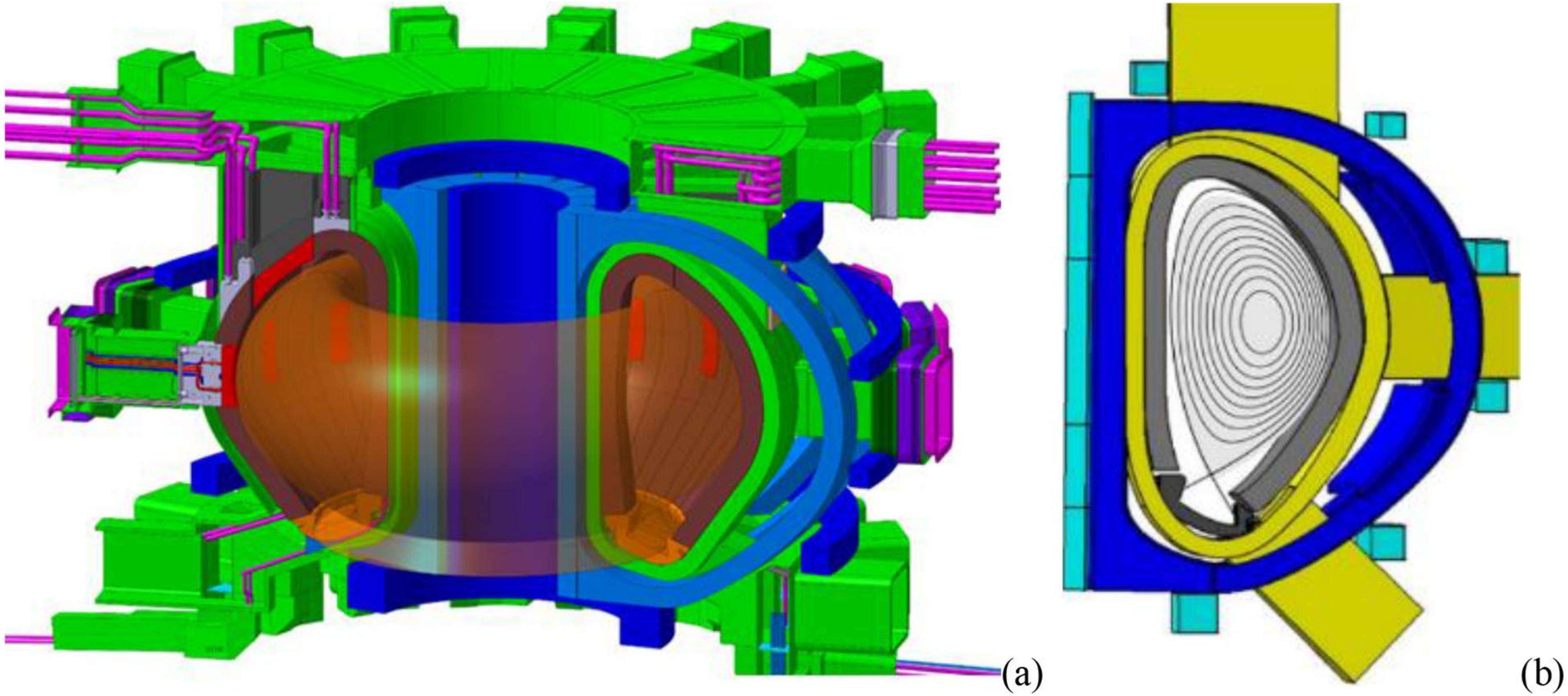
1. EU-DEMO divertor project: objectives
2. Pre-conceptual baseline design concept (as of 2020).
   - Requirements, Architecture, Loads
   - Performance, Design issues
3. Conceptual Design Activity CDA (2021-2027)
4. High-heat-flux technologies
5. Conclusions



Objectives in the Pre-conceptual design phase (FP8: 2014-2020)

1. To deliver a feasible design concept for the CDA phase.

2. To develop & verify reliable high-heat-flux technologies for the targets.



CAD configuration model of the European DEMO showing the internal cut view (a) and the poloidal magnetic configuration adapted from [*] (b).

*H. Reimerdes, et al., Assessment of alternative divertor configurations as an exhaust solution for DEMO, Nucl. Fusion 60 (2020), 066030

Pre-conceptual baseline design - 1st Phase

- European DEMO and ITER Key plasma parameters and Selected characteristics
- DEMO divertor:

1. Requirements
2. Architecture
3. Loads

European DEMO and ITER Key plasma parameters and Divertor Selected characteristics

Key plasma parameters of the European DEMO and ITER related to power exhaust*.

Parameters	EU-DEMO	ITER
Pulse (s)	7200	400
R_p/a_p (m), A	9.0/2.9, 3.1	6.2/2.0, 3.1
q_{95}	3.5	3
β_N	2.6	1.8
f_{GW} $(= n_e/n_{GW})$ GW $(= ne/nGW)$	1.2	0.83
P_{fusion} (MW_{th})	2000	500
P_{el} (MW_e)	500	–
P_{aux} (MW)	50	73 (installed)
P_{heat} $(= P_\alpha + P_{aux})$ (MW)	457	173
Q	41	5/10
$c_{imp,\ core}$ $(= n_{imp}/n_e)$	0.039 (Xe) + Ar	N_2, Ne, Ar, ...
$P_{rad,\ core}$ (MW)	306	~50
$f_{rad,\ core}$ $(= P_{rad,\ core}/P_{heat})$	0.67	~0.33
P_{sep} (MW)	154	~100
P_{sep}/R_p (MW/m)	17	~16
$P_{L\text{-}H\ th}$ (MW)	133MW	~84
$f_{L\text{-}H\ th}$ $(= P_{sep}/P_{L\text{-}H\ th})$	1.2	~1.2

* N. Asakura, et al., Power exhaust studies and divertor Designs for Japanese and European DEMO fusion reactors, Nucl. Fusion 61 (2021) 126057.

Selected characteristics of the European DEMO divertor contrasted with the ITER divertor [7, 8, 89-92].

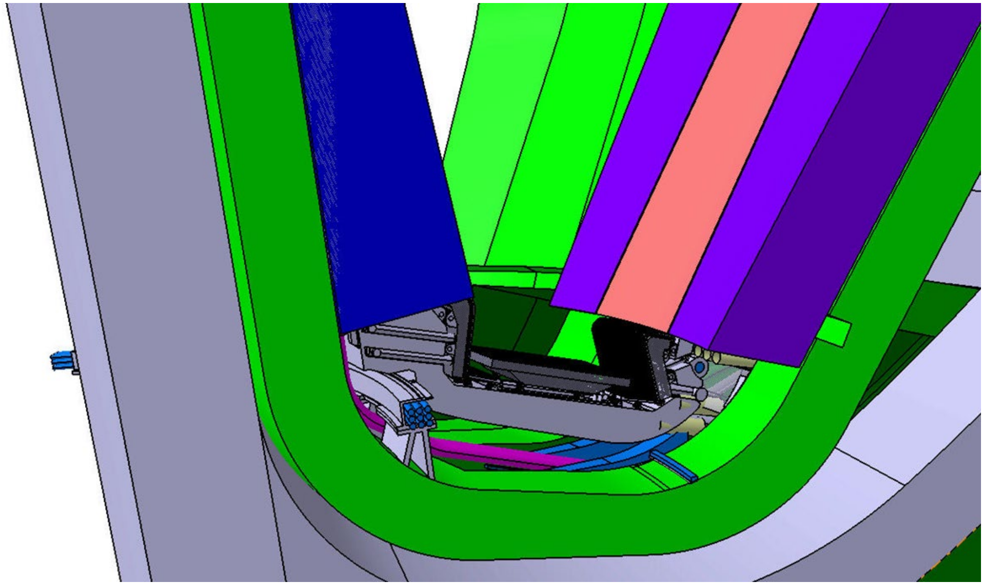
	DEMO divertor	ITER divertor
Structural materials	CB: EUROFER97 steel IVT/OVT: CuCrZr-IG alloy SL: EUROFER97 steel	CB: SS 316 L(N)-IG/ XM-19 IVT/OVT: CuCrZr-IG alloy Dome: CuCrZr-IG alloy
Max. irradiation dose (dpa/ fpy)	CB: 1 (target supports: 4) SL (EUROFER97): 5 OVT: 2 (W), 7 (Cu)	CB: 0.1 Dome (Cu heat sink): 3.5 OVT: ≤0.5 (W), ≤2 (Cu)
Bulk nuclear heating (MW)	−134	−102
SOL conduction heat (MW)	−220 (incl. radiative dissipation)	−100 (D-T burning)
Inlet temperature (water)	CB: 180 °C OVT: 130 °C	CB: 70/100 °C VT: ≤140 °C (nominal)
He production (appm/fpy)	SL (EUROFER97): 94 CB (EUROFER97): 49 OVT (Cu heat sink): 57	Dome (Cu heat sink): 31 CB (316 L(N)): 2.5 OVT (Cu heat sink): 13
Peak heat flux (MW/m^2)	Steady state: 10 (2 h) Slow transient: 20 (10 s)	Steady state: 10 (400 s) Slow transient: 20 (10 s)
Transient events (assumed scenarios)	ELM: suppressed or mitigated Disruptions: tbd.	ELM: suppressed or mitigated Disruptions: 25 times
Lifetime (cycles/fpy)	6600 (+ overhead)/1.5	3000/0.1

[7] R. Tivey, et al., ITER divertor, design issues and research and development, Fusion Eng. Des. 46 (1999) 207–220. [8] A.S. Kukushkin, et al., Divertor issues on ITER and extrapolation to reactors, Fusion Eng. Des. 65 (2003) 355–366. [88] V. Barabash, et al., Specification of CuCrZr alloy properties after various thermo-mechanical treatments and design allowables including neutron irradiation effects, J. Nucl. Mater. 417 (2011) 904–907. [89] M. Merola, et al., Engineering challenges and development of the ITER blanket system and divertor, Fusion Eng. Des. 96–97 (2015) 34–41. [90] R.A. Pitts, et al., A full tungsten divertor for ITER: physics issues and design status, J. Nucl. Mater. 438 (2013) S48–S56.

Requirements (based on the functions)

- Removing heat for power exhaust
  (*nuclear*: 139 MW, *particle*: 122 MW, *radiation*: 78 MW)
- Shielding the vacuum vessel from nuclear loads (≤ 1 dpa/6 fpy)
- Facilitating the neutral gas streaming for particle exhaust

48 cassette modules, 16 lower ports



- Specified lifetime: ≥ 1.5 fpy
- Reduced activation (ALARA), no HLW
- R.A.M.I. + recyclability

fpy: full power year

Requirements (based on the functions)

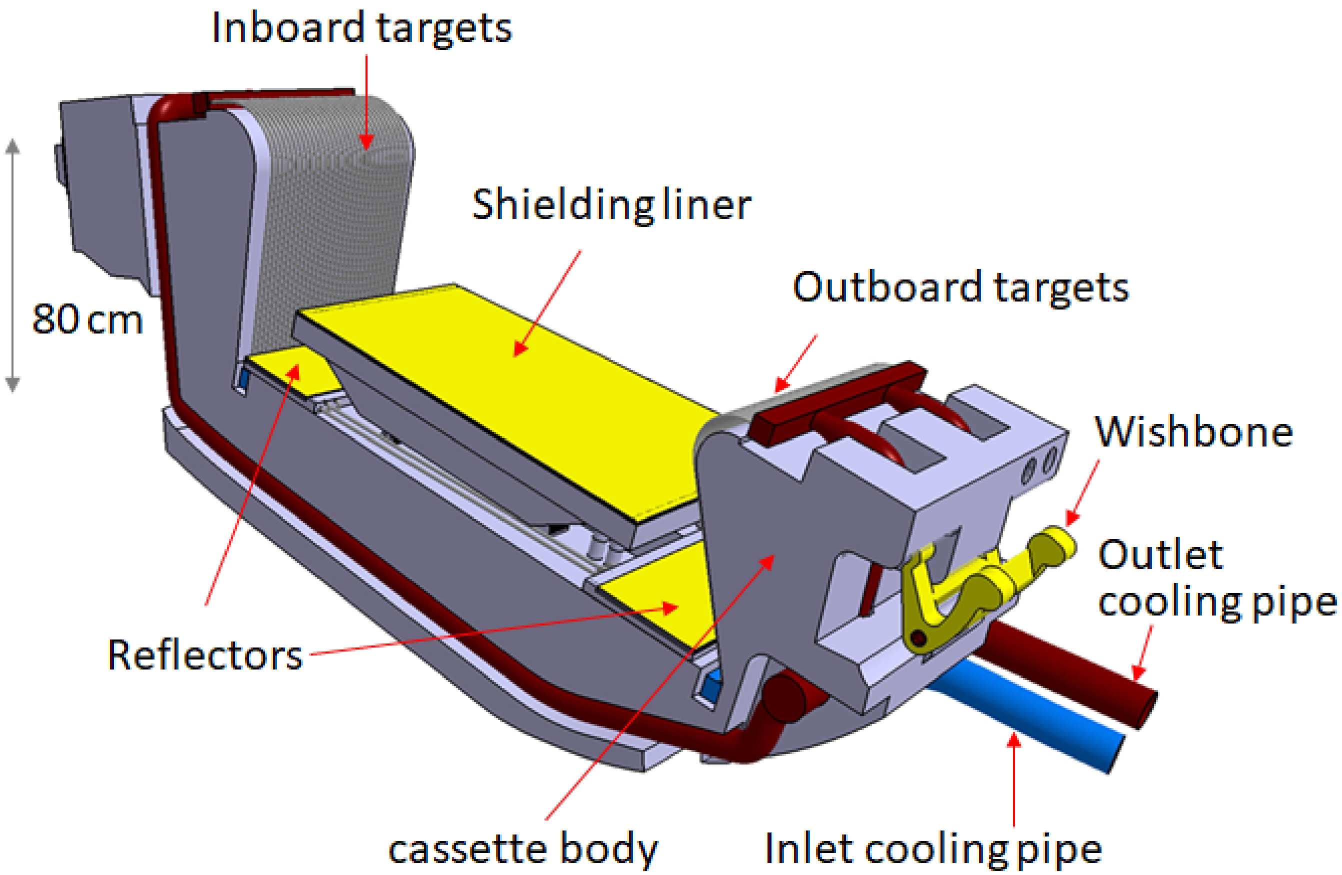
High-level system requirements imposed on the European DEMO divertor.

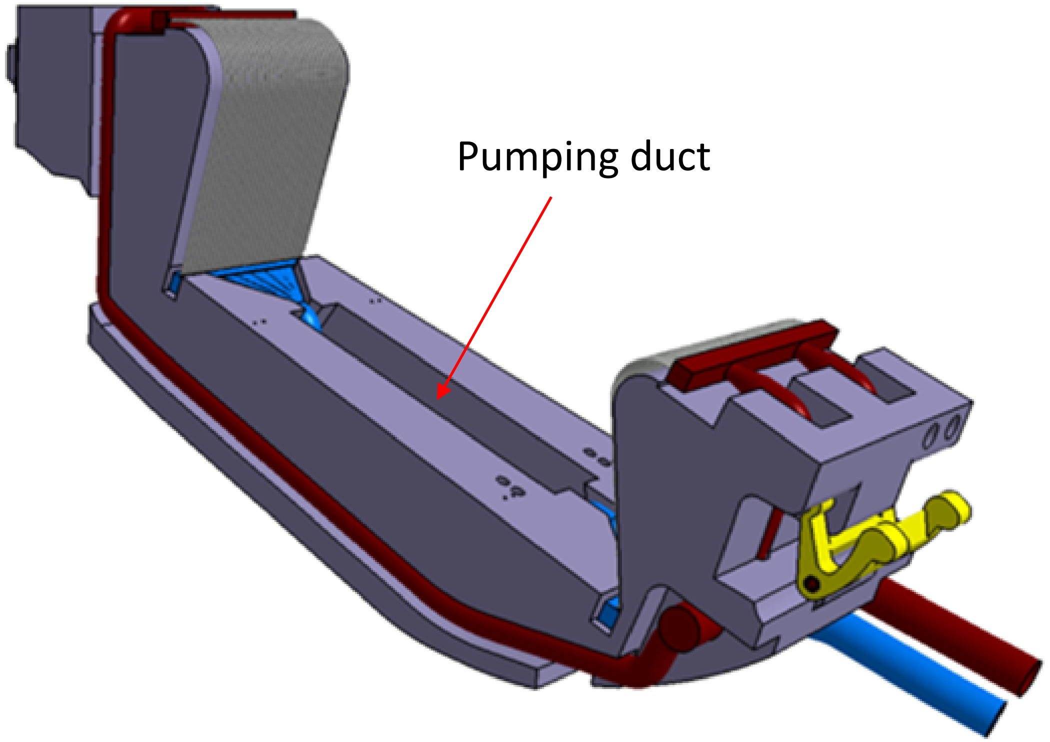
ID	Descriptions
SR- 1	The divertor shall reliably perform the key functions over the entire lifetime withstanding the extrinsic loads and the induced effects of the loads (e.g. secondary stresses, armor surface erosion, material damage, corrosion, etc.).
SR- 2	The specified minimum lifetime (interval between replacements) is 1.5fpy[1]. *Rationale*: Operational lifetime is specified considering a reasonable balance between the power plant availability and structural/functional reliability. This requirement is of tentative nature since materials data from relevant irradiation tests are very limited. The initial lifetime shall be redefined again once materials data and design criteria from dedicated irradiation tests are available, also taking into account the evolving maintenance scheme.
SR- 3	Tungsten shall be used as plasma-facing armor of PFCs. EUROFER97 steel shall be used as structural material for the cassette body and fixation units. *Rationale*: The material options should comply with the high-level requirements such as physical compatibility with fusion plasma (for PFCs) and reduced activation to assure recyclability (for major structures).
SR- 4	The design concept should be able to be realized by means of feasible technology options (≥TRL[2] 4 at the 3rd Gate review in 2027) within an acceptable cost frame and the DEMO project timeline (EDA[3] phase from 2028 on). Technology maturity shall be evaluated at the 2nd Gate review in terms of the technology readiness level (TRL[2]).
SR- 5	The divertor (incl. pipework) shall be compatible with the interfacing plant sub-systems.
SR- 6	The divertor must protect adjacent Vacuum Vessel (VV) (AISI 316LN-IG) and magnets from neutron radiation keeping nuclear loads below the specified limits. - max. allowable irradiation damage dose limit in VV: 1.0 dpa[4]/6fpy - max. allowable nuclear heating limit in superconducting magnets: 50 W/m^3

[1] fpy: full-power-year (of operation). [2] TRL: Technology Readiness Level. [3] EDA: Engineering Design Activity. [4] displacement per atom.

Architecture

- Targets: charged particles, nuclear heat, radiation
- Cassette body: nuclear heat
- Shielding liner: radiation, nuclear heat, neutrals

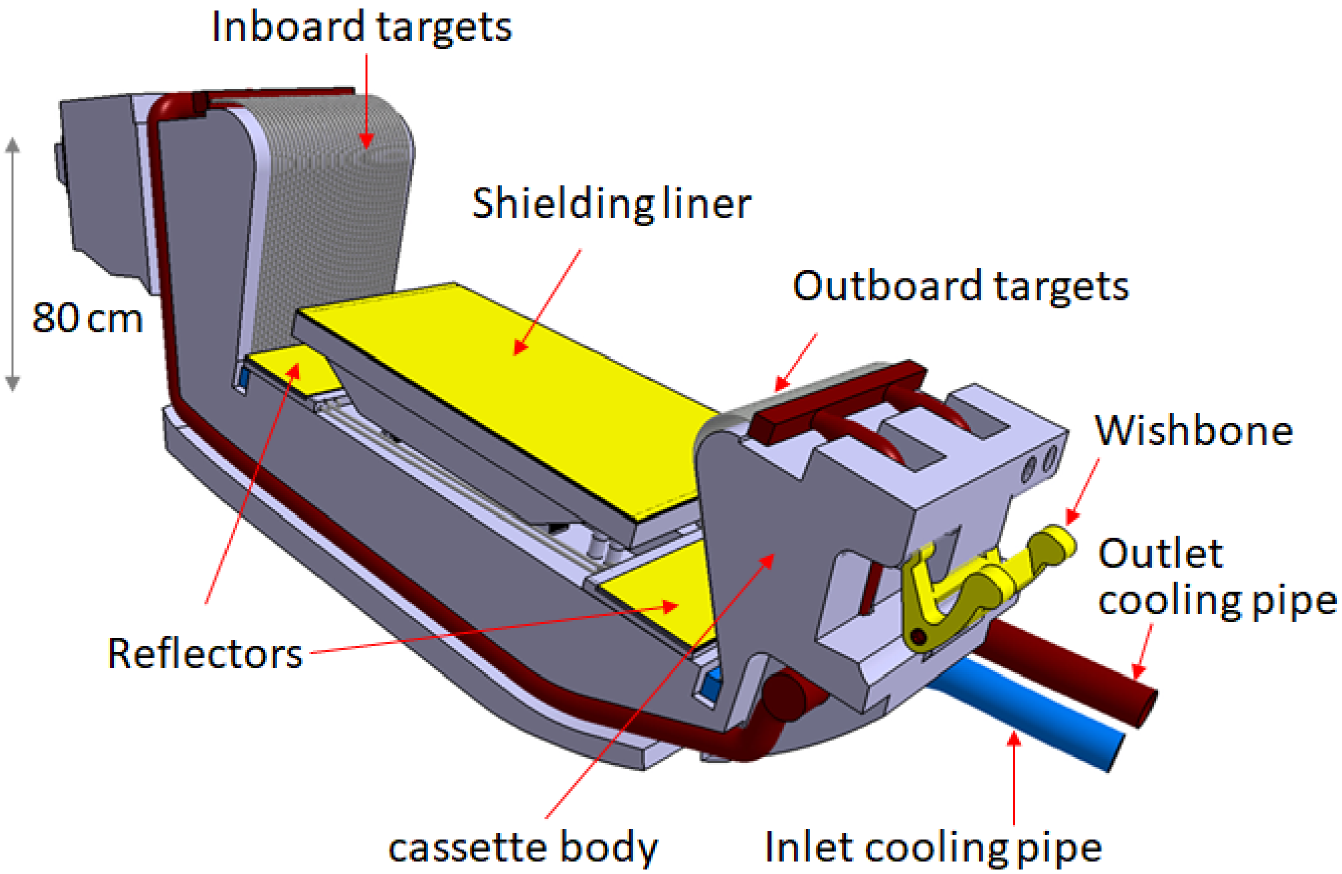


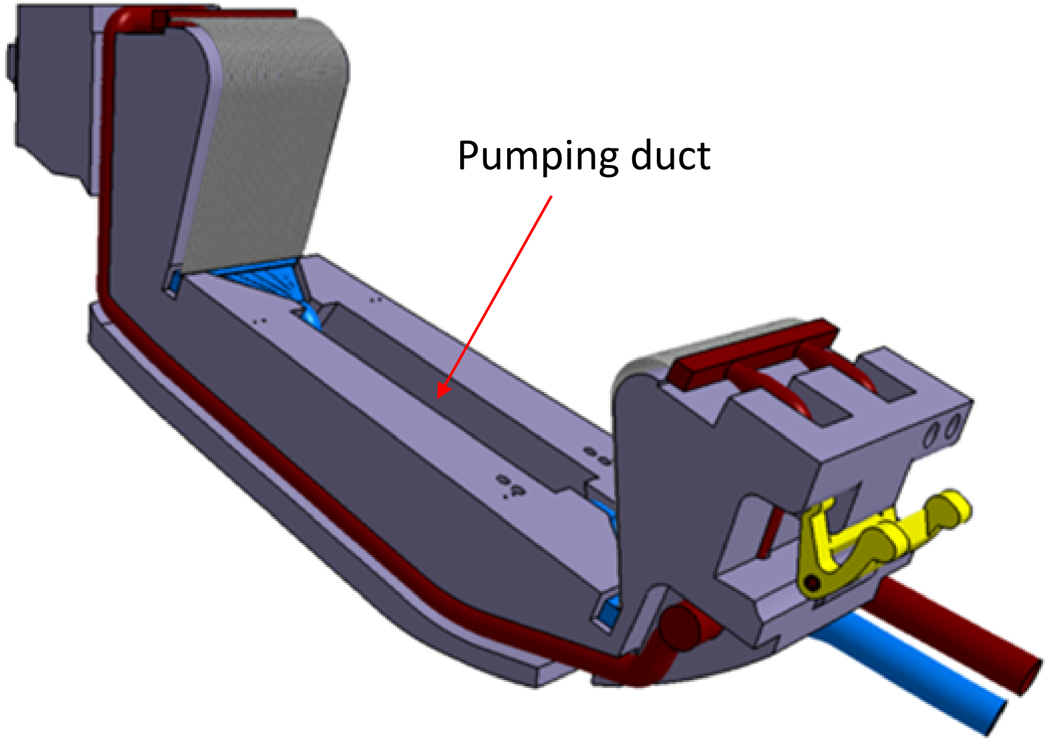


J.H. You et al., FED (2022)

Architecture

- Targets: W armor + CuCrZr heat sink
- Cassette body: Steel vessel (EUROFER 97)
- Shielding liner/Reflector Plates: W plasma spray + steel (EUROFER 97) heat sink





Loads:

The naming convention of the IDs is as follows:
– Load-1: Volumetric thermal load (nuclear);
– Load-2: Surface thermal load by particles;
– Load-3: Surface thermal load by radiation;
– Load-4: Dynamic impact load (electromagnetic loads)
– Load-5: Surface particle flux;
– Load-6: Volumetric neutron flux;
– Load-7: Static primary load (pressure);
– Load-8: Chemical load (radiolysis).

Remember also:
-EM forces due to Ferromagnetic effect;
- Dead Weight and Seismic Loads;

Extrinsic loads specified for the European DEMO divertor 2020*

* C. Bachmann, Plant Description Document (v. 1.9), Eurofusion report (2021) 2KVWQZ.

ID	Loads	Specifications
Load- 1a	Volumetric thermal power Volumetric thermal power density	~139 MW (by nuclear heating) ≤8MW/m^3
Load- 1b	Baking temperature	~240 ◦C (uniform heating)
Load- 2a	Surface thermal power on the targets (Total core radiation fraction: 90%)	~45MW (by charged particles) ~108MW (by SOL radiation)
Load- 2b	Peak heat flux density in normal operation (pulse length at flat top: 2 h, number of cycles: ≥ 6600 + overhead)	~10 MW/m^2 (on the targets) ~1 MW/m^2 (on the shielding liner) ~0.2 MW/m^2 (on the reflector plates)
Load- 2c	Peak heat flux density in slow transients (thermal equilibrium: ~10 s, frequency: tbd.)	~20MW/m^2 (on the targets)
Load- 2d	Peak heat flux density in short transients (no thermal equilibrium: ≤1 s, frequency: tbd.)	≤70MW/m^2 (on the targets) with sweeping (e.g. 1 Hz, 0.2 m)
Load- 2e	Energy deposition on targets upon fast transients (off-normal events, frequency: tbd.)	≤150 kJ/m^2
Load- 2f	Energy deposition and peak heat flux density on targets upon major (centred) disruption	≤1GJ, 79-111GW/m^2 (without limiter) Thermal quench: 1-4ms
Load- 2g	Surface heat flux density due to neutral particles	~2 kW/m^2 (baffle region)
Load- 3a	Surface thermal power due to core radiation	≤78MW
Load- 3b	Surface heat flux density due to core radiation	~1MW/m^2
Load- 4	Peak electromagnetic impact load (downward disruption)	~1.3MN (vertical) excl. dynamic amplification (tbd.)
Load- 5	Particle flux density in front of the targets	~1024/m^2•s (≤10 eV)
Load- 6	Neutron flux density in the surface layer	~1.7 × 1018·n/m^2·s
Load- 7	Coolant pressure at the circuit inlet	~5 MPa (targets) ~3.5 MPa (cassette body)
Load- 8	Coolant water chemistry (radiolysis control)	purified water with reducing agent (H)

Design seismic accelerations of divertor cassette**

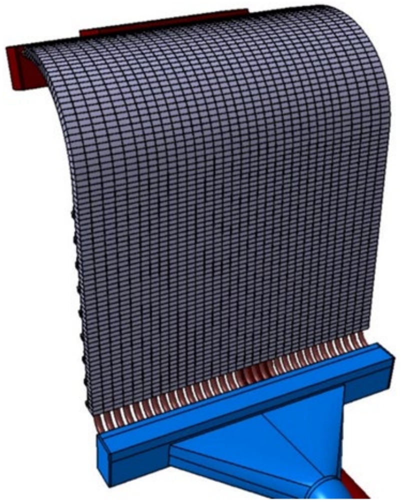
	SL-2	SMHV	SL-1
Seismic acceleration	g	g	g
Radial A_x	0.4	0.3	0.14
Toroidal A_y	0.4	0.3	0.14
Vertical A_z	3.8	2.8	1.3

** P. Frosi, Divertor Assembly Load Specification 2021 (v. 1.1), Eurofusion report (2021) 2PJ3JA.

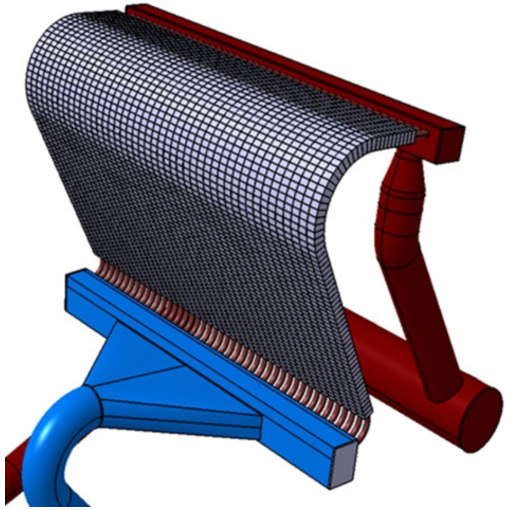
Loads: thermal (targets)

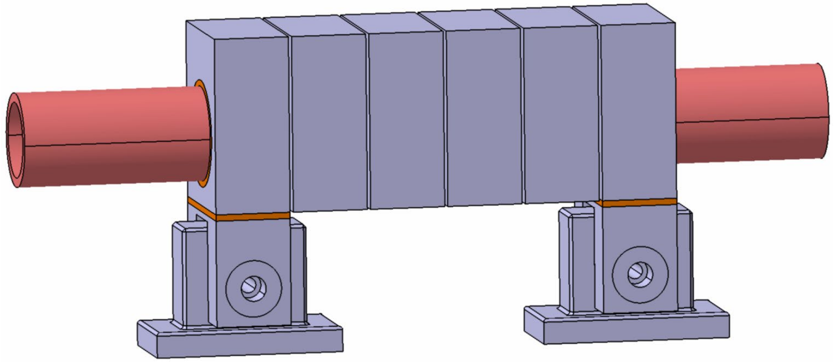
- SOL particle flux: 122 MW
- Peak heat flux density: 10 MW/m^2 (2h), ≥6600 normal operation pulses
  (strike point: ~100 mm)
  20–25? MW/m^2 (~10-100s), a few 1000 slow transient events
  25–70? MW/m^2 (~1-10s?), sweeping shall be activated

Inboard target



Outboard target

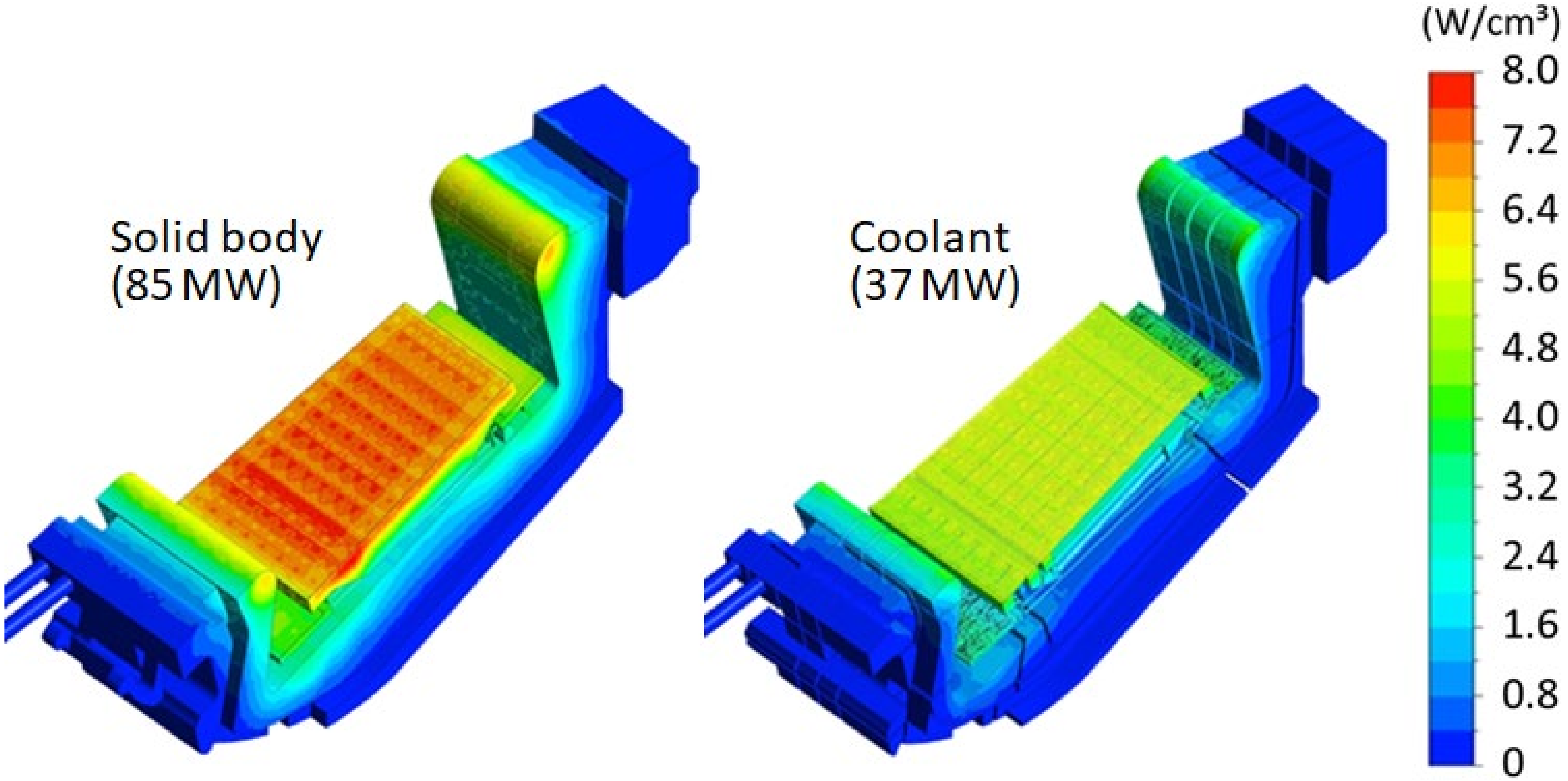




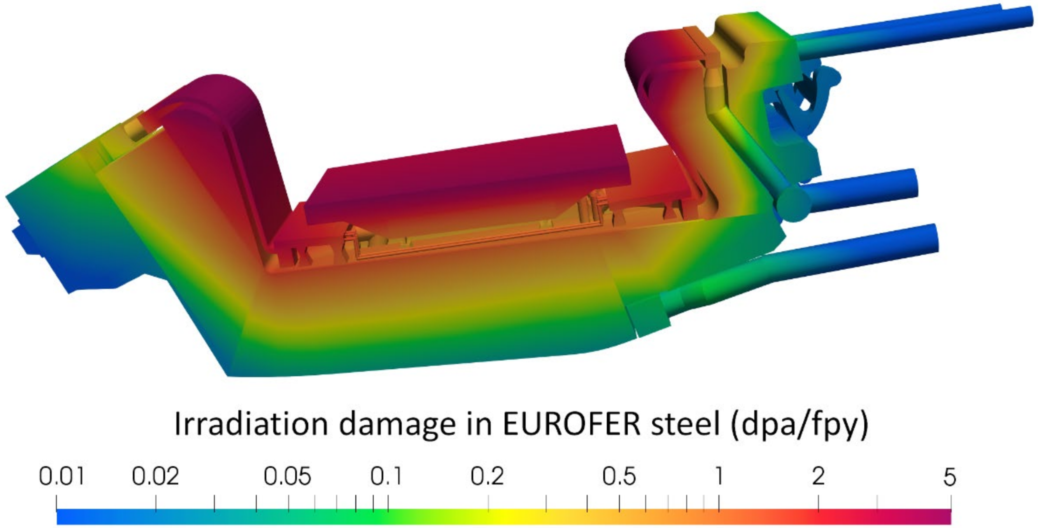
Loads: thermal (cassette & coolant)

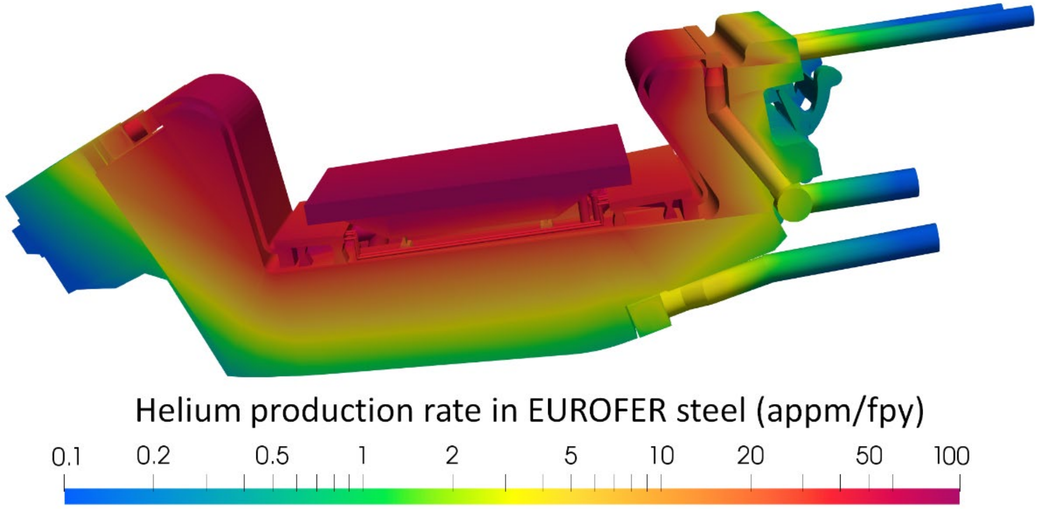
Volumetric nuclear heating power density

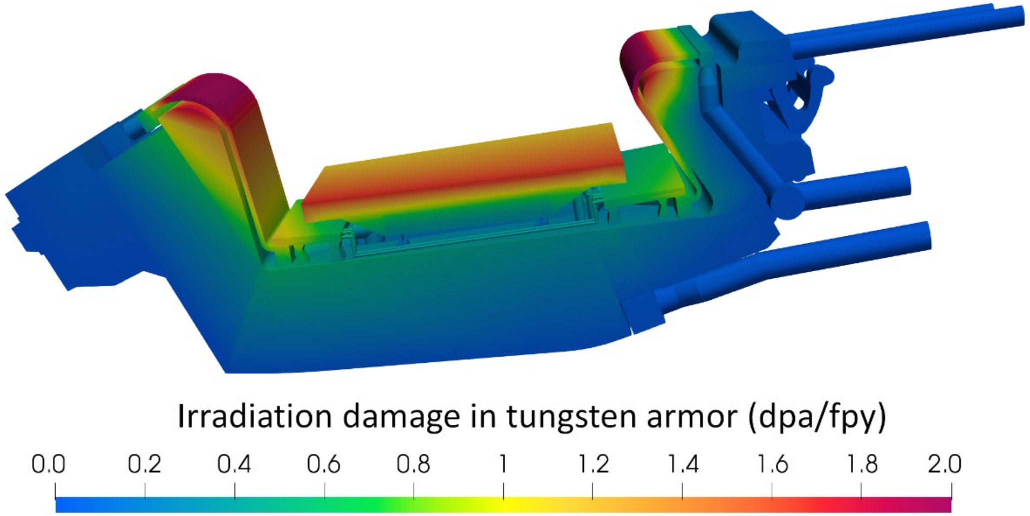
- Solid body: γ-ray emission by nuclear excitation
- Coolant: neutron moderation



Loads: nuclear (due to neutron flux)





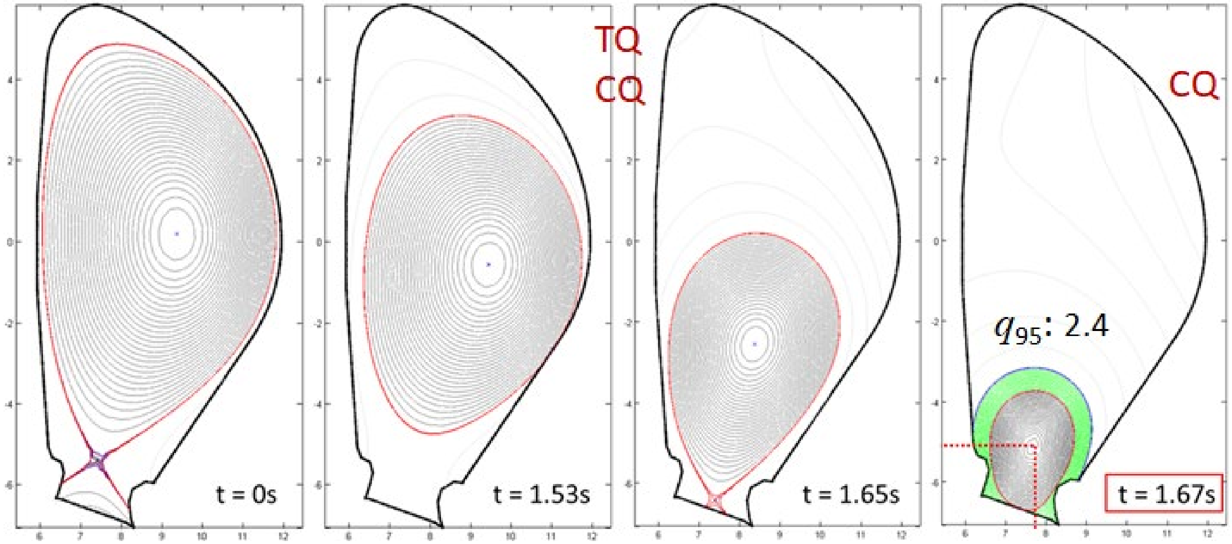


max. values	Lattice damage (dpa/fpy)	He production (appm/fpy)
Tungsten armor	~2	~2
Copper pipe	~7	~55!
Steel liner	~5	~95!

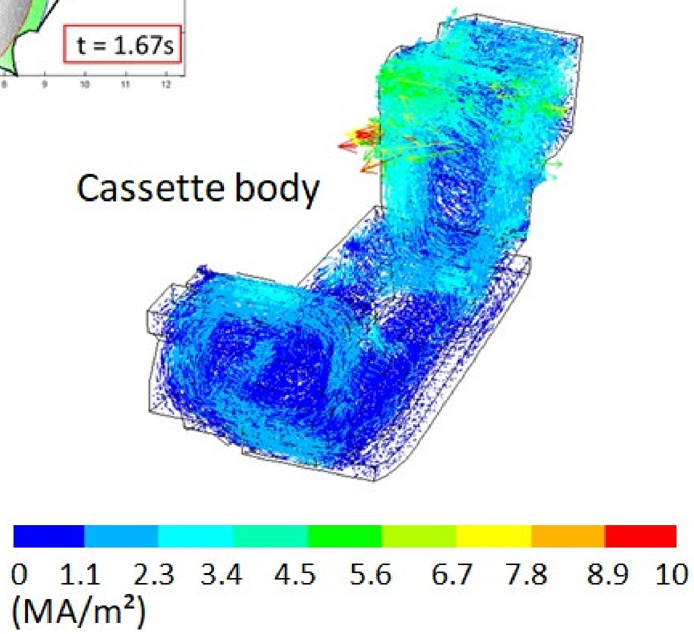
(specified lifetime: 1.5 fpy)

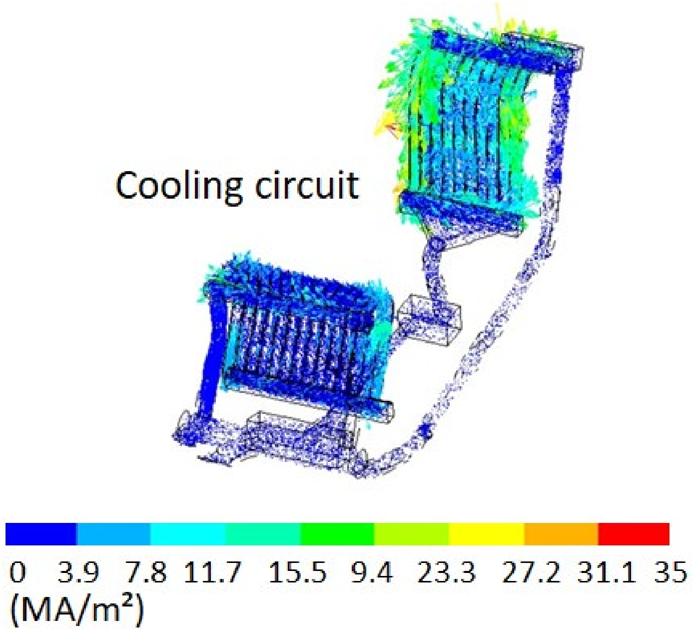
Loads: mechanical (electromagnetic impact)

Plasma configurations during a downward VDE



Halo currents flowing in the solid structures

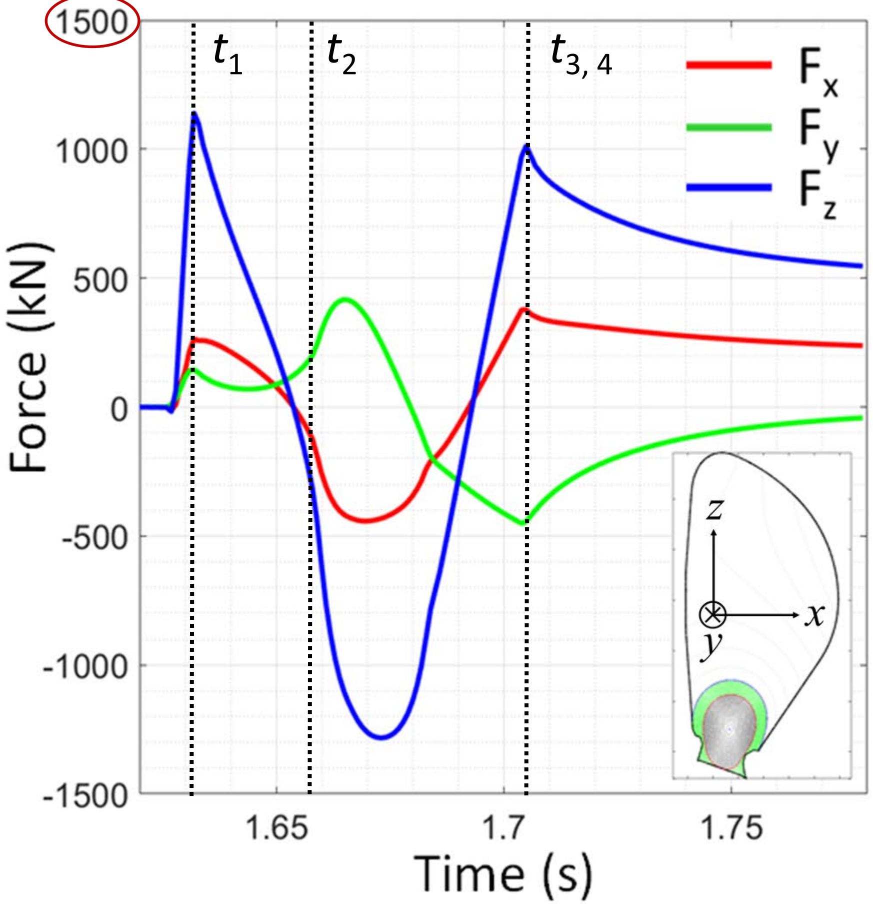




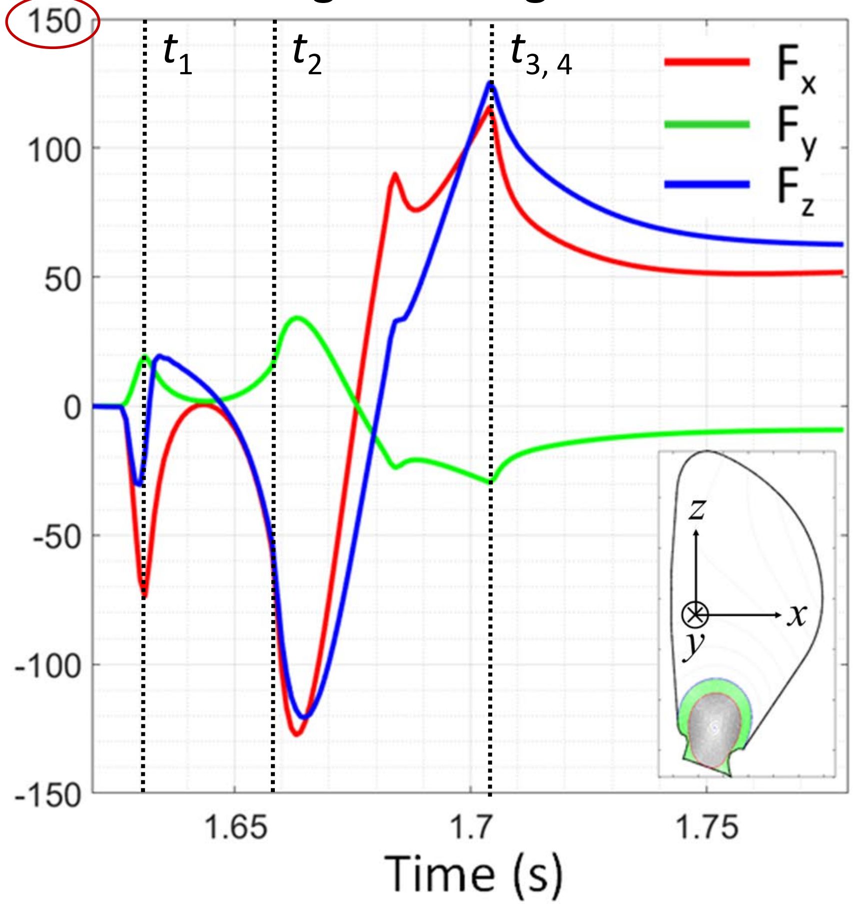
Loads: mechanical (electromagnetic impact)

Time evolution of the resultant Lorentz forces upon VDE-D

Entire divertor



Target cooling circuit



t_1 : start of current quench (CQ)

t_2 : start of halo currents (HC)

t_3 : end of CQ

t_4 : end of HC

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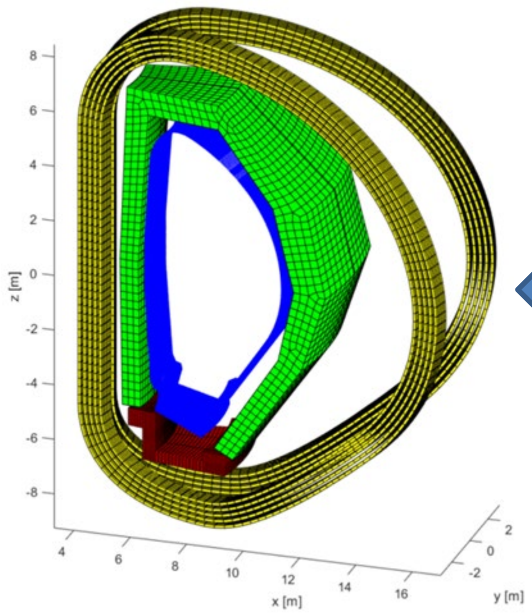
Loads: mechanical (Ferromagnetic forces)



The figure analyzed 22.5° sector of DEMO in-vessel assembly, including the divertors (in red), blankets (in green), the toroidal field coils (in yellow) and the layer with the equivalent sources associated to plasma currents (in blue).

	Fx [MN]	Fy [MN]	Fz [MN]	Mx [MN m]	My [MN m]	Mz [MN m]
Central Cassette	- 1.25	- 0.02	0.25	- 0.13	6.30	-0.14
External Cassette 1	- 1.20	0.11	- 0.09	0.67	8.60	2.00
External Cassette 2	- 1.19	- 0.08	- 0.12	- 0.50	8.71	-1.83
Blanket 1	-3.27	0.05	-0.02	0.05	-2.66	-2.57
Blanket 2	-3.27	-0.05	0.06	-0.04	-2.81	2.57

The table Computed values of the resultants of ferromagnetic forces and moments.

Mechanical loads produced by the ferromagnetic effects in the divertor. The exact assessment of this force is an important prerequisite for a reliable structural design, for instance for a correct choice of the fixing supports. The problem has been solved by using CARIDDI code, that implements an integral formulation and provides a significant simplification of the numerical model, since the mesh can be limited to the magnetic materials only. In our case, the main components of the model (divertor and breeding blankets) are made of a ferromagnetic material (EUROFER97 steel). The model considers all the sources of such magnetizing fields, namely: (i) the external toroidal field produced by the currents circulating in the external toroidal field coils, (ii) the internal field induced by the toroidal plasma current.
Expected static field in the considered components ranges from 3.4 T to 8.6 T. Torques and forces have been computed from the known external magnetic fields and the magnetization vector calculated for the ferromagnetic steel.

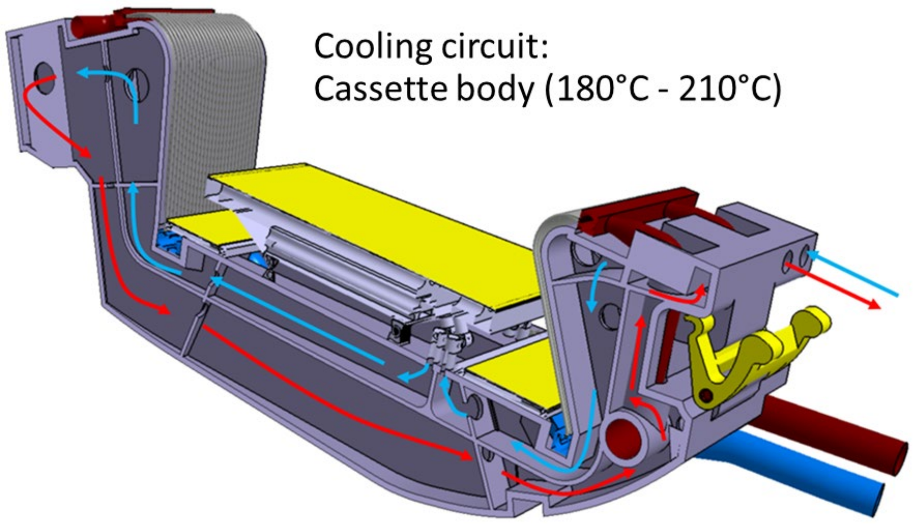
G. Di Mambro et al., FED (2022)

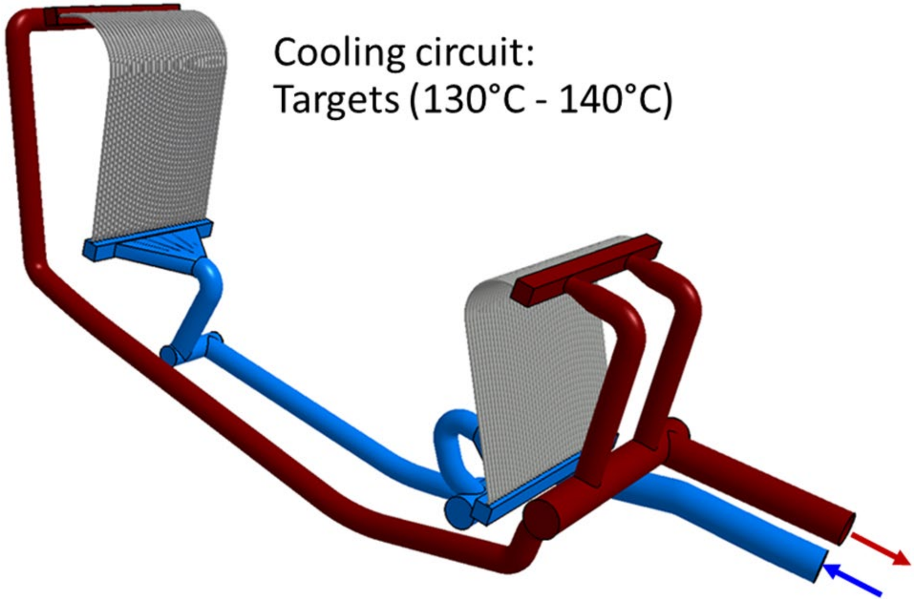
Pre-conceptual baseline design 2^{nd} phase

- Performance (20 MW/m²)
- Design issues

🙂	Feasible, no or minor issues only
😐	Concerning, probably acceptable or improvable
😔	Critical, potentially serious or unacceptable risks

Performance: cooling (operation conditions)





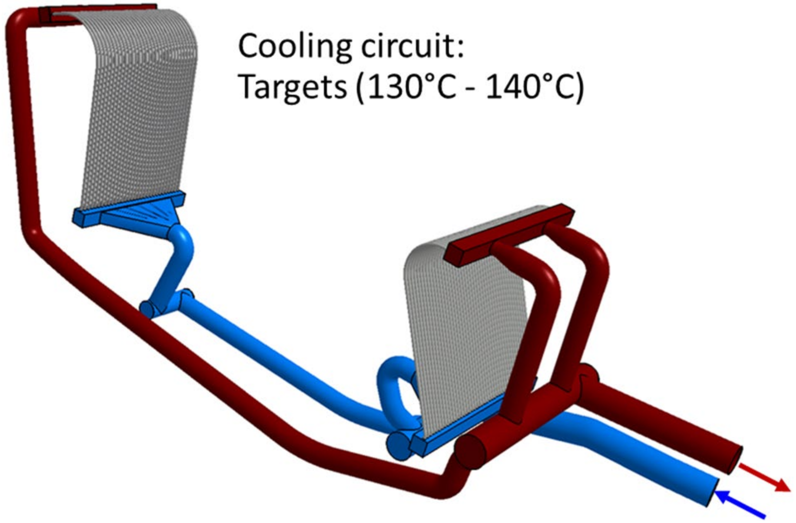
Cooling circuit of the Cassette body

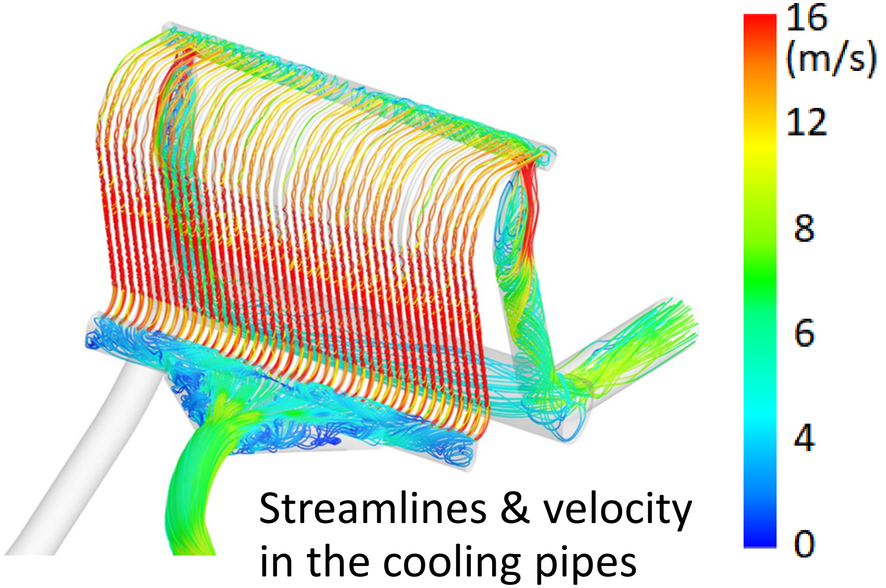
Mass flow rate per cassette	31.2 kg/s	
Coolant temperature (inlet)	180 °C	😐
Coolant pressure (inlet)	3.5 MPa	🙂
Pumping power (per cassette)	20 kW	🙂

Cooling circuit of the targets

Mass flow rate per cassette	~99 kg/s	
Coolant temperature (inlet)	130 °C	😐
Coolant pressure (inlet)	5 MPa	🙂
Pumping power (per cassette)	~100 kW	🙂

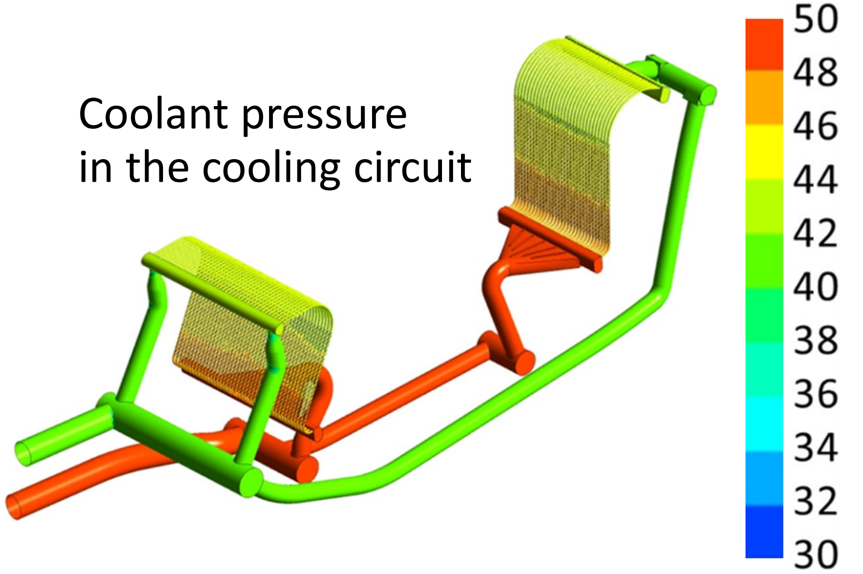
Performance: cooling (thermohydraulic response)



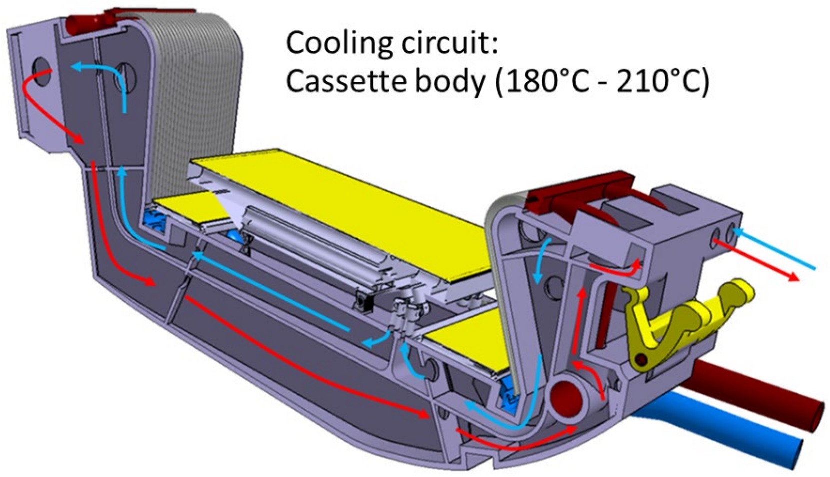


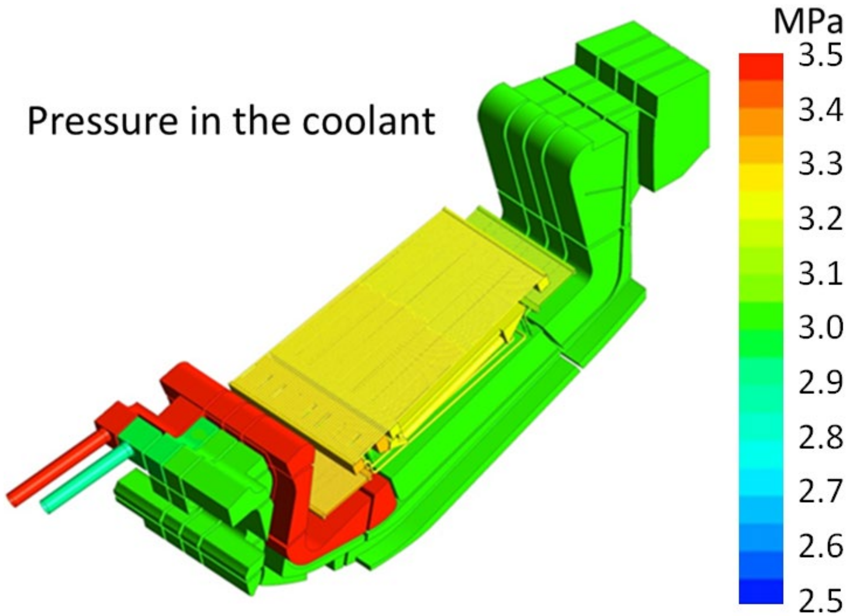
Pressure drop (outlet)	< 1 MPa
Temperature rise	+6 °C
Critical heat flux margin	> 40 %
Coolant velocity	~14 m/s
Local max. temp. of the pipe	310/440 °C

(10/20 MW/m²)

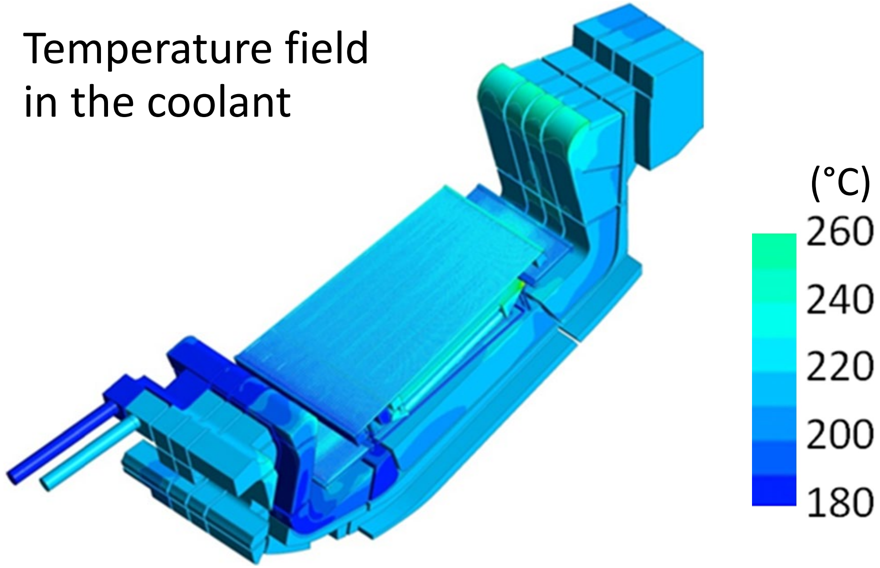


Performance: cooling (thermohydraulic response)

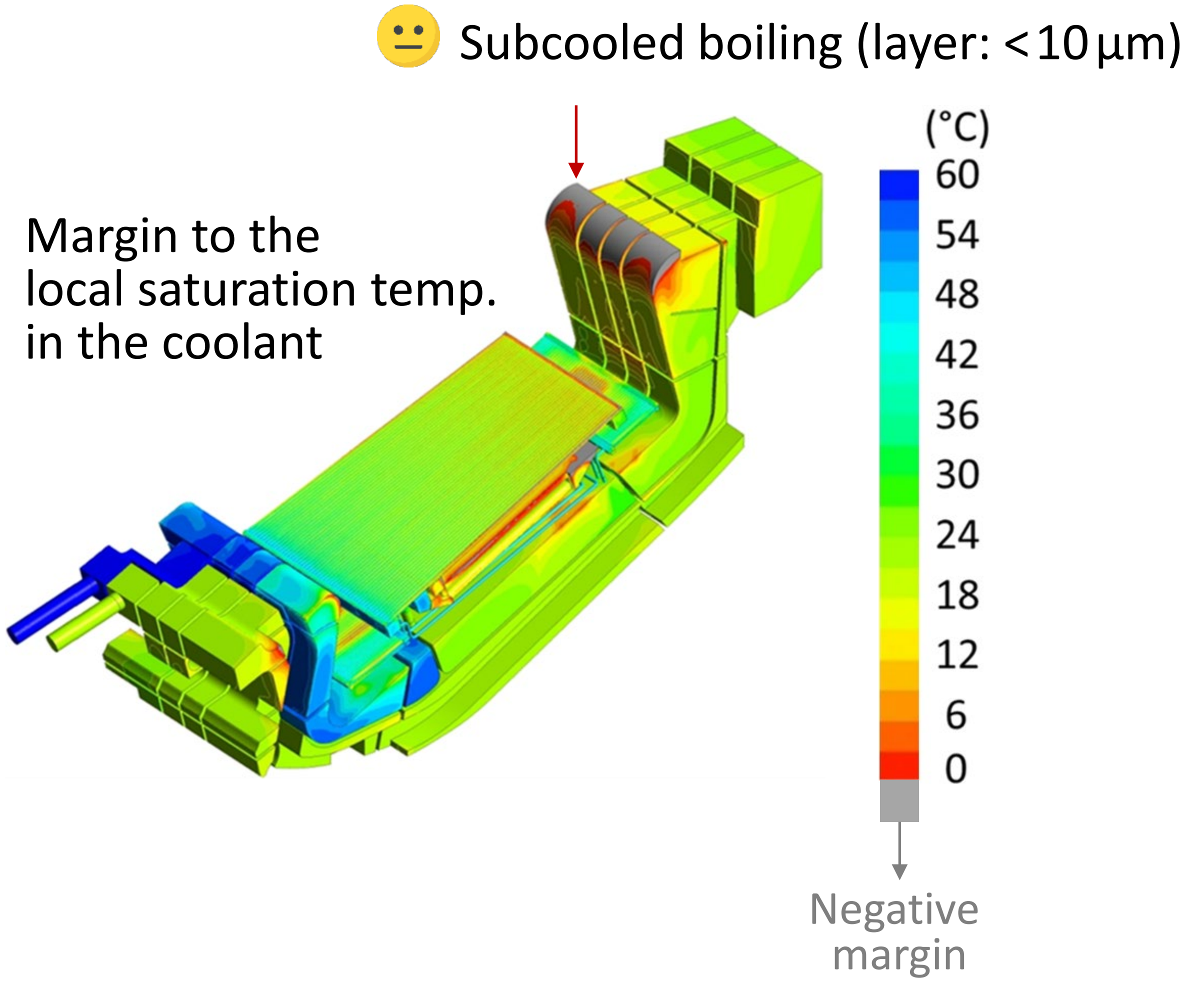


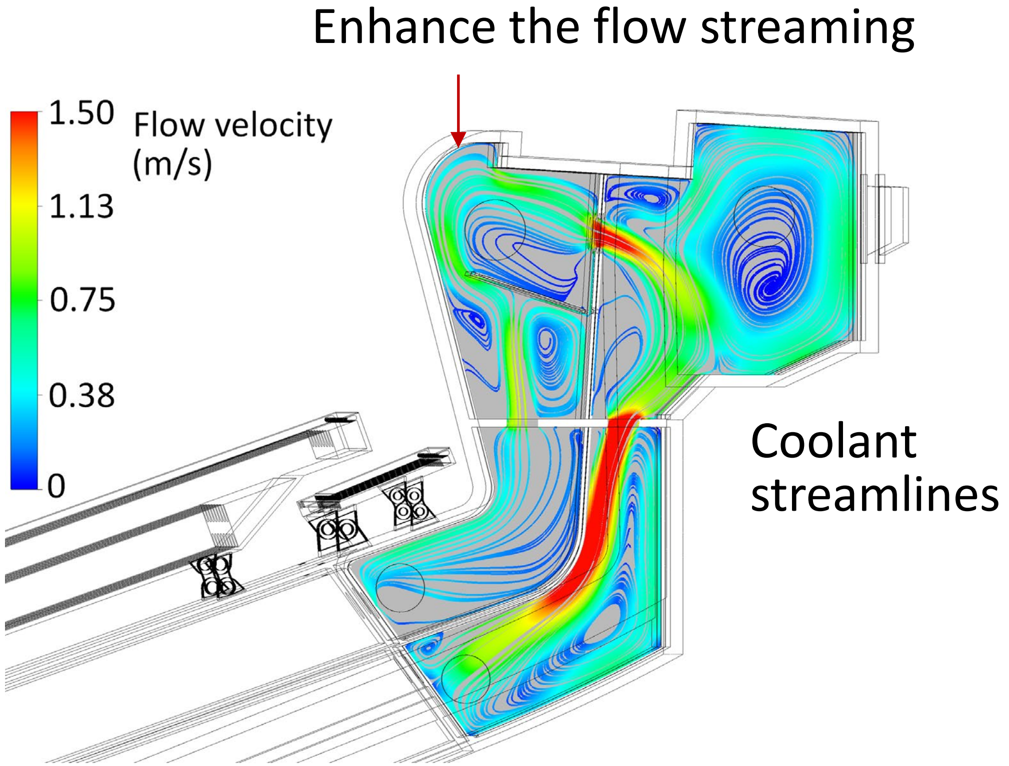


Pressure drop (outlet)	< 0.6 MPa	🙂
Temperature rise (outlet)	30 °C	🙂
Margin to the saturation temp.	≥ 22 °C	🙂
Local max. temp. of coolant	230 °C	😐
Local max. temp. of the body	555 °C	🙂



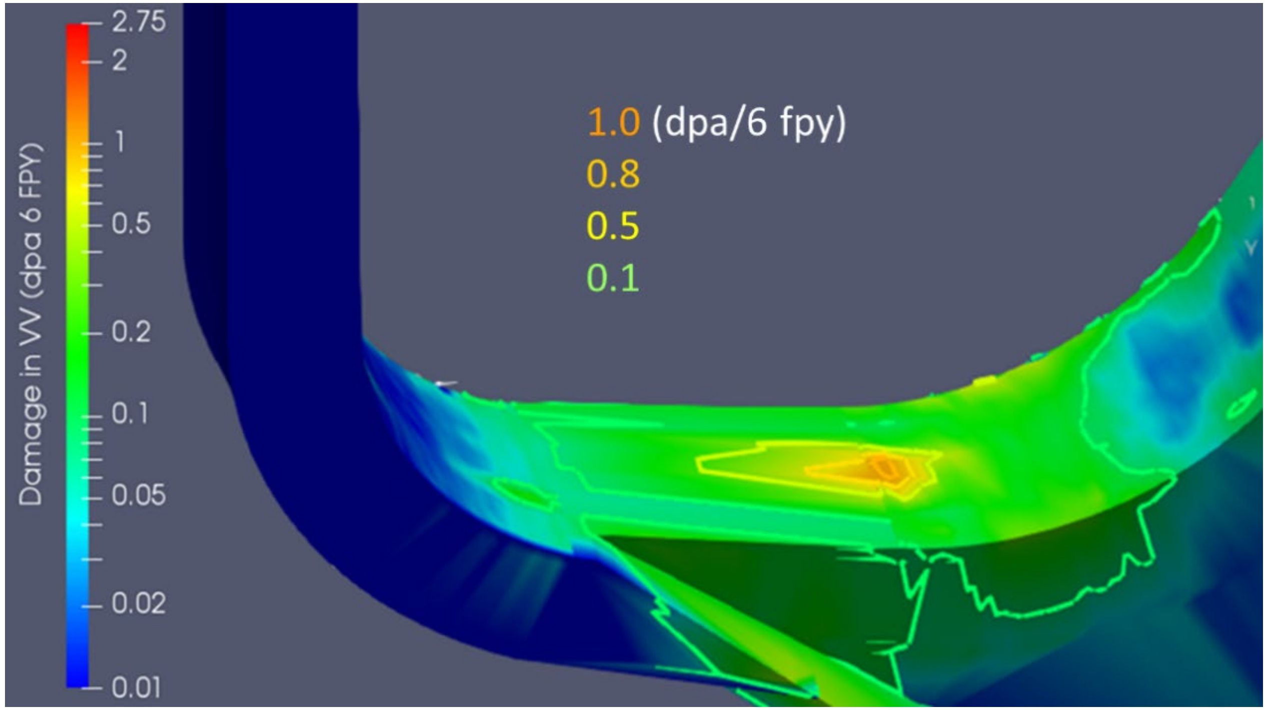
Cooling: design issue (cassette body)

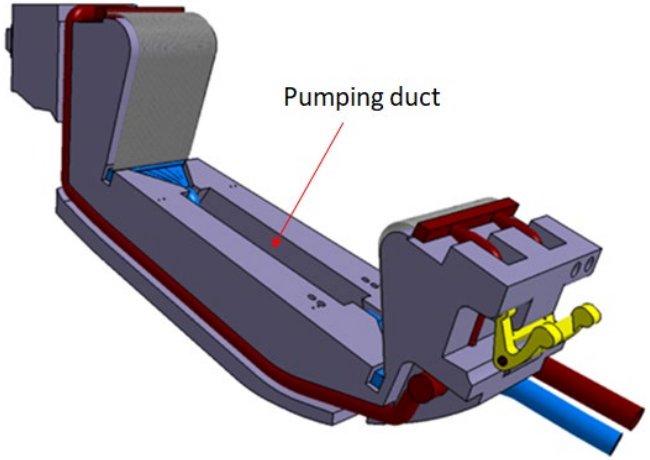




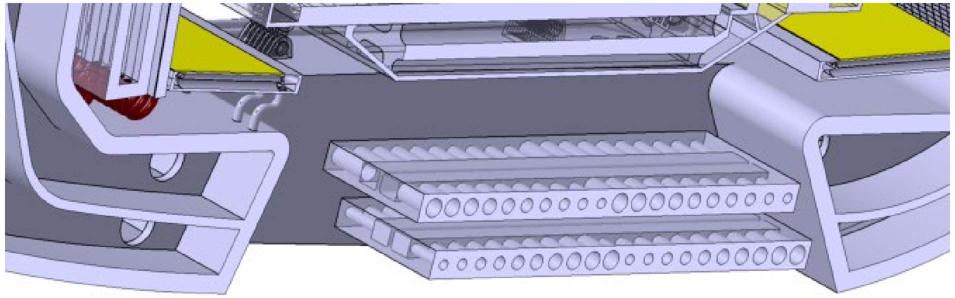
Performance: shielding on VV

Irradiation damage dose in the vacuum vessel
(<1 dpa after 6 fpy operation) 🙂

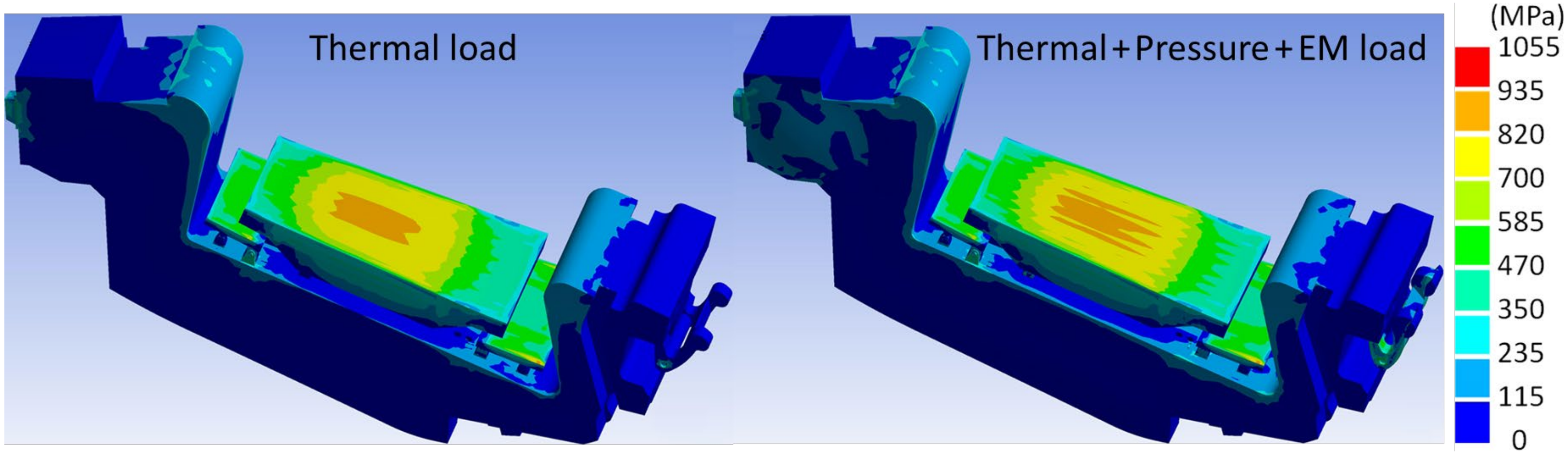




Actively-cooled shielding barrier



Stress fields (von Mises)



- Steel body: RCC-MRx, draft DDC-IC* (fracture, multi-axial fatigue, creep-fatigue, ratchetting)
- W/Cu target: Ad-hoc rules (fatigue, exhaustion of ductility)

Elastic rules with irradiation/creep effects

$$\overline{P_m} \leq S_m(\theta_m)$$

$$\overline{P_m + Pb} \leq 1.5\, S_m(\theta_m)$$

$$\overline{P_m + Q_m} < S_{em}^{A}(\theta_m, G_{tm})$$

$$\overline{P_m + P_b + Q + F} < S_{et}^{A}(\theta_m, G_t)$$

$$Max(P_m + Q_m) + \Delta Q \leq 3S_m$$

$$Max(\sigma_m) = \frac{1}{2} \cdot [Max(\overline{P_m}) + (\sigma_m)_N]$$

$$Max(\sigma_L + \sigma_b) = \frac{1}{2} \cdot [Max(\overline{P_L + P_b}) + (\sigma_L + \sigma_b)_N]$$

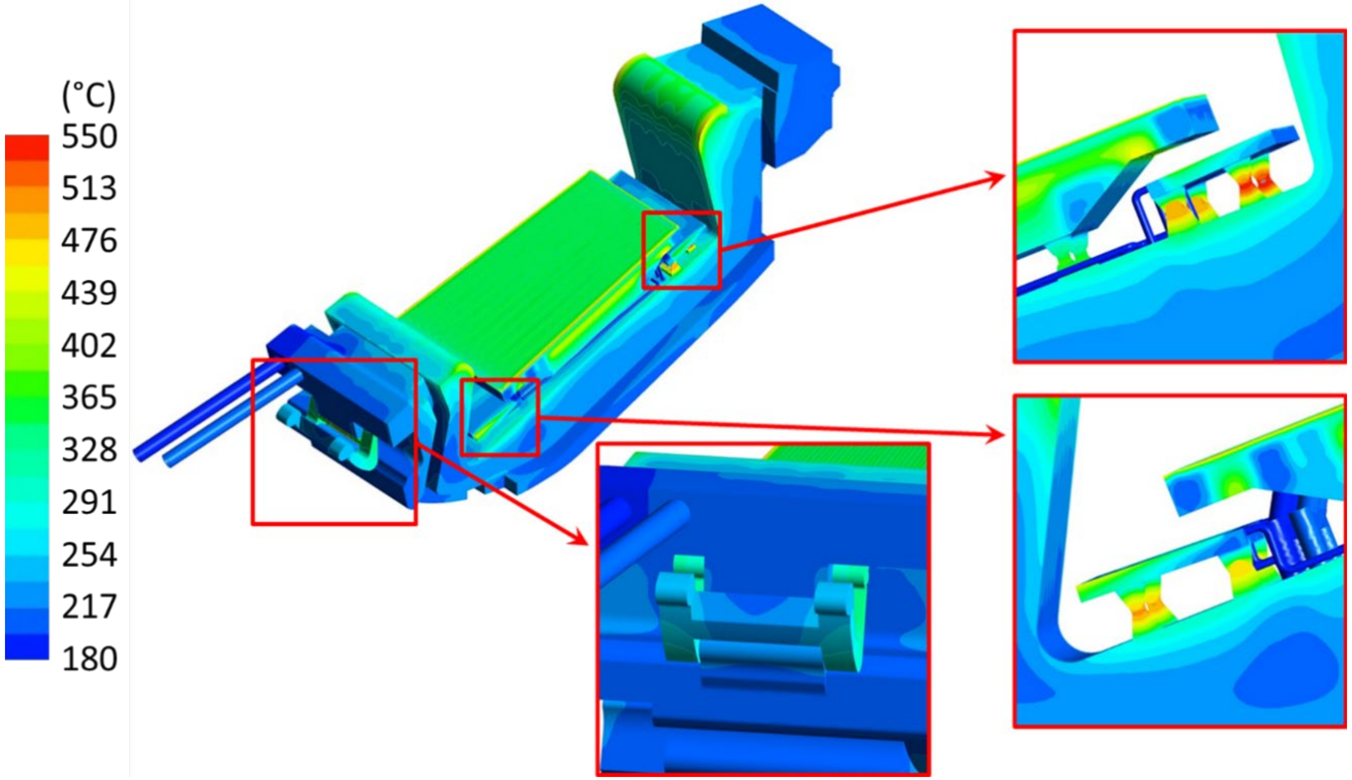
$$U_{A',C}(\square\ \overline{P_m}) = \sum_{i}^{N} \frac{t_i}{T_i} \leq 1$$

$$U_{A',C}(\overline{P_l + \phi P_b}) = \sum_{i}^{N} \frac{t_i}{T_i} \leq 1$$

* DDC-IC DEMO design criteria for in-vessel components

Structural reliability: design issues (accidental impact loads)

Temperature field in the cassette body



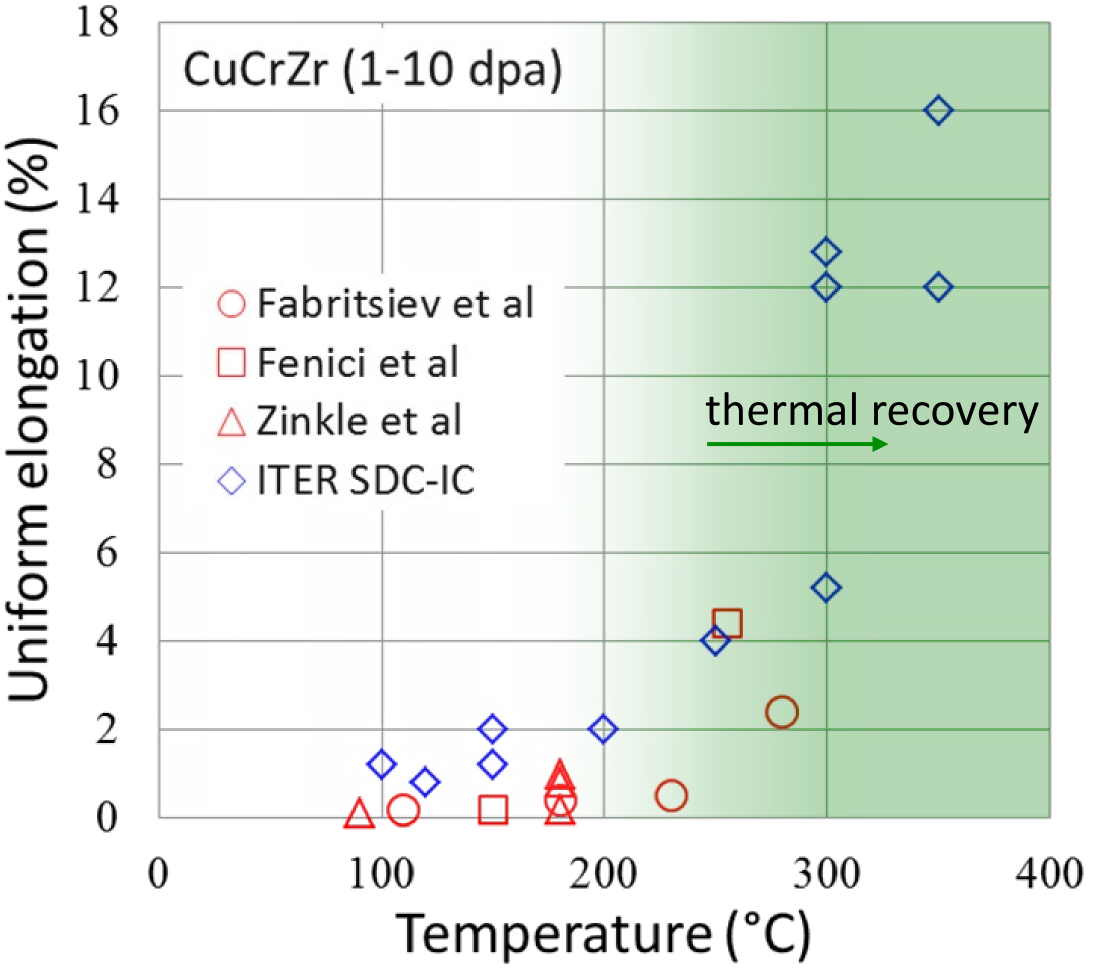
Failure predicted at the steel supports 😔 under impact loads (due to thermal softening)

$\Rightarrow$ Improve the heat conduction at the supports

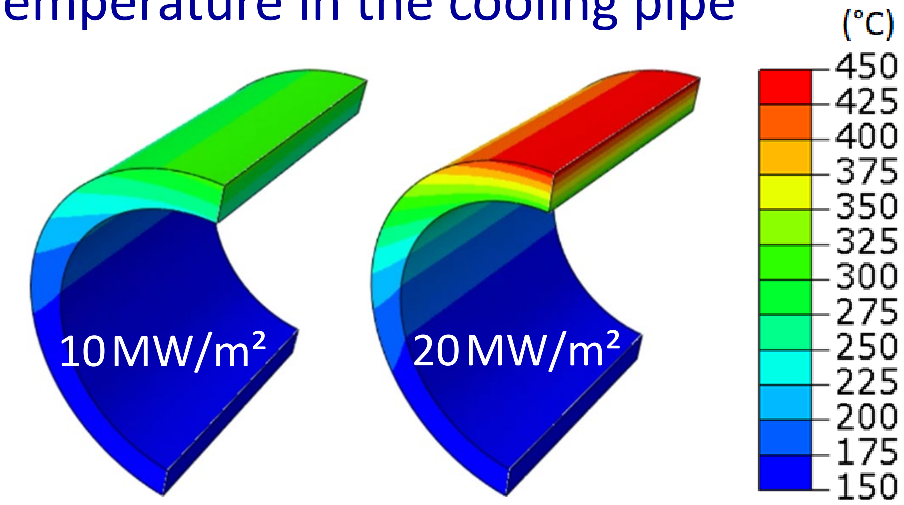
$\Rightarrow$ ODS steel?

Structural reliability: design issues (embrittled cooling pipe)

Irradiated CuCrZr alloy

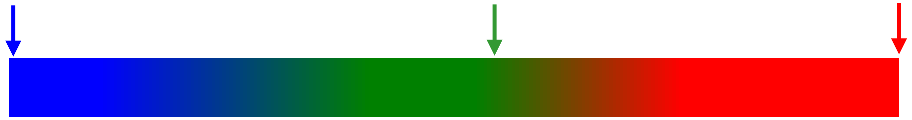


Temperature in the cooling pipe



Cooling pipe operation temp. range

Cooling	10 MW/m²	20 MW/m²
130-140°C	245°C-310°C	310-440°C



loss of ductility

optimal range (250°C-300°C)

loss of strength

Conceptual Design Activity CDA (2021-2027)

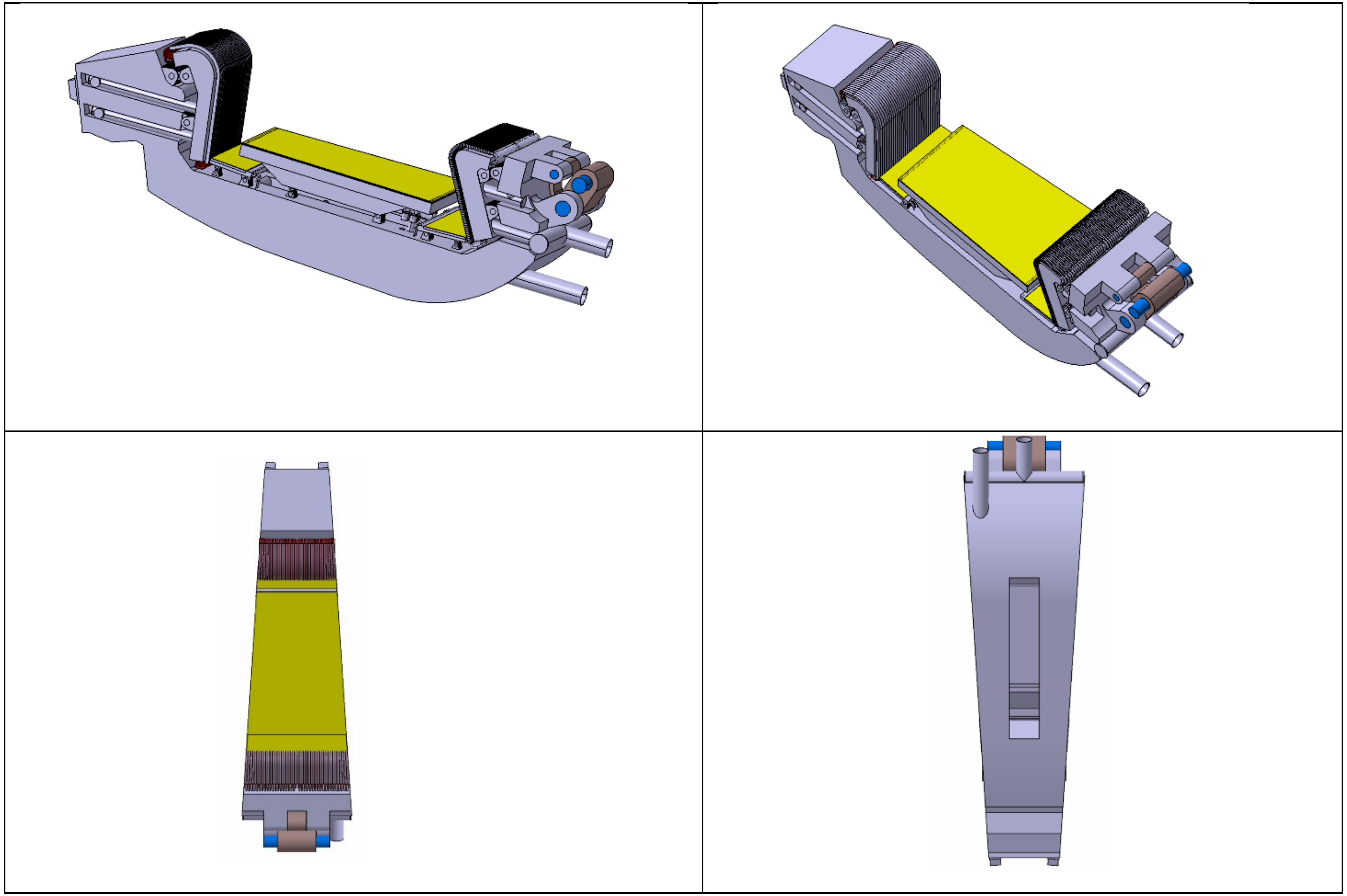
Summary of the thermal-hydraulic performances of Single and Double-circuit concepts.

PEP Deliverable DIV-D.S.1-D02 - Divertor Cooling Options EFDA_D_2PL9X7

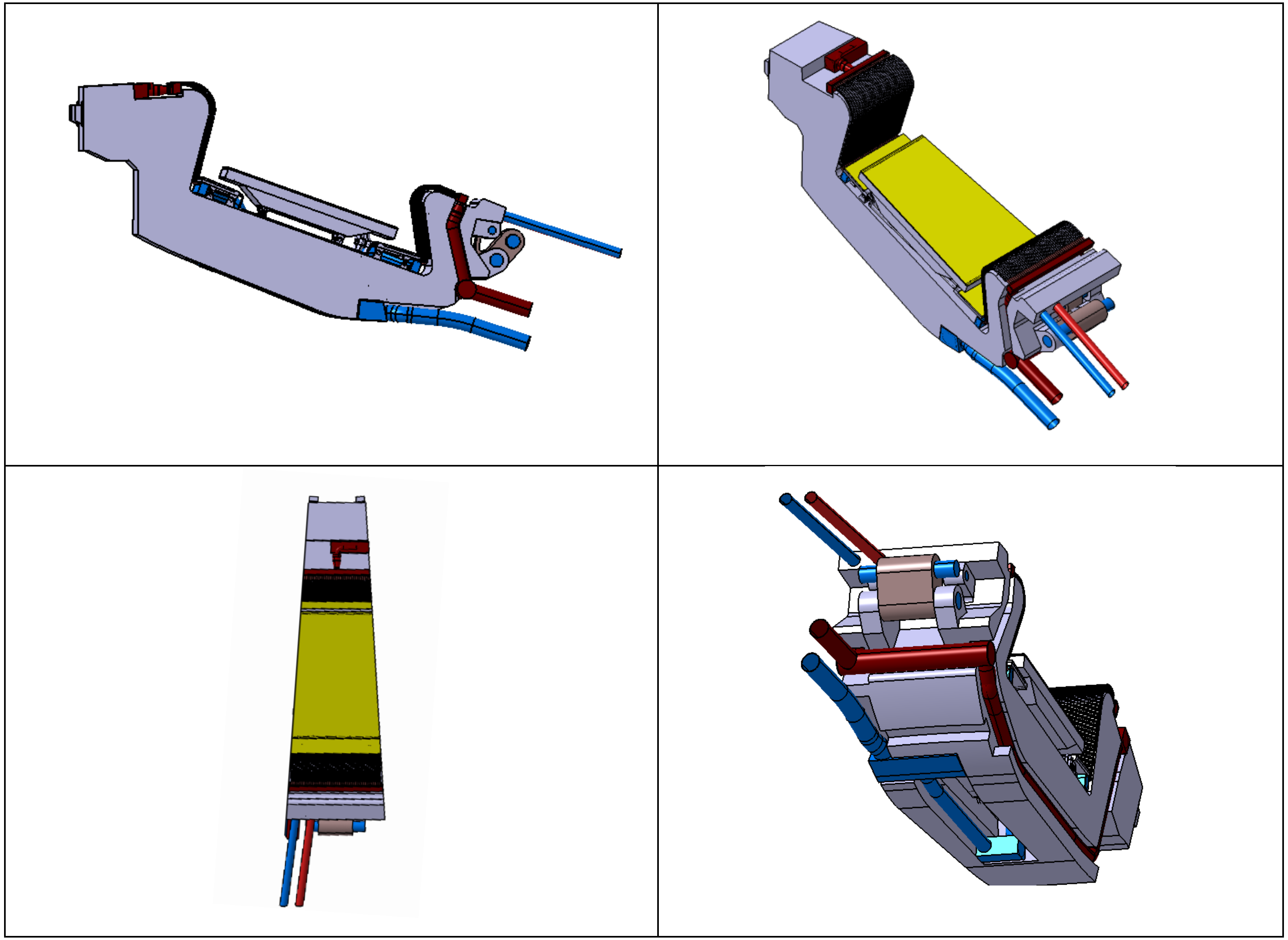
Divertor concept	Double-circuit concept (Reference option)				Single-circuit concept (Alternative option)-2021
Operating condition	Normal Operating Conditions- 2021		PWR Conditions 2022		-
Cooling circuit	CB Cooling circuit	PFC Cooling circuit	CB Cooling circuit	PFC Cooling circuit	CB+PFC Cooling circuit
Reference	[*]	[*]	[**]	[*]	[**]
Mass Flow Rate/Cassette [kg/s]	31.17	98.63	21.64	98.63	32.00
Nuclear Deposited Power/Cassette [MW]	4.17	2.79	4.17	2.79	7.70
Coolant Inlet Temperature [°C]	180	130	295	130	130
Coolant Inlet Pressure [MPa]	3.5	5.0	15.5	5.0	5.0
Coolant Pressure Drop [MPa]	0.56	0.94	0.33	0.94	0.98
Coolant Pumping Power/Cassette [kW]	19.93	99.24	10.21	99.24	34.00
Coolant Temperature Variation [°C]	30.00	6.74	33.00	6.74	56.67
Coolant Local Maximum Temperature [°C]	329.89	N.A.	428.80	N.A.	TBC
Structure Maximum Temperature [°C]	554.91	N.A.	669.99	N.A.	TBC
Minimum VTs CHF Margin [-]	-	1.41	-	1.41	1.02
Minimum Saturation Margin [°C]	22.5	114.5	15.0	114.5	74.0

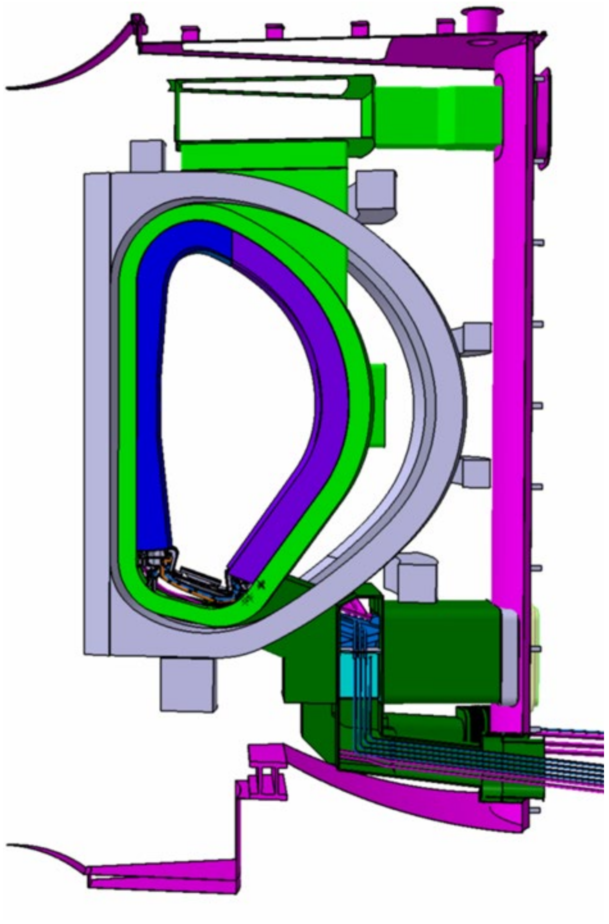
[*] P. A. Di Maio and E. Vallone, DIV-JUS-2-CD1__Thermo-Hydraulics Assessment Report, EFDA_D_2PAMPD v1.0.
[**] P. A. Di Maio, E. Vallone, A. Quartararo, F. M. Castrovinci, S. Basile and M. R. Giardina, DIV-DEMO.S.1-T001-D001 - Divertor Thermo-hydraulic assessment 2021, EFD_D_2PHWSW.

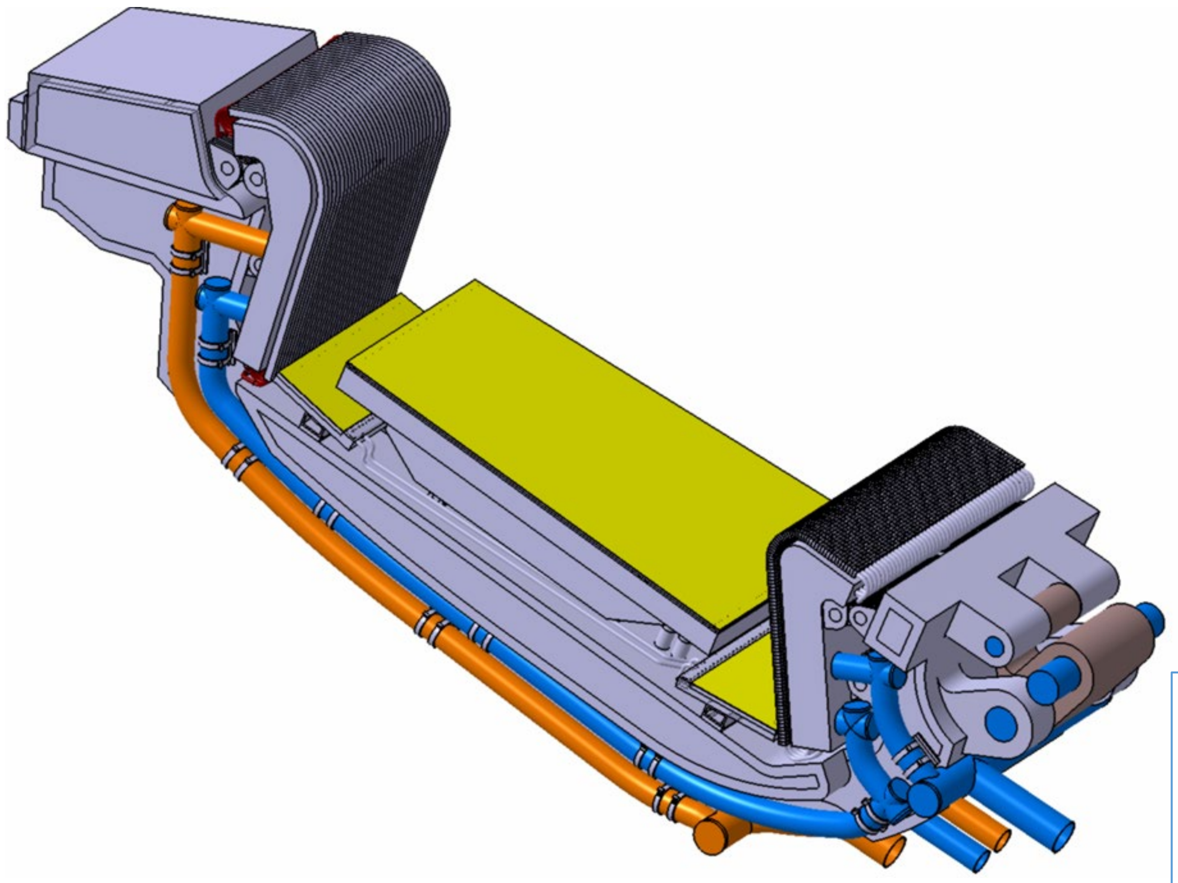
DEMO DIV 2021 single cooling option (EUROfusion IDM Reference: 2PRJTE)



DEMO DIVERTOR 2021 Double cooling option (EUROfusion IDM Reference: 2PTU79)







The PFUs are mounted onto a steel (EUROFER o AISI 316?) supporting structure of VT. Each cassette carries two Vertical Targets (VTs): Inner Vertical Target (IVT) and Outer Vertical Target (OVT).

Eurofer weight in 1 divertor assembly:

IVT	-> 460 Kg
OVT	-> 540 Kg
Shielding Liner	-> 1150 Kg
Divertor assembly	-> 8130 Kg

DIV Demo Divertor 2022 - Two cooling options with cassette cooled with water at high pressure and temperature (2PPMQB). The cassette and other Eurofer components (as reflector plates, shielding liner etc.) a cooling circuit with high pressure and temperature (p=15 MPa; T= 300 °C) similar to the breeding blanket cooling conditions.

Main changes:

1. Revision of the divertor cassette taking into account the PWR cooling condition (~15 MPa, ~300°C) with two separated cooling circuits for CB (+SL e RPs) and VTs;

2. Revision of the divertor layout taking into account the VTs removable from the CB;

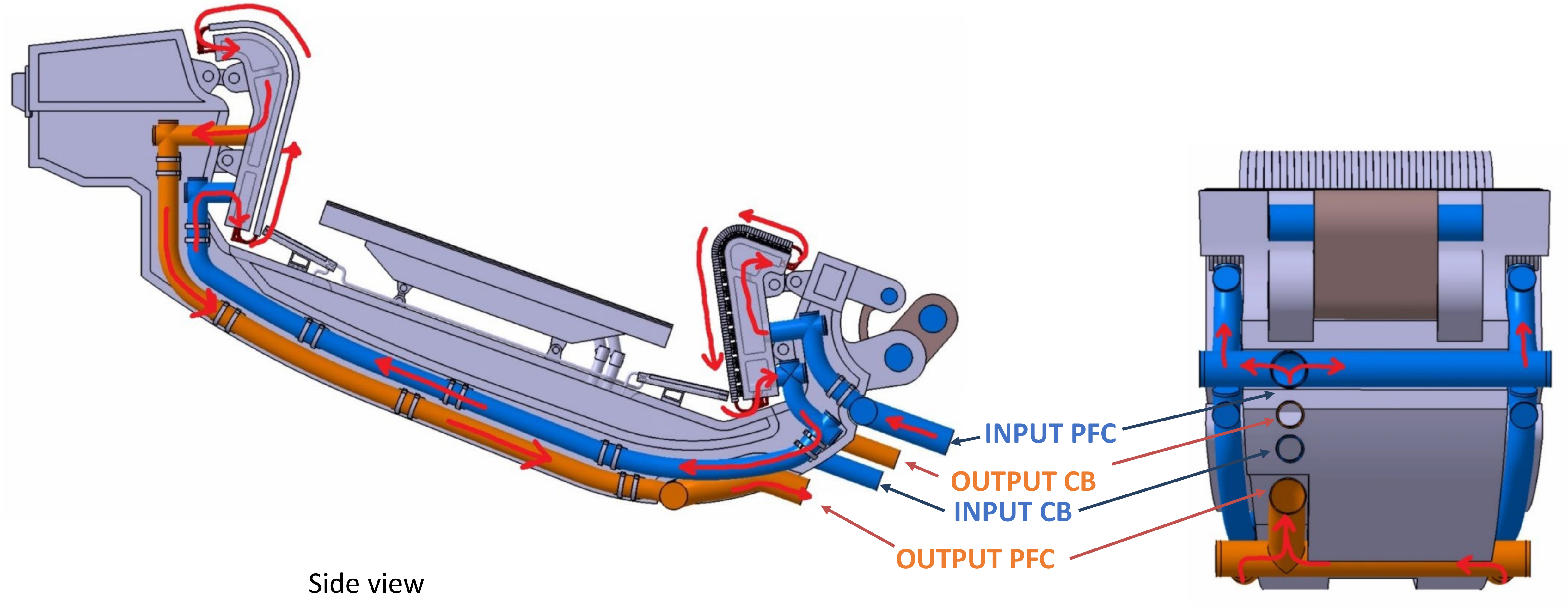
3. Increase of the structural behavior of the CB (+SL e RPs) and relative cooling pipes taking into account higher pressure and temperature;

4. Introduction of the VTs cooling pipes supports;

5. Revision of the Reflector Plates supporting system;

6. Updated design of neutron shield plates;

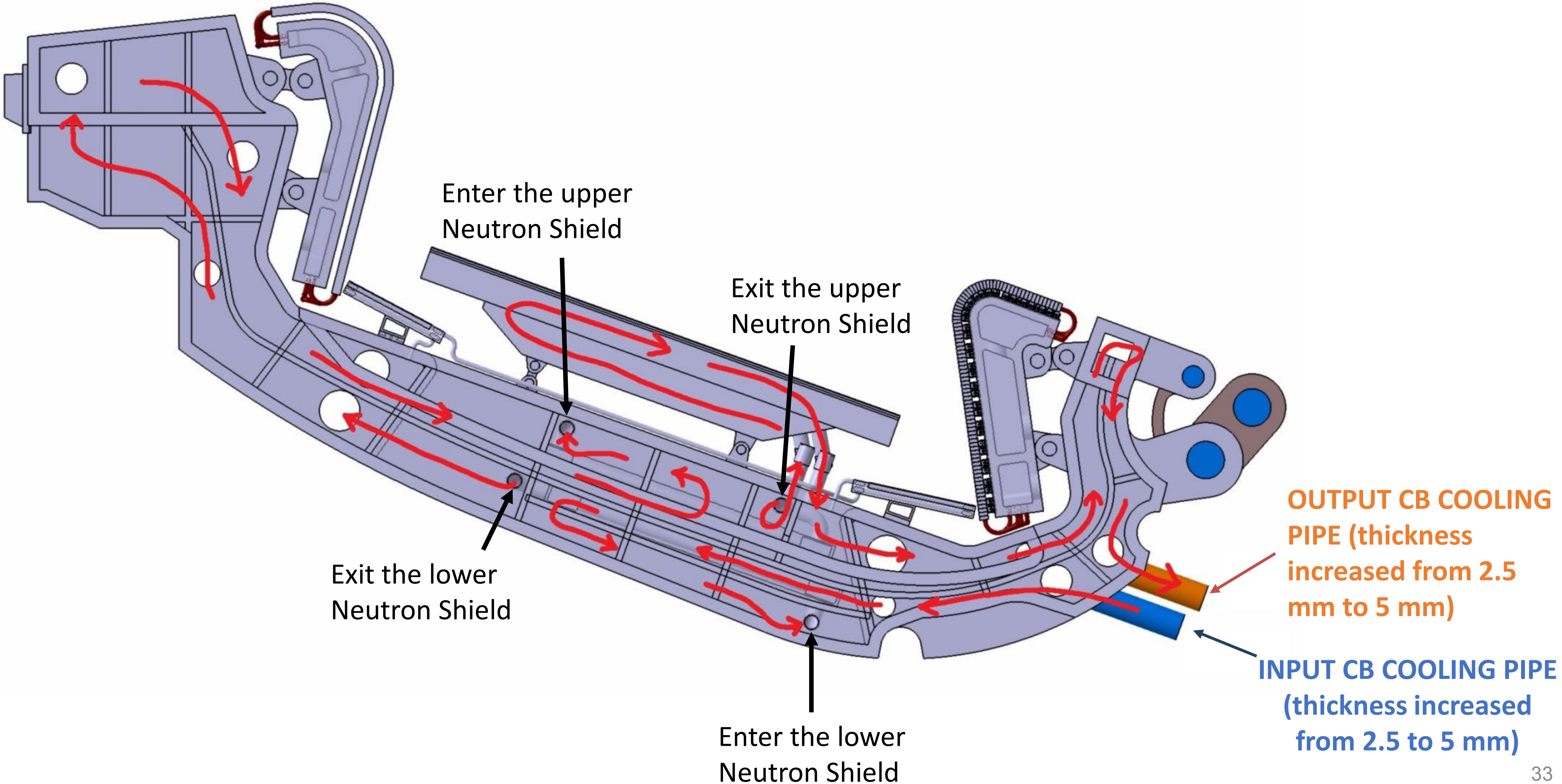
Vertical target water cooling circuit



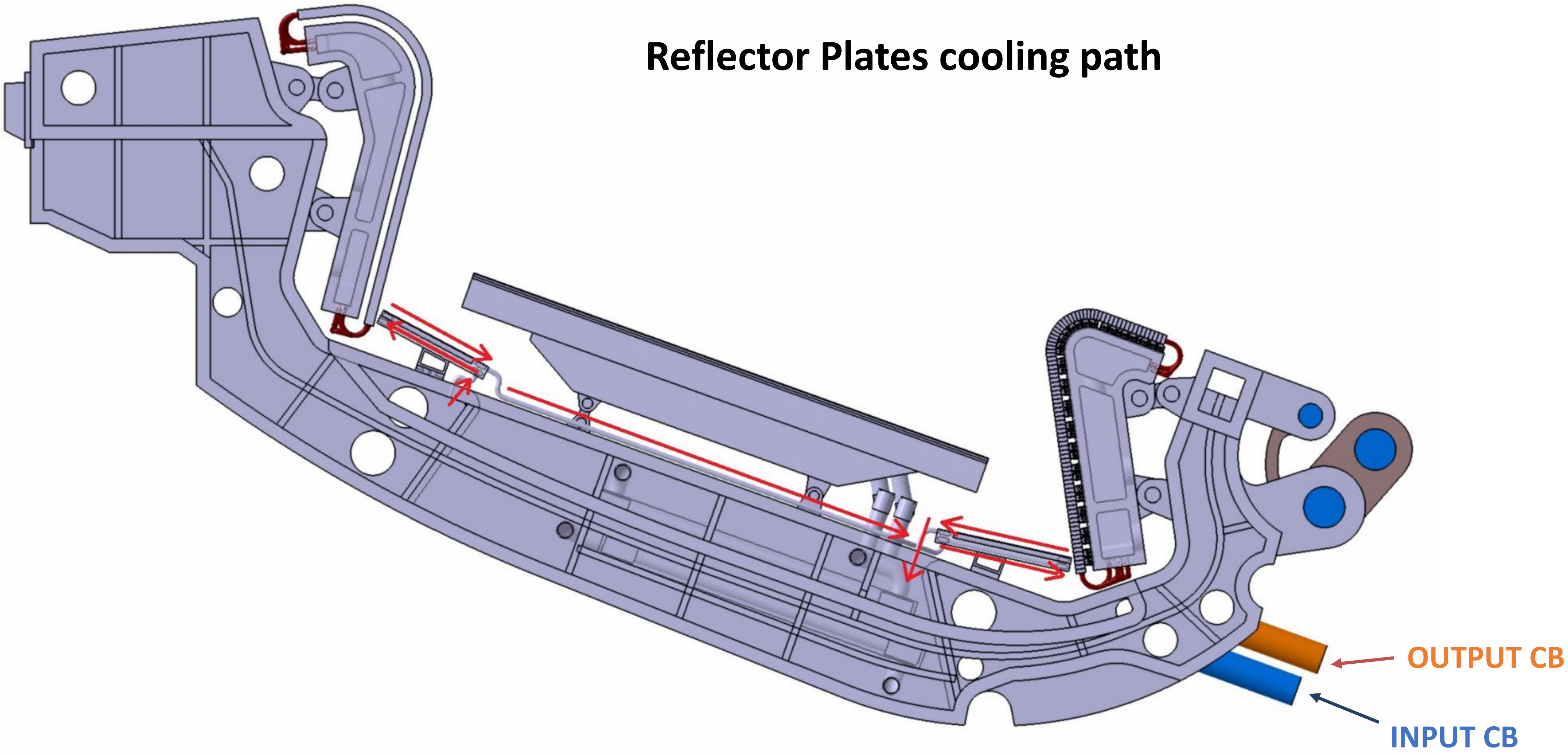
Side view

Back view

Cassette Body water cooling circuit



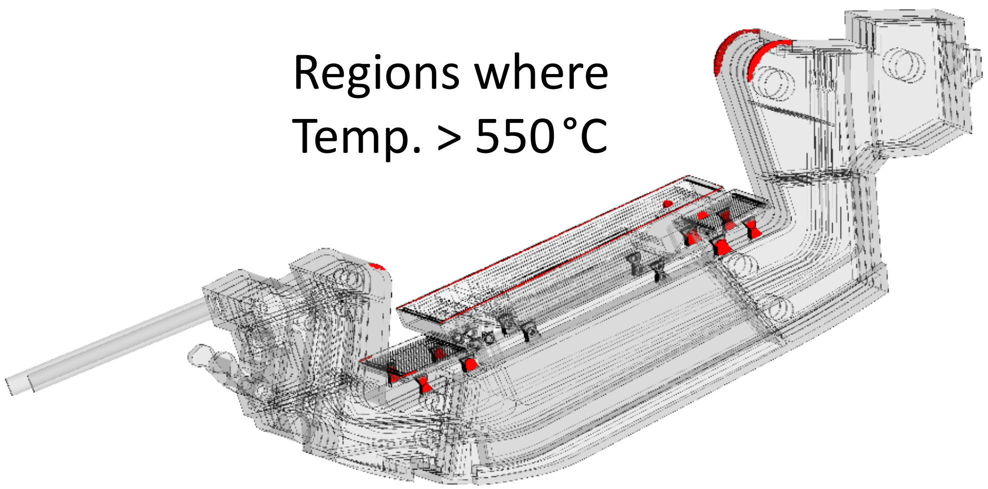
Cassette Body water cooling circuit

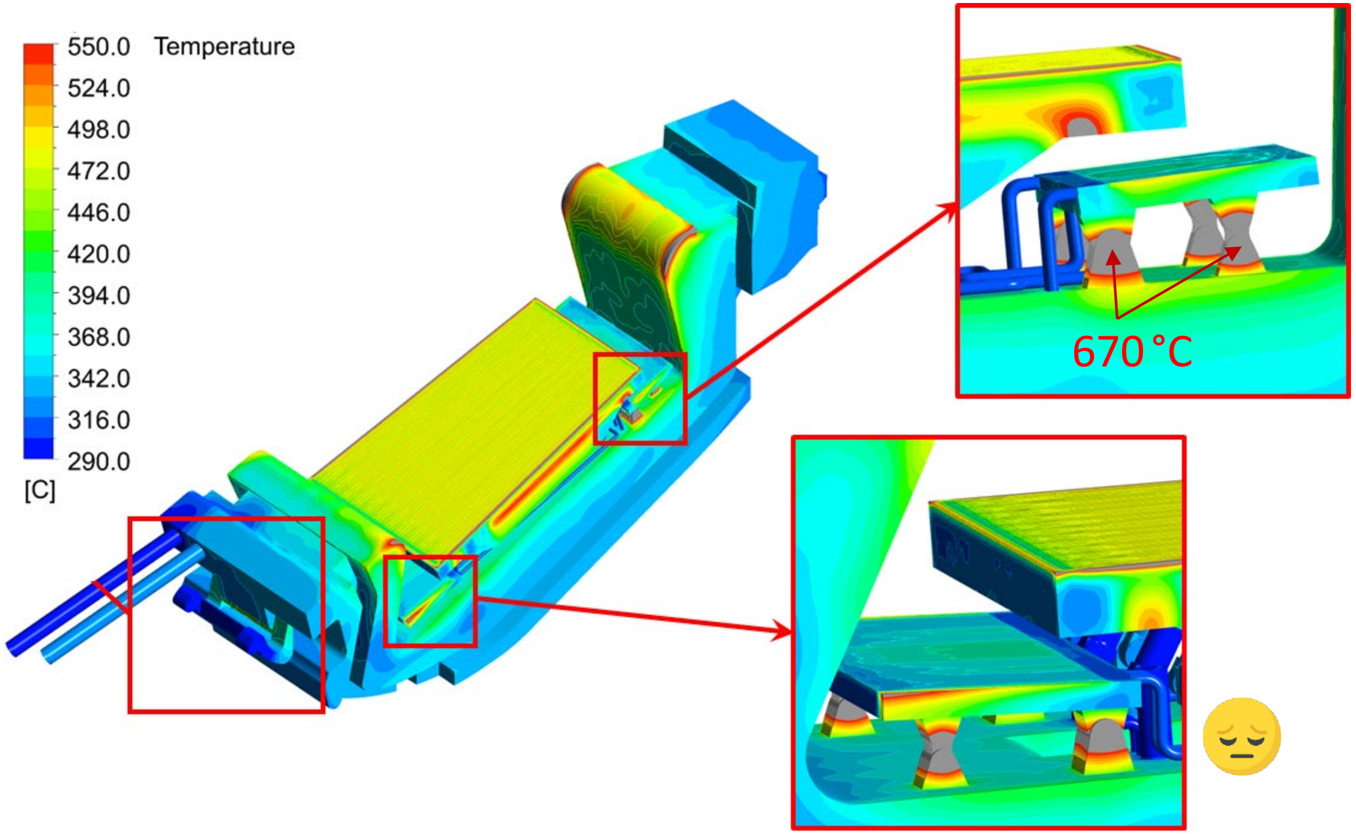


Alternative cooling option for the cassette body

Options	Inlet temp.	Outlet temp.	Inlet pressure	Pressure drop	Mass flow rate
LT Baseline	180 °C	210 °C	3.5 MPa	< 0.6 MPa	31 Kg/s
HT coolant	295 °C	328 °C	15.5 MPa	< 0.4 MPa	22 Kg/s

Regions where Temp. > 550 °C





Advantages:

- Eurofer components cooled at PWR Condition -> higher Operational lifetime (from 6 dpa to 20 dpa);
  - -Reduction of ~~waste~~ during the life of the DEMO machine;
  - -Reduction of the total divertor cost due to due re-use of cassette body;
- PFU fixed on VTs -> reduce Remote Handling time operation (it's possible remove the complete VT from the cassette and replace with a new VT sub assembly);
- Tokamak Cooling system simpler having the same cooling condition for Divertor and Breeding Blanket Eurofer components~~;~~

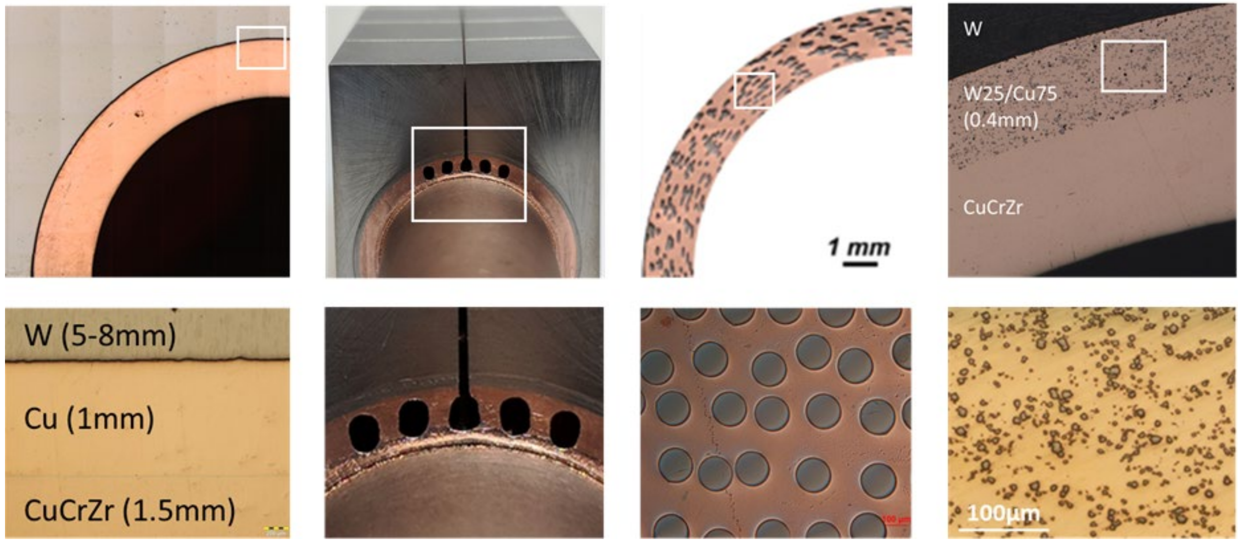
Disadvantages:

- Eurofer components (CB, SL, RP and cooling piping) design and fabrication more expensive due to high pressure and temperature design conditions;
- Max. temperature at PFC supports reaches 650 °C (excessive softening of EUROFER);
- The back plate of the VT are cooled with the PFU cooling water (130°C, 5 MPa) -> The structural material can be Eurofer or AISI 316 -> important factors in this choice will be Activation, Swelling for AISI 316 and Embrittlement for Eurofer under neutron irradiation at low temperature.

High-heat-flux technologies

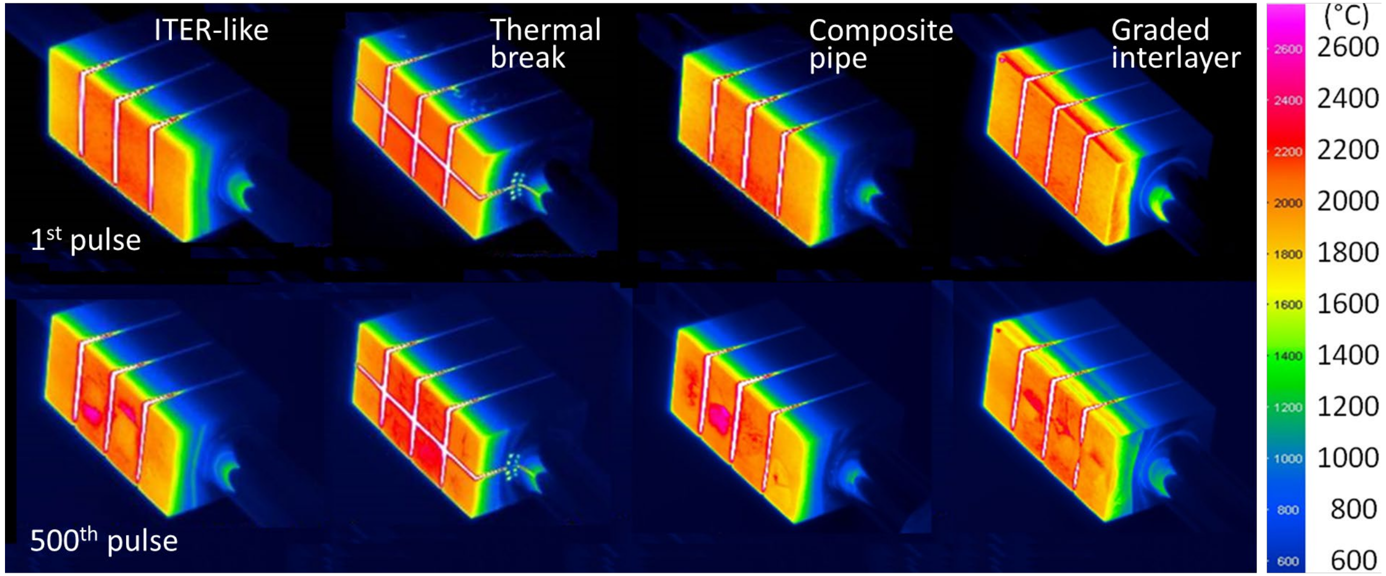
Tungsten-monoblock type design variants

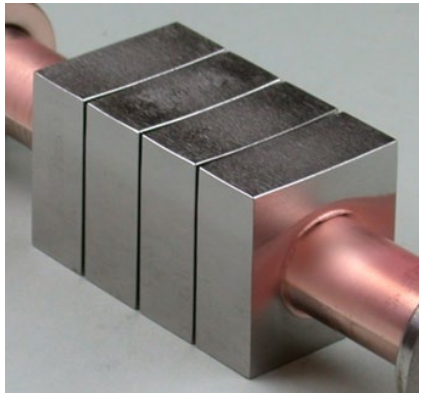
ITER-like (Cu interlayer)	Thermal break (bores, notch)	Composite pipe (W wire/Cu)	Graded interlayer (W particle/Cu)



- High manufacture quality demonstrated 🙂
- Qualified for cyclic HHF loads at 20/25 MW/m² 🙂 (up to 2000/1500 pulses)

IR thermography images (GLADIS)
20 MW/m², 500 pulses (10s, coolant: 130°C)



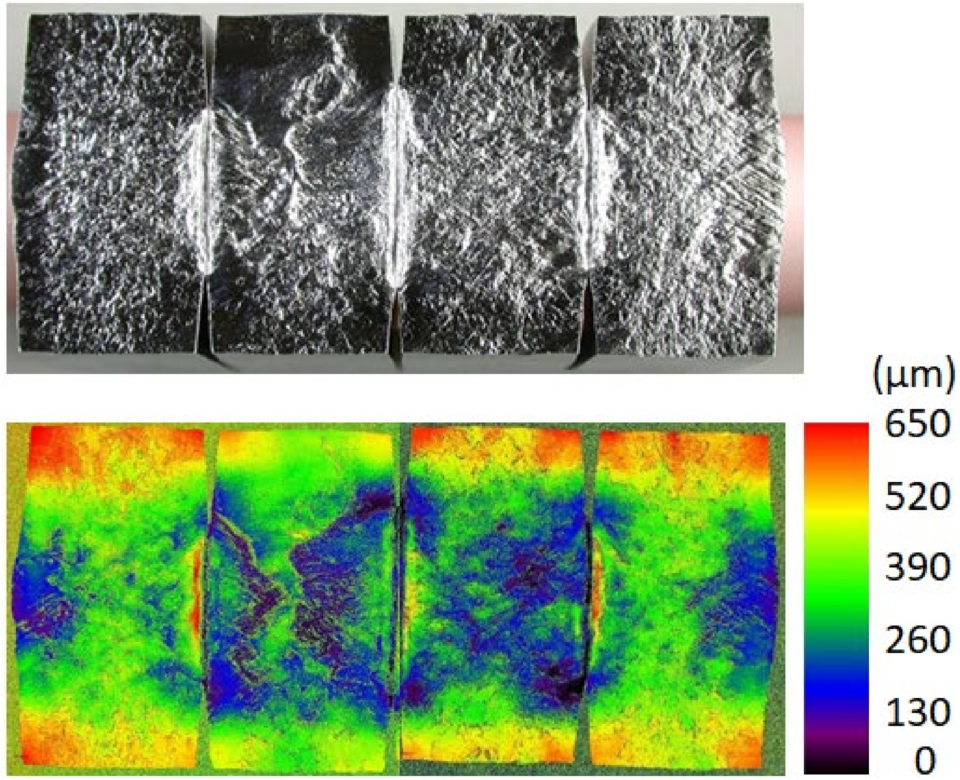


Block width: 23 mm
Armor thickness: 8 mm
Block thickness: 12 mm

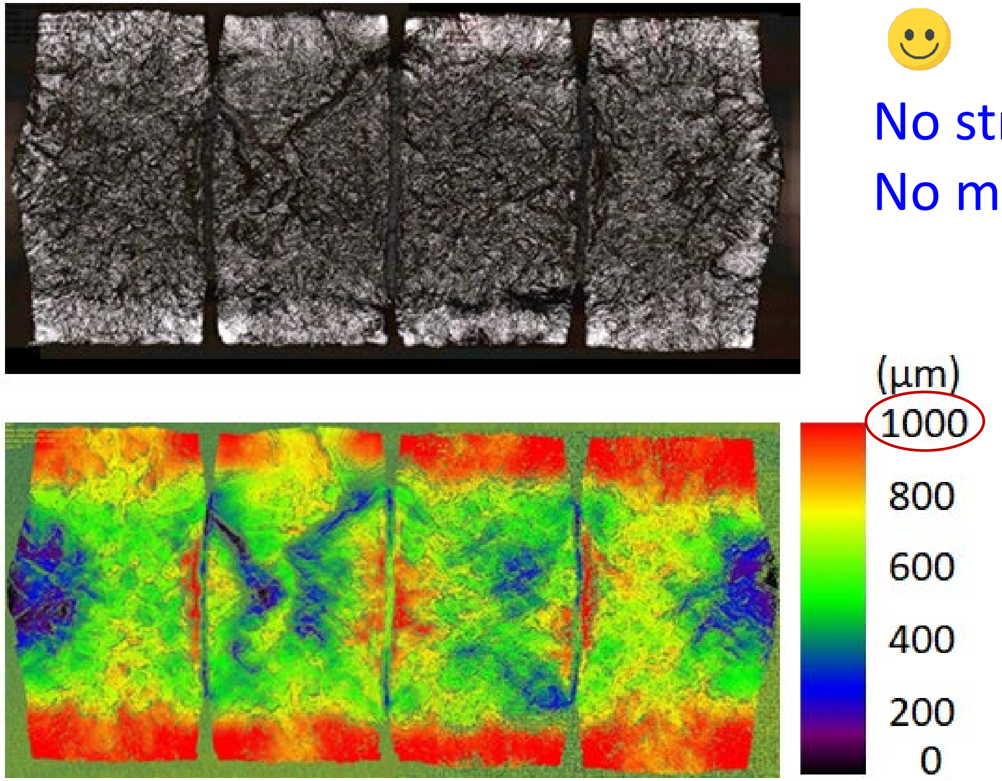
J.H. You et al., Journal of Nuclear Materials (2021)

High-heat-flux performance: 25 MW/m² (ITER-like target mock-up)

25 MW/m², 500 cycles (Coolant: 105 °C)



25 MW/m², 1000 cycles (Coolant: 105 °C)



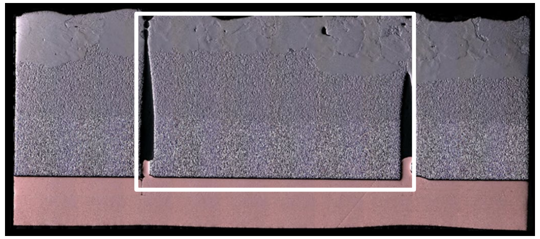
No structural failure
No major armor cracks

Neutral hydrogen beam, GLADIS facility (MPG-IPP)

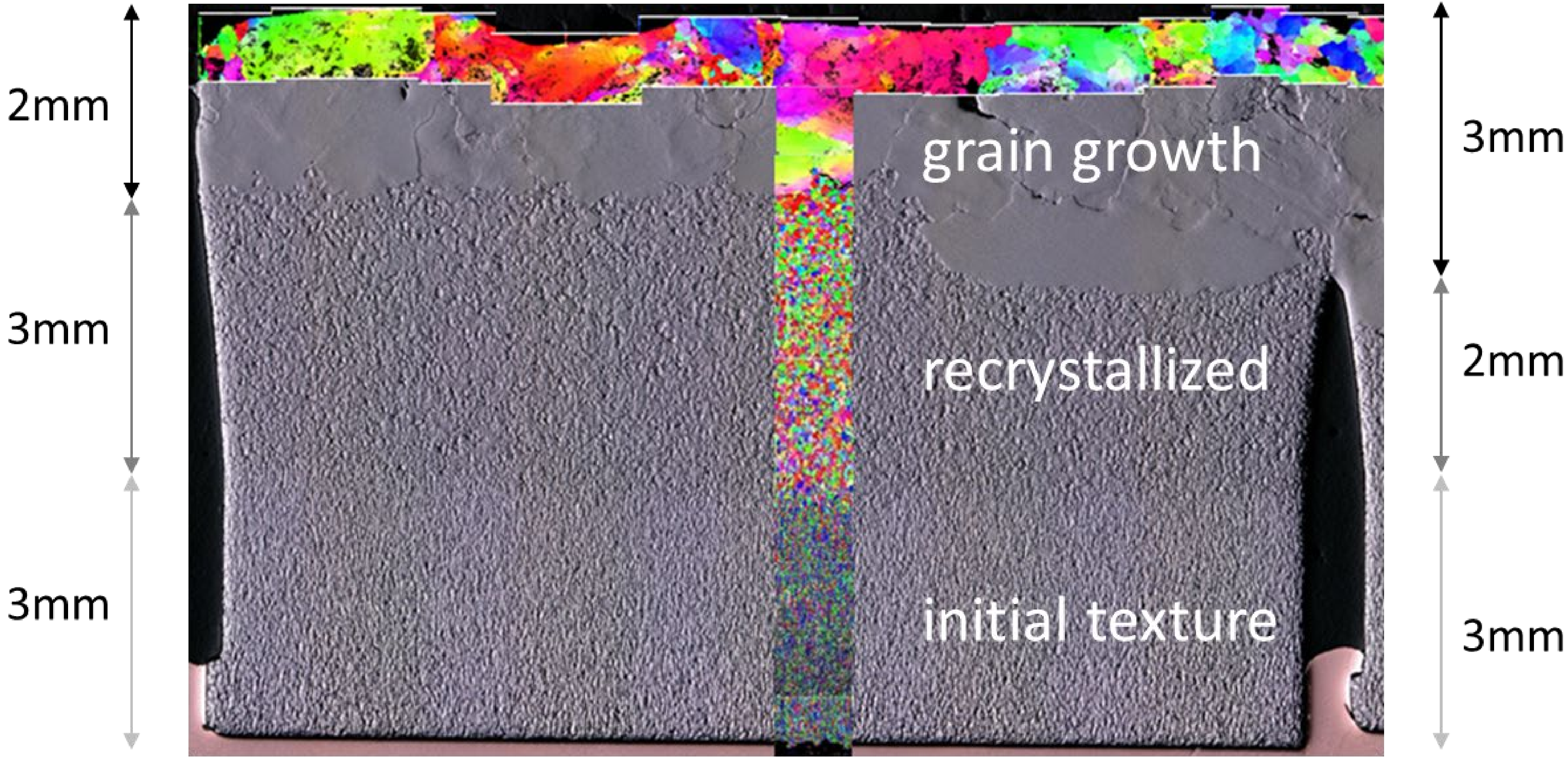
Severe surface damage
(Leading edge issue?)

J.H. You et al., NME (2022)

High-heat-flux performance: 25 MW/m²



Axial cut section of the tungsten armor
revealing microstructural change after 100-500 pulses



Conclusions & Outlook

Pre-CDA (2014-2020)

- The objectives mostly achieved delivering a feasible baseline design. 🙂
- Several outstanding design issues still remaining (revision in progress). 😐
- High-heat-flux technologies verified up to 20-25 MW/m^2. 🙂

CDA (2021-2027)

- Optimizing the baseline design, exploring alternative options.
- High-level requirements (w.r.t. R.A.M.I., costs, waste) as design driver.
- Technology R&D for the key components of the entire divertor

Thank you for your attention

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Divertor of the European DEMO: Engineering and technologies for power exhaust

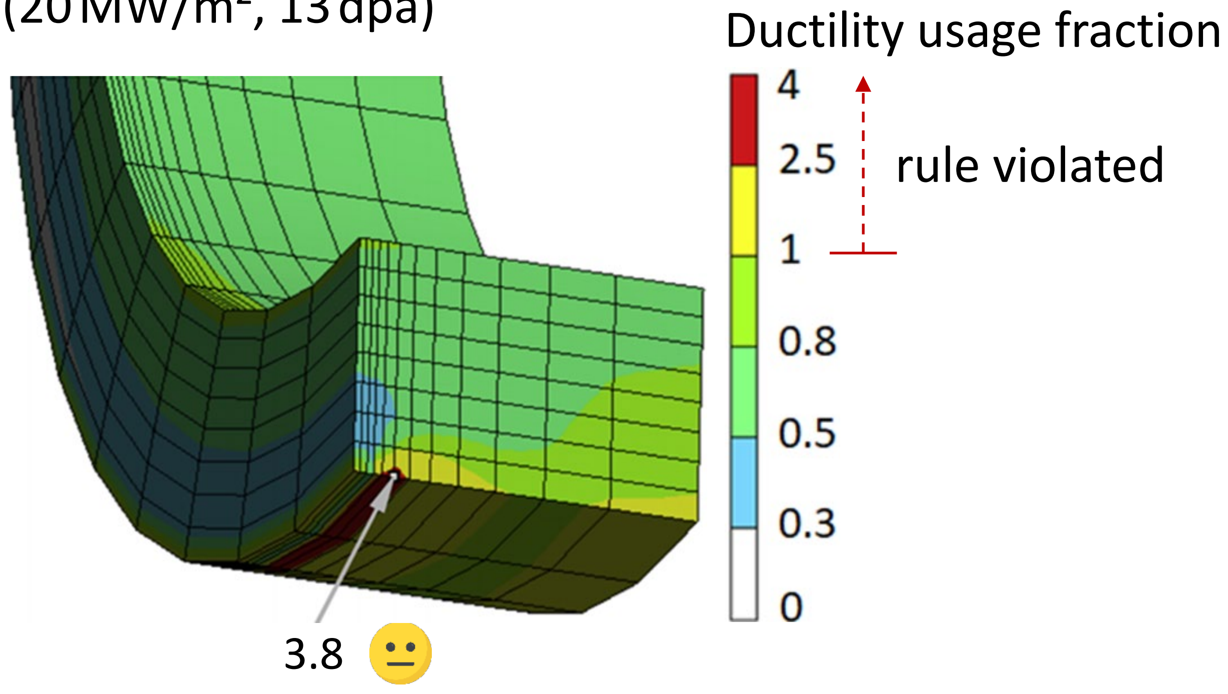
J.H. You[a,*], G. Mazzone[b], E. Visca[b], H. Greuner[a], M. Fursdon[c], Y. Addab[d], C. Bachmann[e], T. Barrett[c], U. Bonavolontà[f], B. Böswirth[a], F.M. Castrovinci[g], C. Carelli[c], D. Coccorese[f], R. Coppola[h], F. Crescenzi[b], G. Di Gironimo[f], P.A. Di Maio[g], G. Di Mambro[i], F. Domptail[c], D. Dongiovanni[b], G. Dose[j], D. Flammini[b], L. Forest[k], P. Frosi[b], F. Gallay[d], B.E. Ghidersa[l], C. Harrington[c], K. Hunger[a], V. Imbriani[f], M. Li[a], A. Lukenskas[c], A. Maffucci[i], N. Mantel[c], D. Marzullo[m], T. Minniti[c], A.V. Müller[a], S. Noce[j], M.T. Porfiri[b], A. Quartararo[g], M. Richou[d], S. Roccella[b], D. Terentyev[n], A. Tincani[o], E. Vallone[g], S. Ventre[i], R. Villari[b], F. Villone[p], C. Vorpahl[e], K. Zhang[a]

Back-up slides

Structural reliability: design issues (embrittled cooling pipe)

Exhaustion of ductility in the irradiated cooling pipe

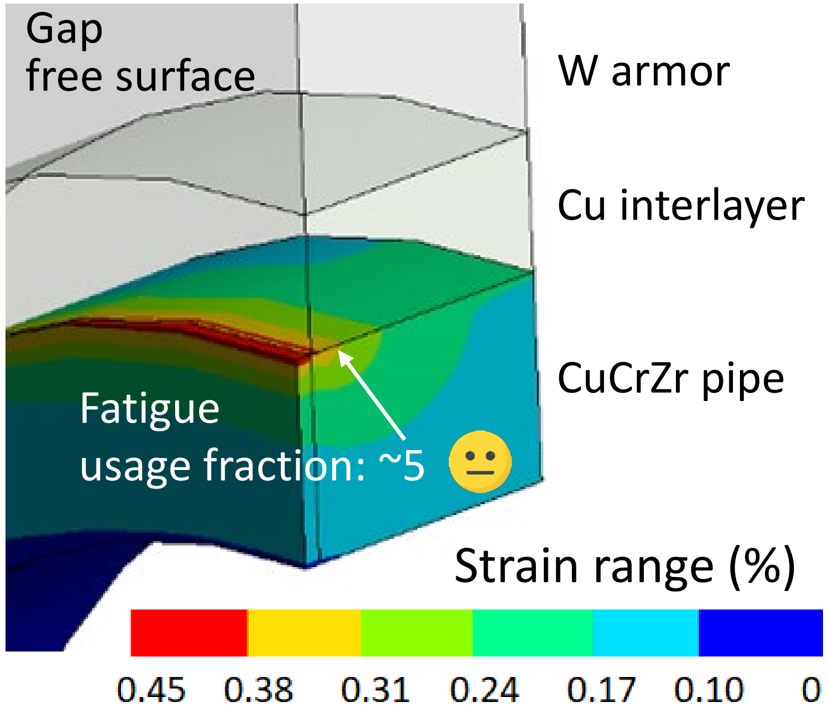
(20 MW/m², 13 dpa)

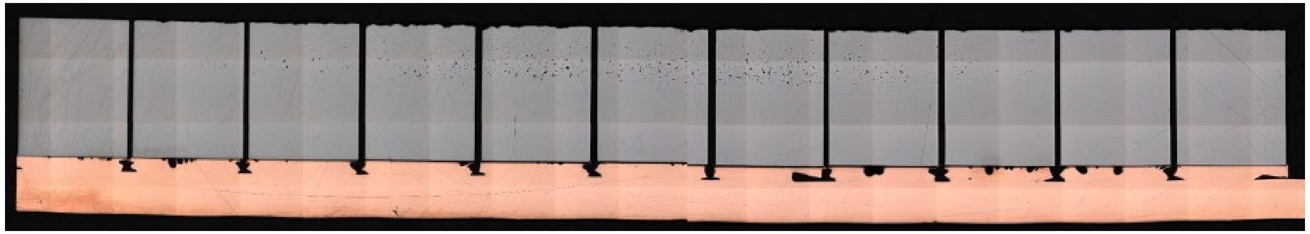


Embrittlement + Stress tri-axiality

Strain concentration in the cooling pipe

(10-20 MW/m², 13 dpa)

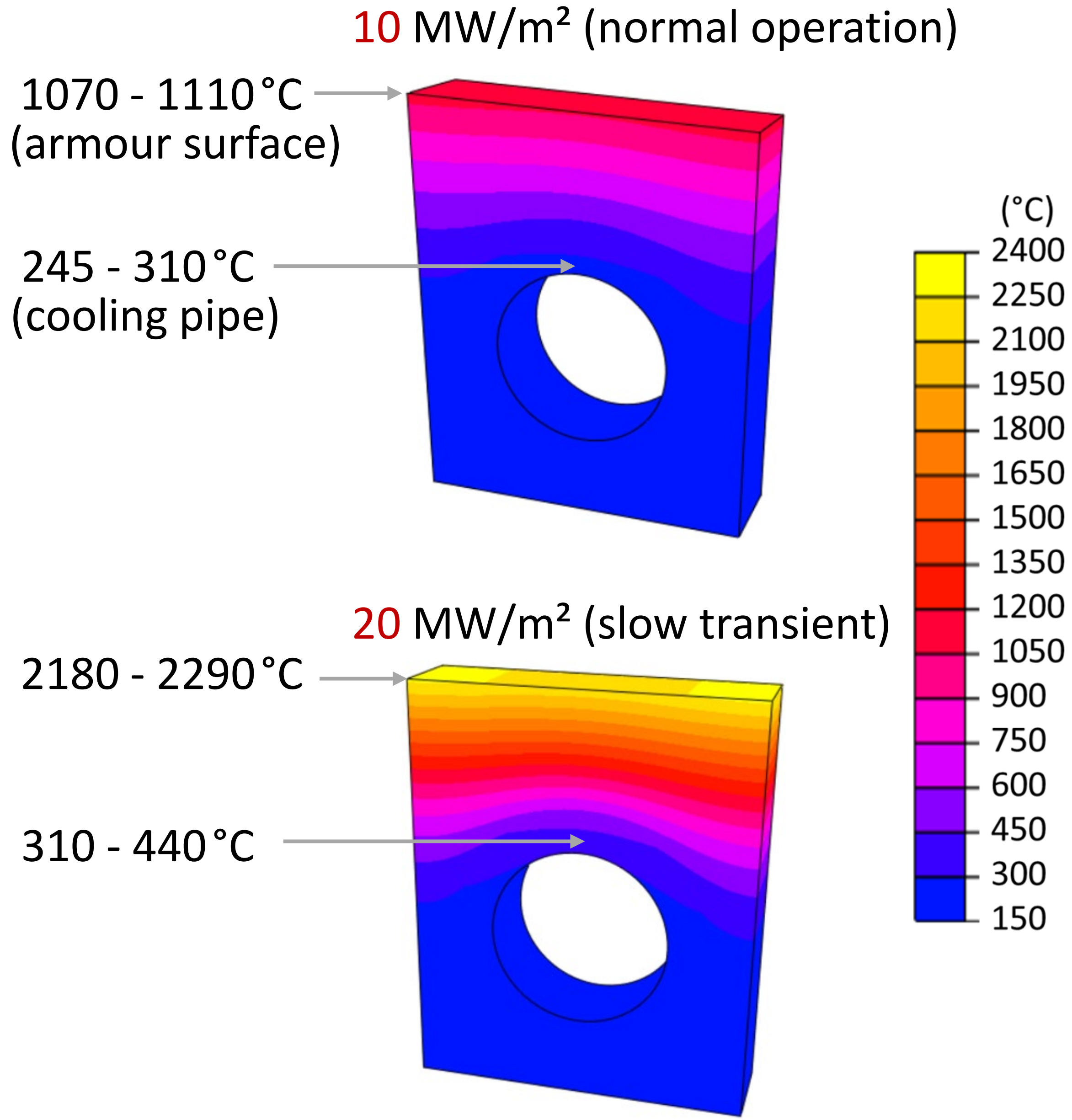




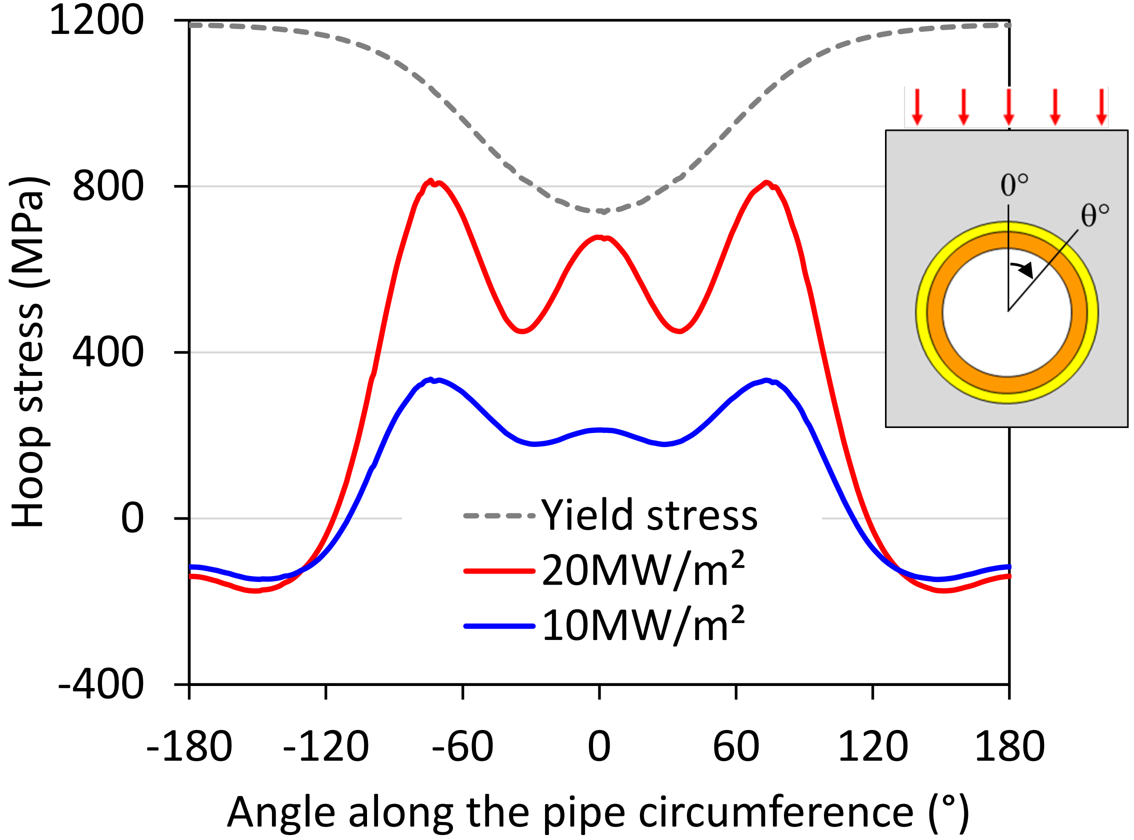
(20 MW/m², 500 pulses)

M. Fursdon, et al., FED (2020)

Temperature & stress profiles under HHF loads



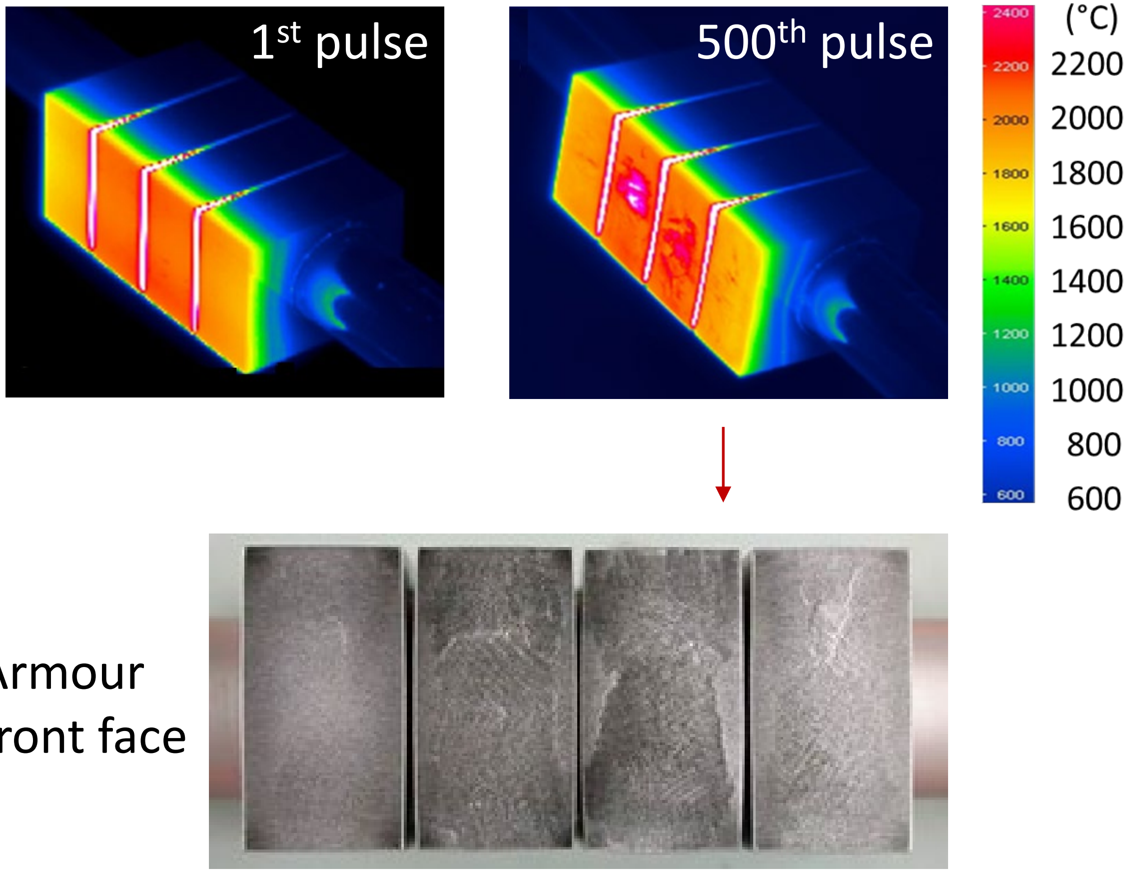
Thermal stress in the tungsten block along the bond interface to the Cu layer



K. Zhang, J.H. You, FED (2022)

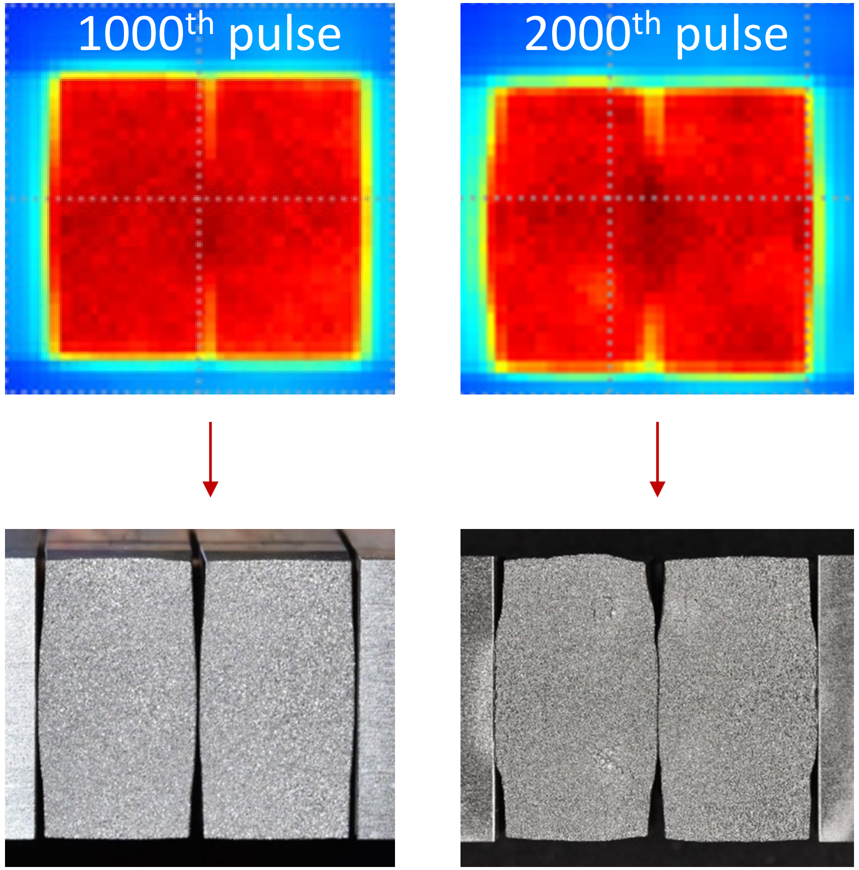
20 MW/m² (10s)

IR thermography (H beam irradiation)



Armour front face

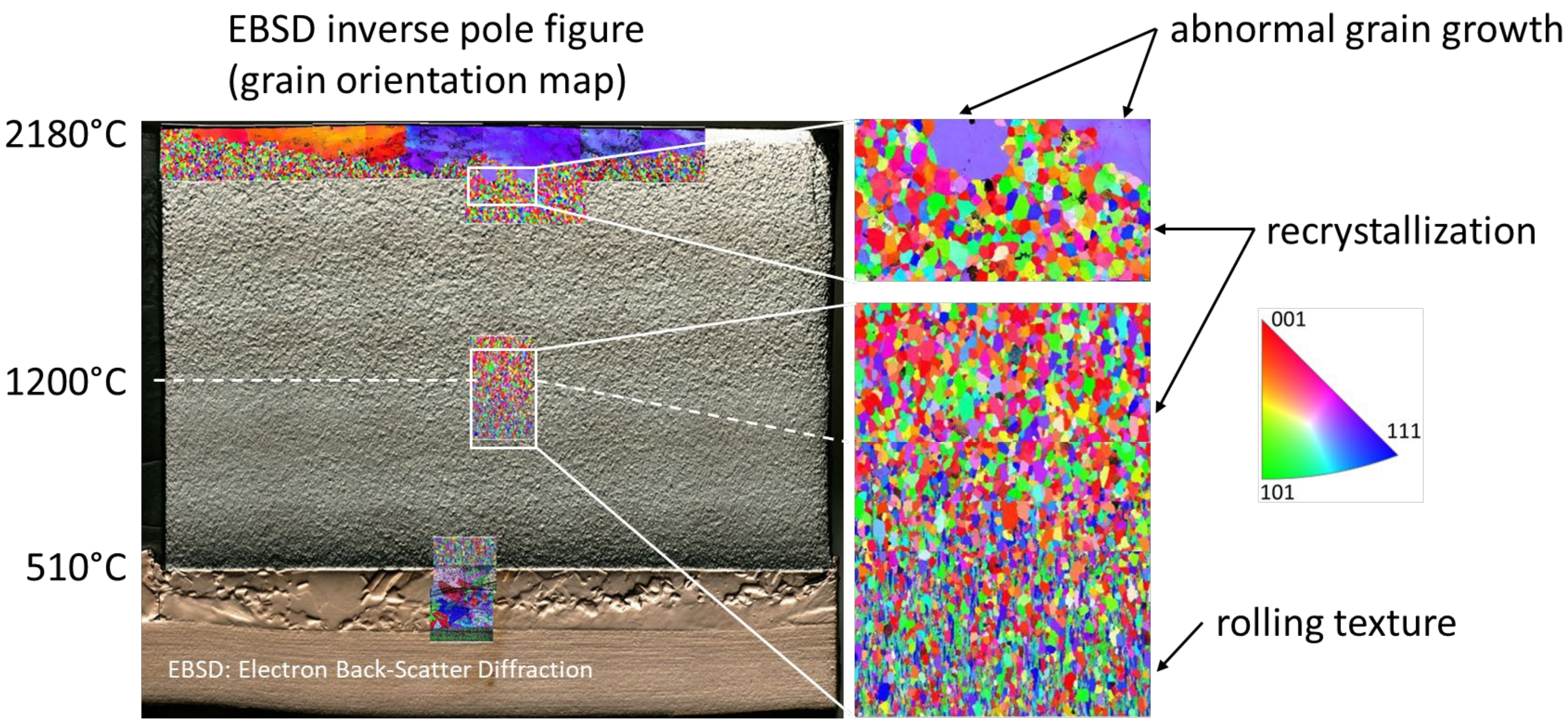
IR thermography (e beam irradiation)



- No crack found (in all 292 tested monoblocks)
- Structural integrity remained intact

J. H. You, et al. JNM (2021)

20 MW/m², 500 pulses



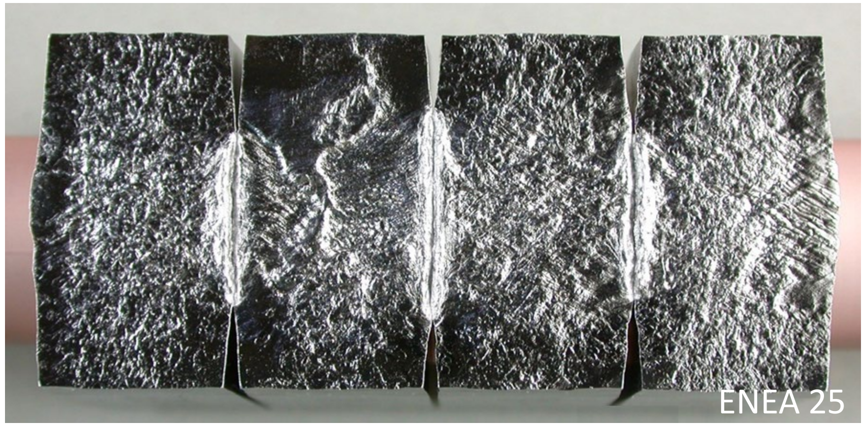
J.H. You, et al. JNM (2021)

- Irreversible microstructural change unavoidable regardless of metallurgy or grades
- Recrystallization or grain growth is not necessarily a cause of crack initiation

EBSD: Electron Back-Scatter Diffraction

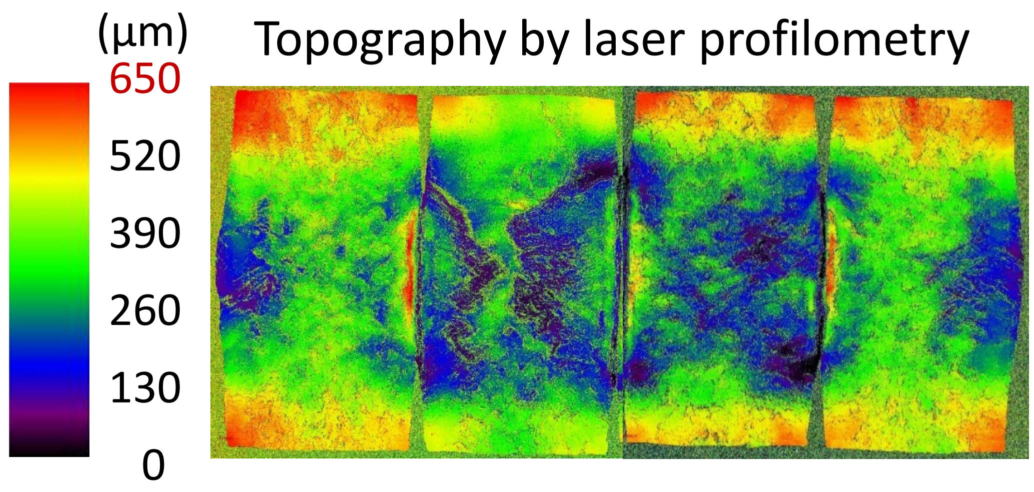
25 MW/m², 500 pulses

Surface roughening due to deformation

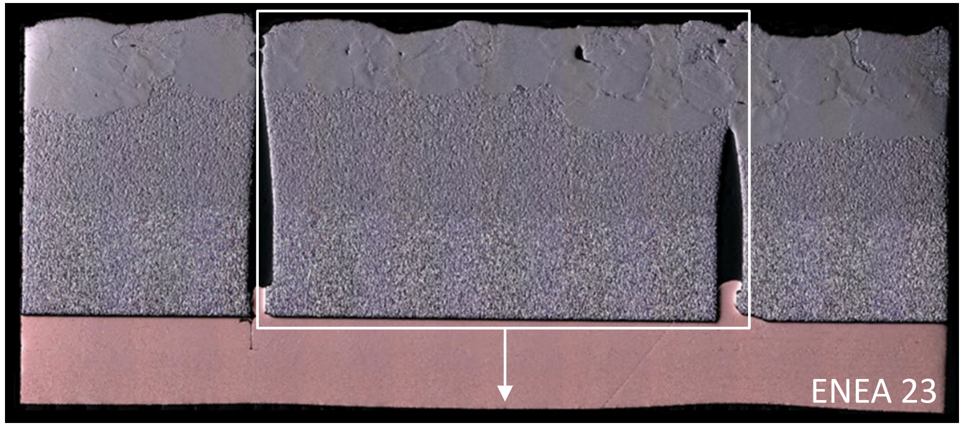


(coolant: 105 °C)

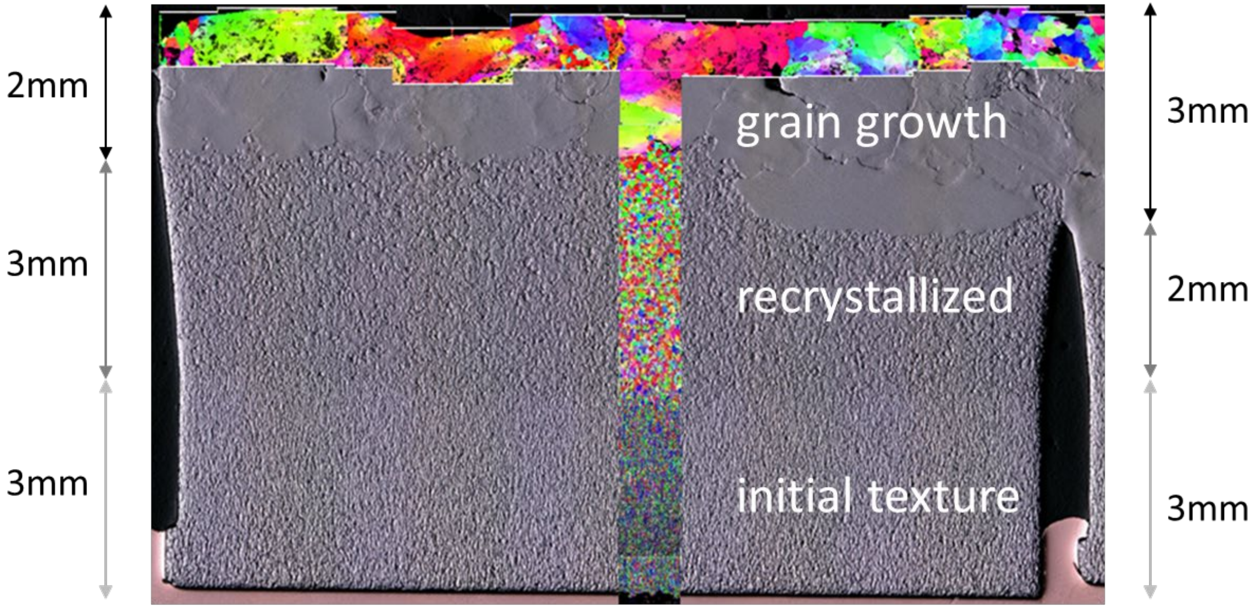
Topography by laser profilometry



Axial cut section revealing deformation

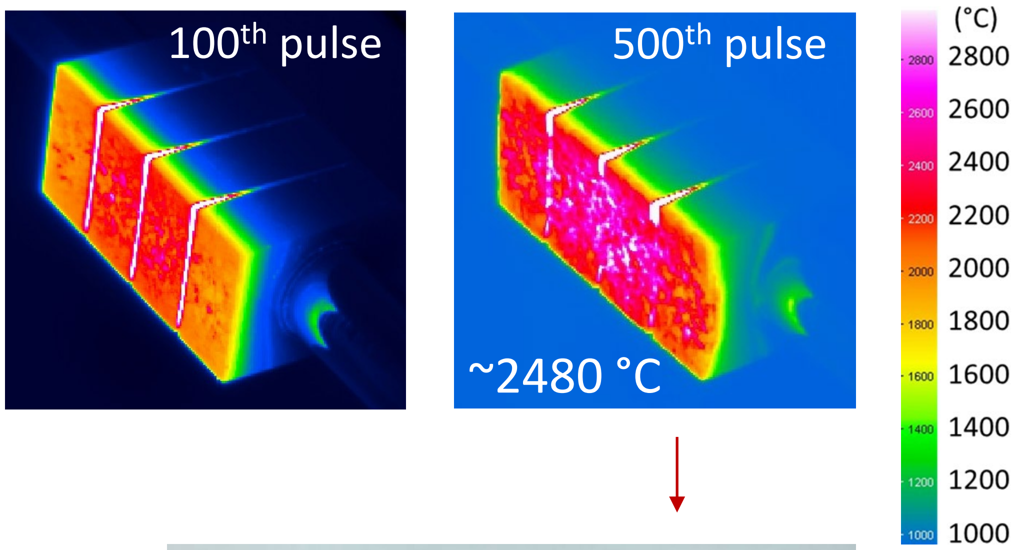


(coolant: 20 °C)

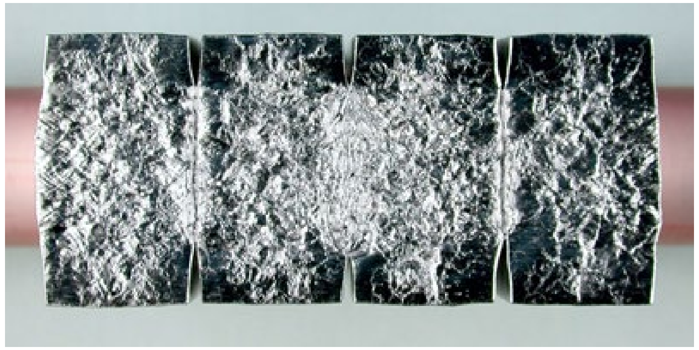


25 MW/m², 500 pulses (recently, extended to 1000 pulses)

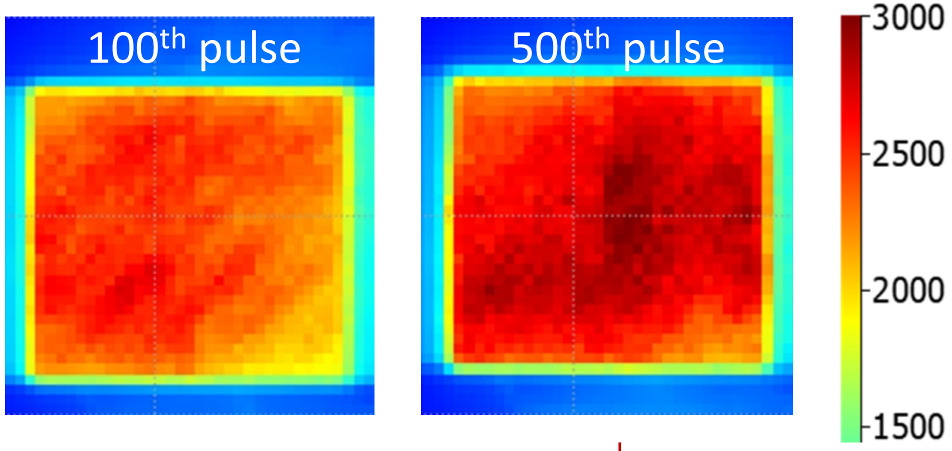
IR thermography (H beam irradiation)



Armour front face



IR thermography (e beam irradiation)

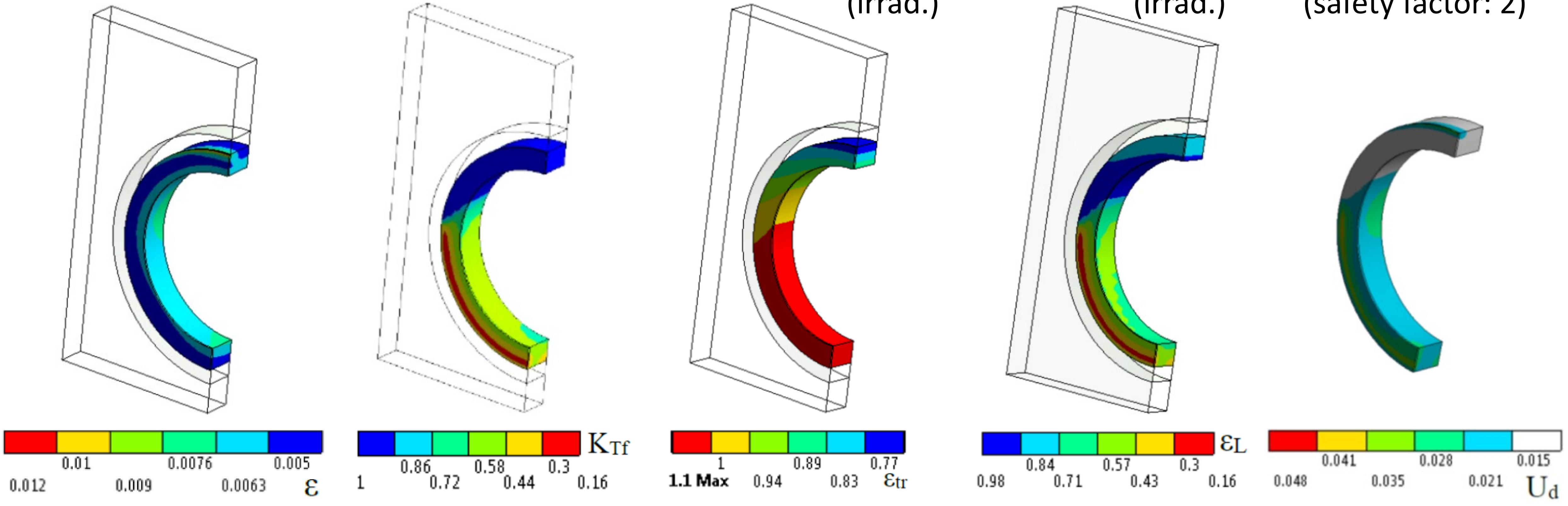


- Substantial visco-plastic surface damage
- Single fine crack was found, but the mock-ups remained intact
- Heat exhaust capacity was not affected

J. H. You, et al. JNM (2021)

Design by analysis: assessment procedure (*ex*: exhaustion of ductility)

Strain | Tri-axiality factor | True strain at rupture (irrad.) | Actual limit strain (irrad.) | Ductility usage fraction (safety factor: 2)

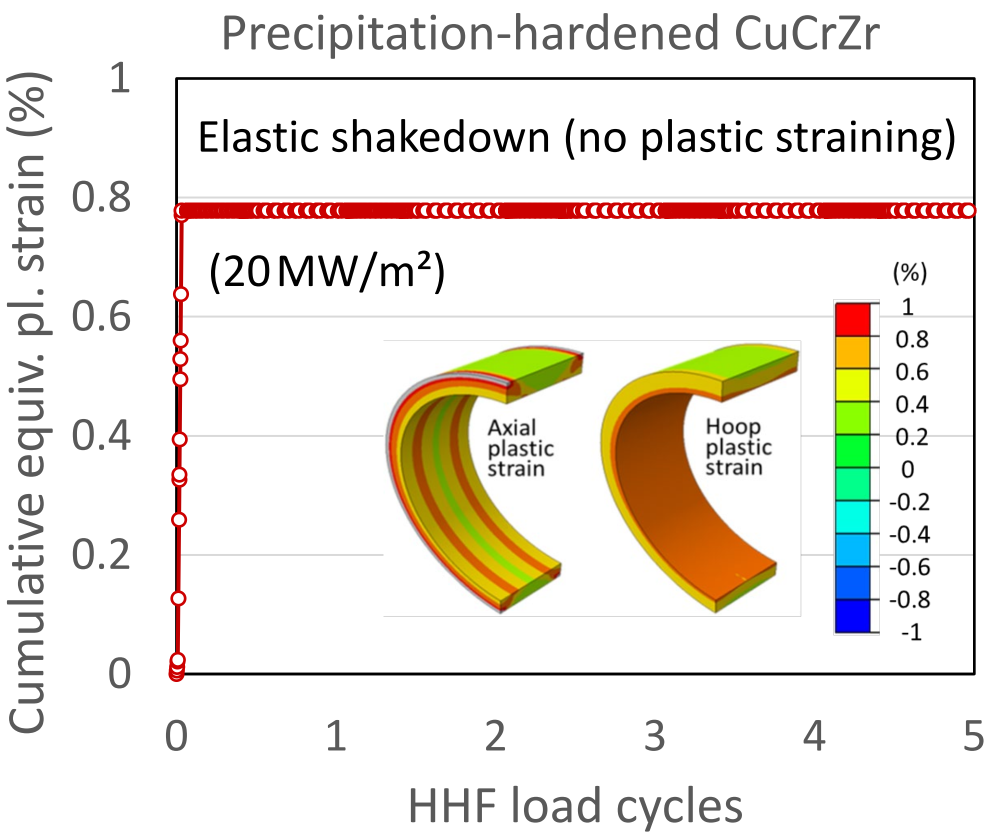


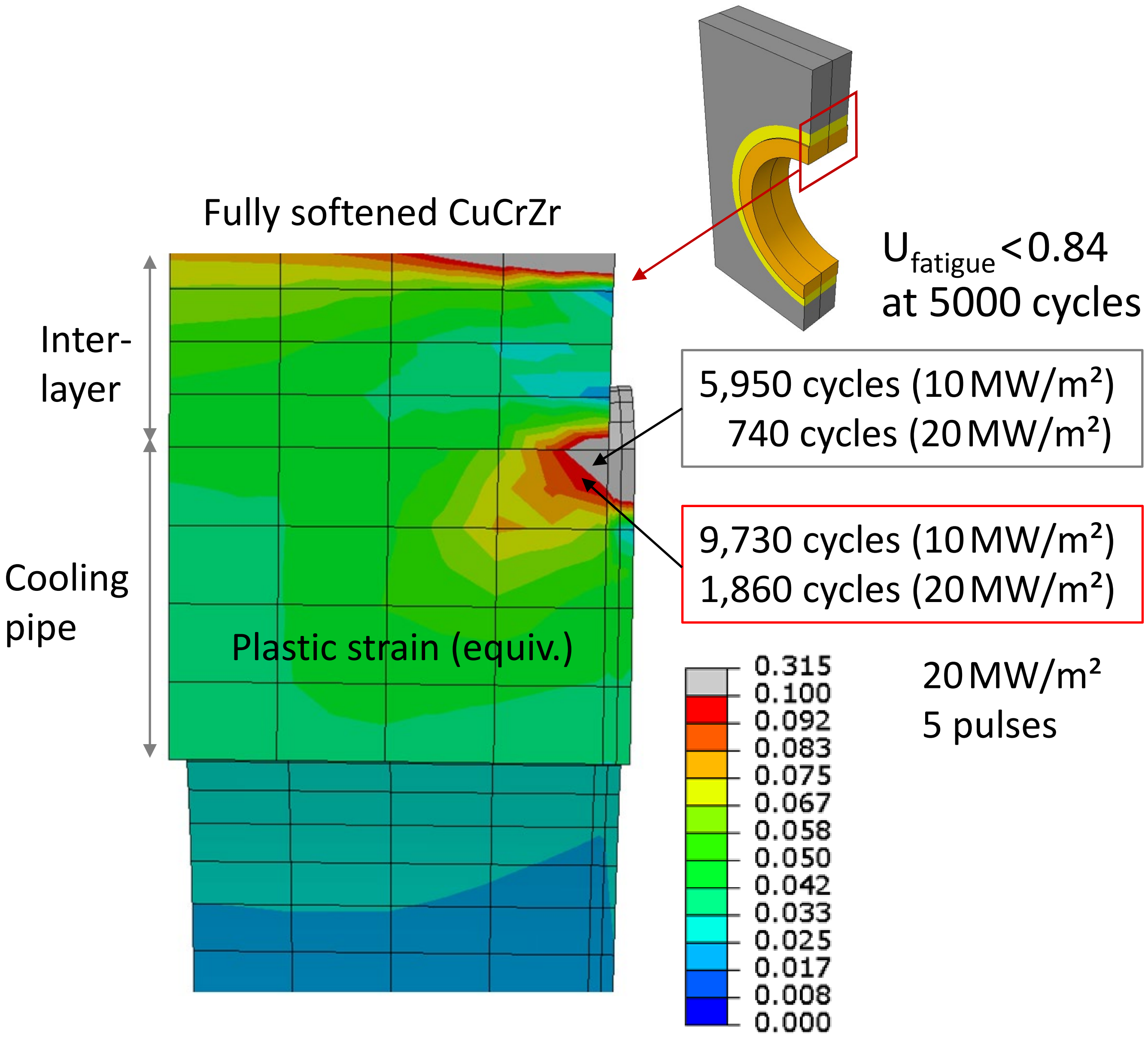
$$\varepsilon_L(T,\emptyset) = \varepsilon_{LU}(T,\emptyset) * Ktf\ (T)$$

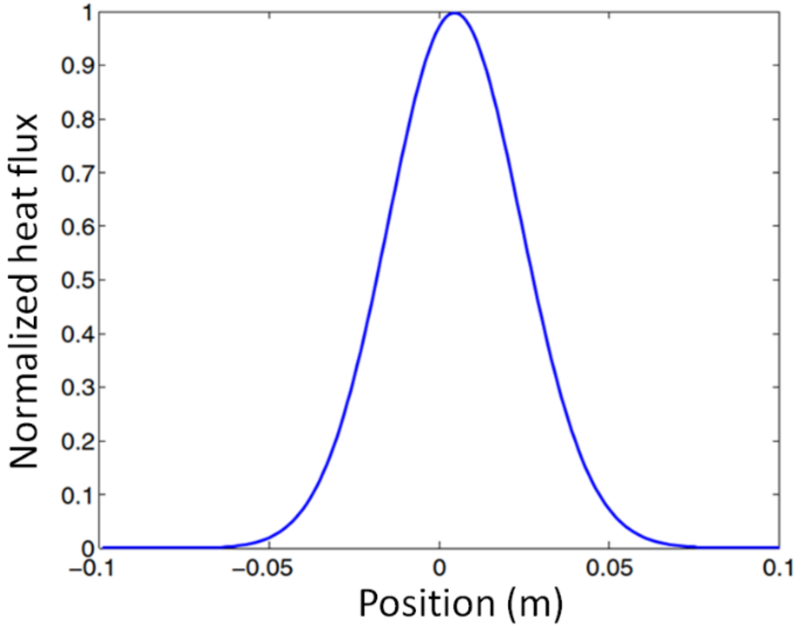
$$Ktf(T,\sigma) = exp\left(-\left(\frac{\alpha_{SL}}{1+m}\right)\left(\left\{\frac{\sigma_1+\sigma_2+\sigma_3}{3\sigma_{eq}}\right\}-\frac{1}{3}\right)\right)$$

failure at $U_d=1$

Design by analysis: fatigue of the cooling pipe (impact of thermal aging)



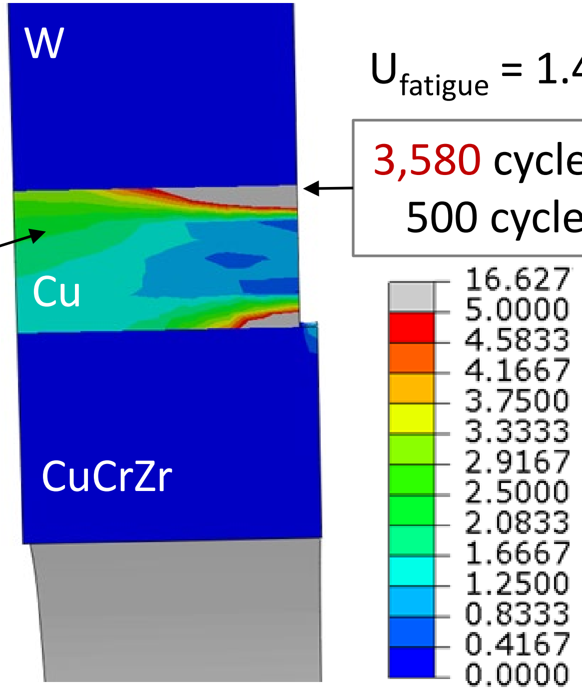




Normalized heat flux
Position (m)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
−0.1
−0.05
0
0.05
0.1

Design by analysis: fatigue & ratchetting of the interlayer (free-edge effect)

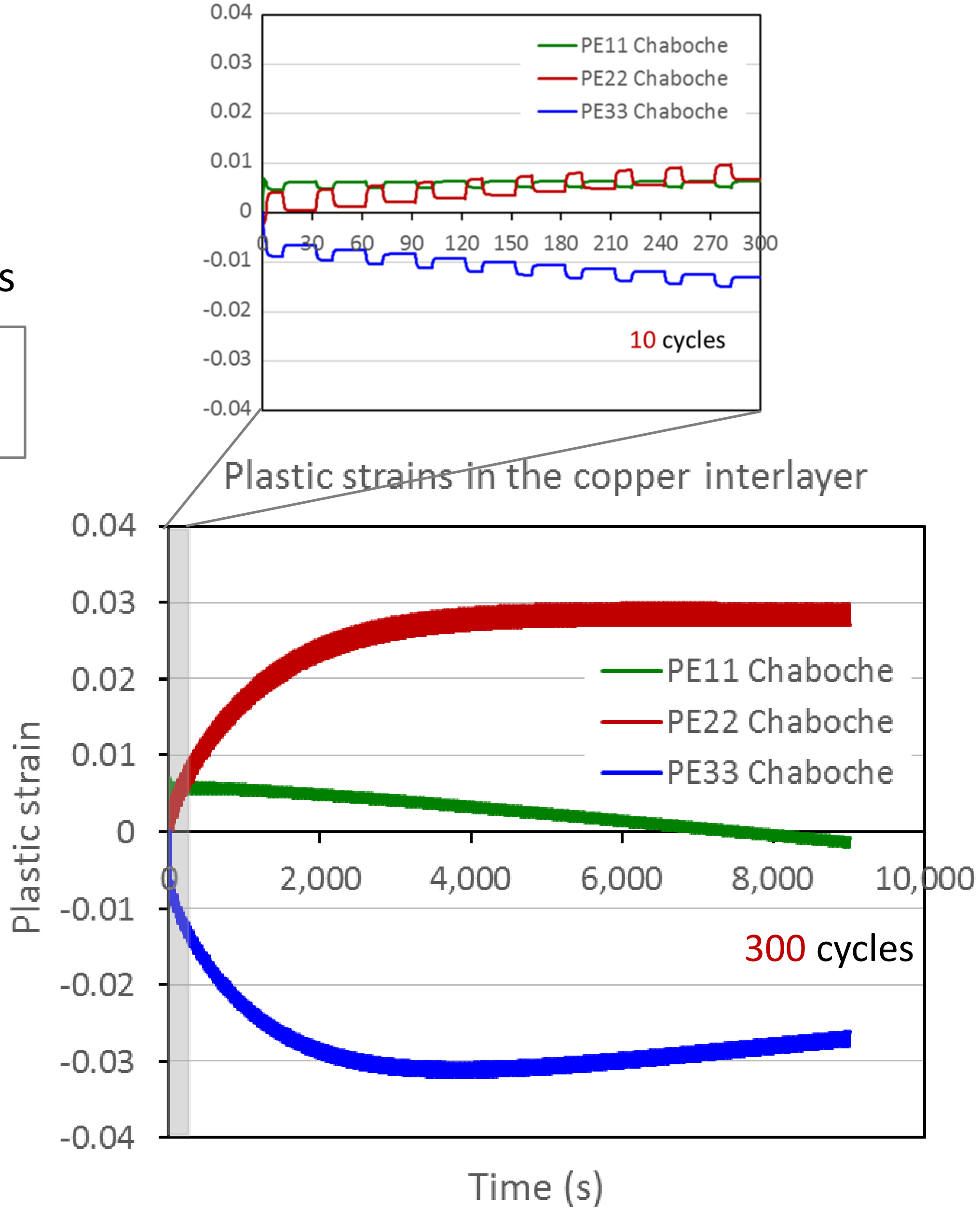
Accumulated plastic strain
(300 cycles at 20 MW/m²)



$U_{fatigue}$ = 1.4 at 5000 cycles

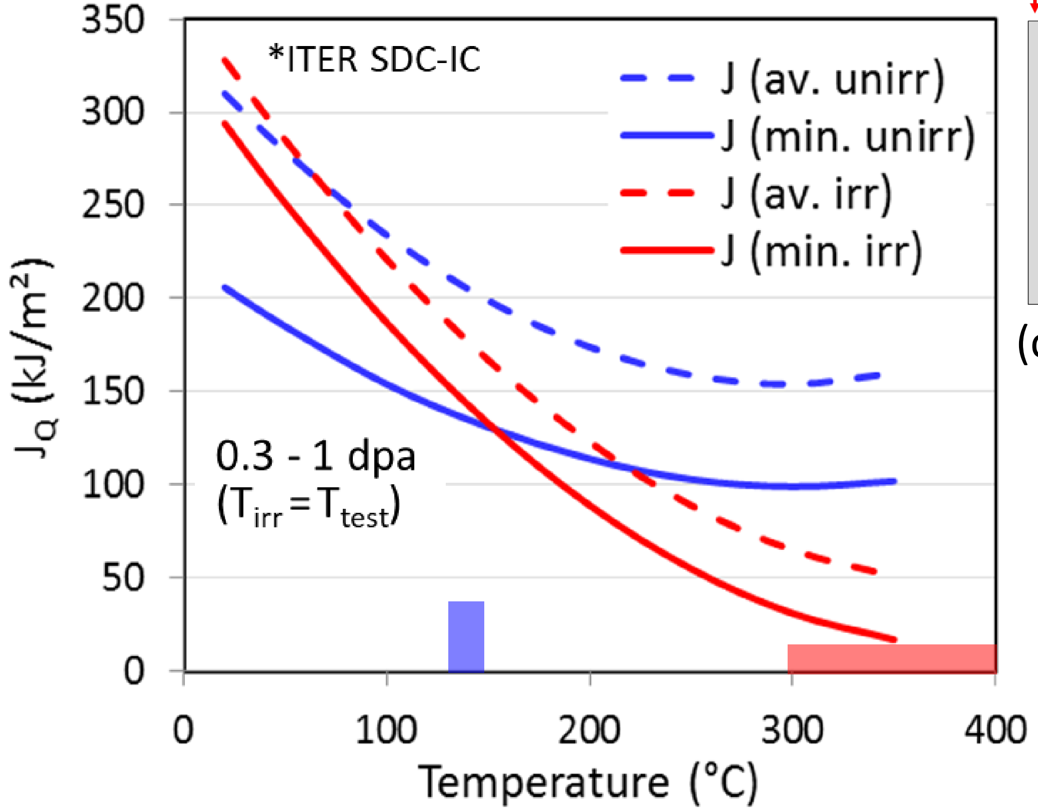
3,580 cycles (10 MW/m²)
500 cycles (20 MW/m²)

26,570 cycles (10 MW/m²)
5,000 cycles (20 MW/m²)



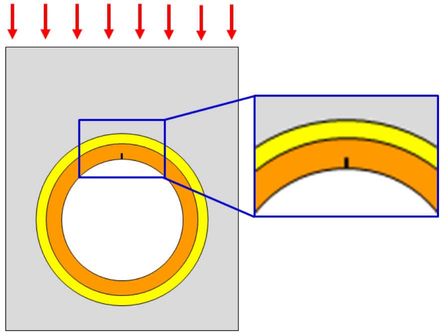
Design by analysis: fracture of the cooling pipe (impact of irradiation)

Crack tip fracture energy range



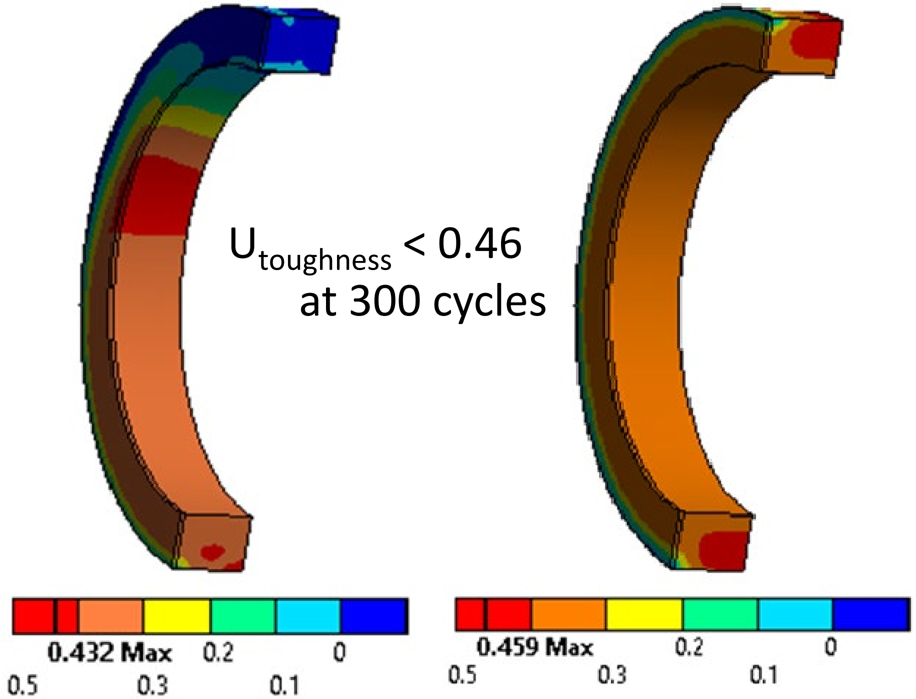
during cooling (150°C)

during operation (20 MW/m²)



(crack size: 0.5 mm)

Fracture toughness usage
(crack size: 0.2 mm, safety factor: 3)



HHF operation
(20 MW/m², 300 cycles)

during cooling
(150°C)