LOFA analysis for the FW of DEMO HCPB blanket concept

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First IAEA Technical Meeting (TM) on the Safety, Design and Technology of Fusion Power Plants

Vienna, Austria

3 - 5 May 2016

Institute for Neutron Physics and Reactor Technology (INR)

EUROfusion WPSAE project

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

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- **LOFA**
- **CFD simulation (ANSYS CFX)**
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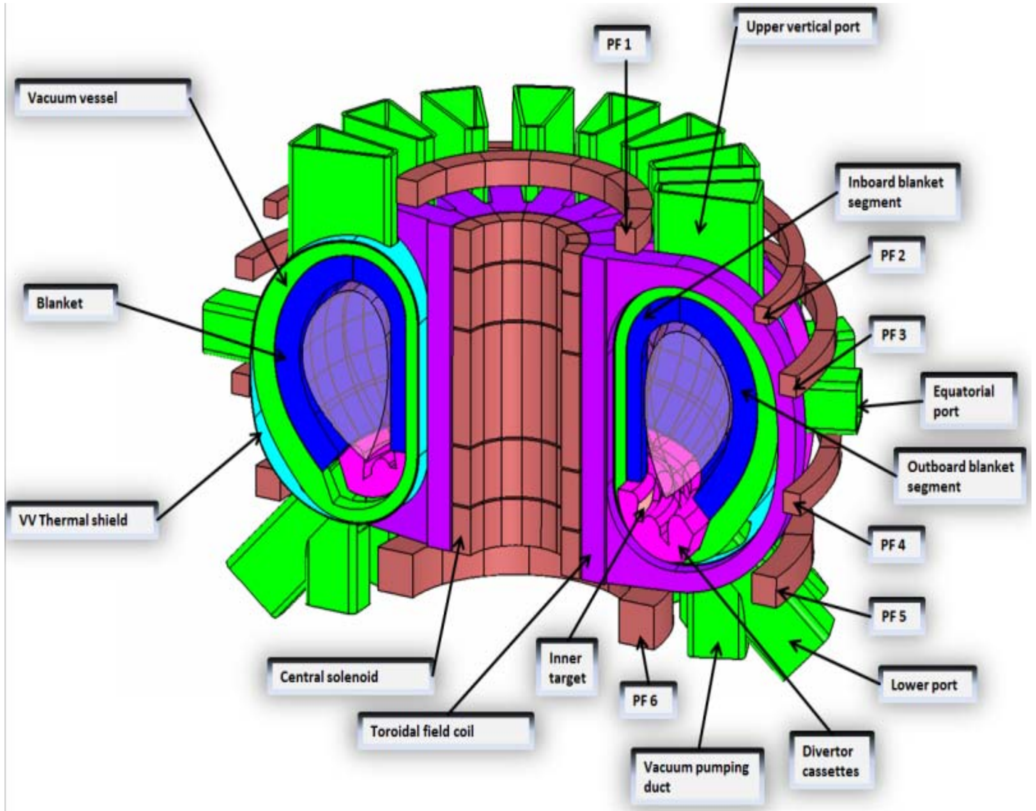
  - ❑ LOFA scenarios and results
- **Simulation with system code**
  - ❑ RELAP5-3D
  - ❑ Modelling
  - ❑ Steady state
  - ❑ LOFA scenarios and results
- **Conclusion**

DEMO HCPB blanket concept (2014)

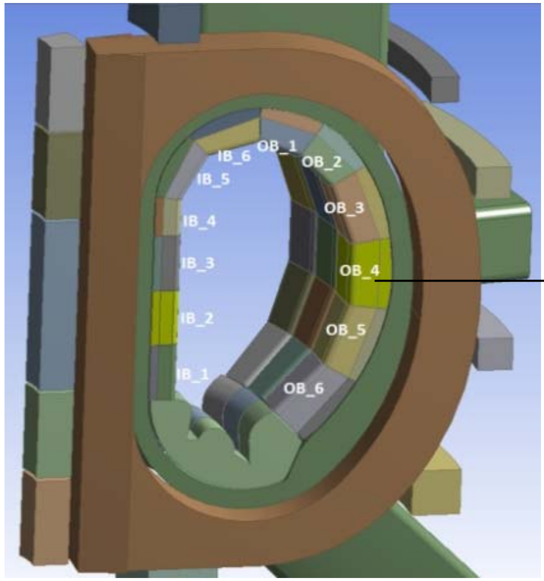


DEMO design 2014 *

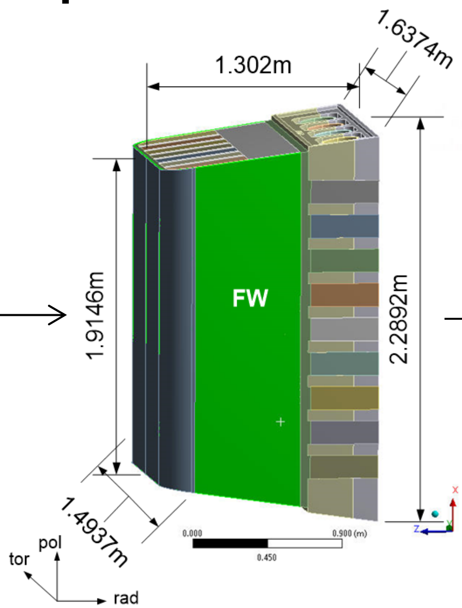
Parameter	Quantity
Plasma power (MW)	1572
Thermal power including n-multiplication in blanket (MW)	1972
Plant electricity output capability (MW)	500
Lifetime neutron damage in steel in the FW (dpa)	20+50
Major radius, R_0 (m)	9.0
Minor radius, a (m)	2.25
Plasma current (MA)	14
Toroidal field, B_0 at R_0 (T)	6.8
Elongation, κ_{95}	1.56
Triangularity, δ_{95}	0.33
Plasma volume (m³)	1453
Plasma surface area (m²)	1084
Auxiliary heating power, P_{inj} (MW)	50
Auxiliary ramp-up power, $P_{ramp-up}$ (MW)	>60
Average neutron wall load (MW/m²)	1.067
Nuclear heating in blanket (MW)	1380
Power to divertor (MW)	180

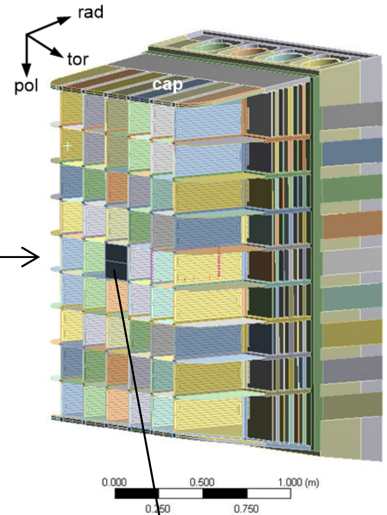
* *C. Bachmann: "Plant Description Document", Version 1.2, EFDA_D_2KVWQZ, 2014.*

HCPB blanket sector *



Equatorial module OB_4

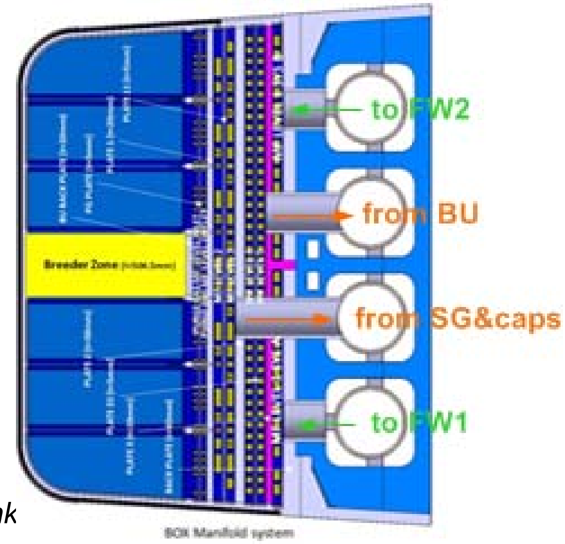


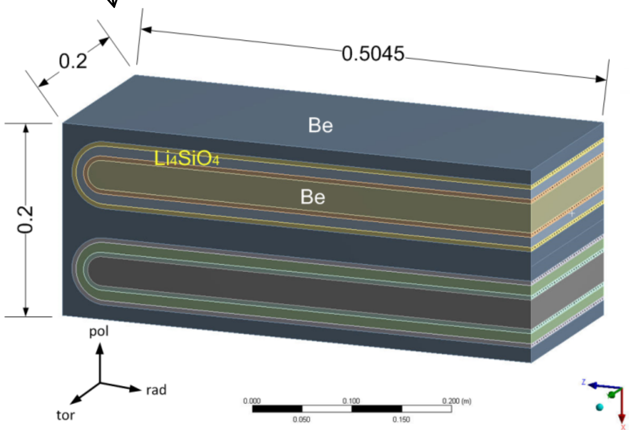


Stiffening grids (SG)

Each sector includes 2 IB and 3 OB segments with 6 modules for each segment (30 modules / sector)

Manifolds (MFs)

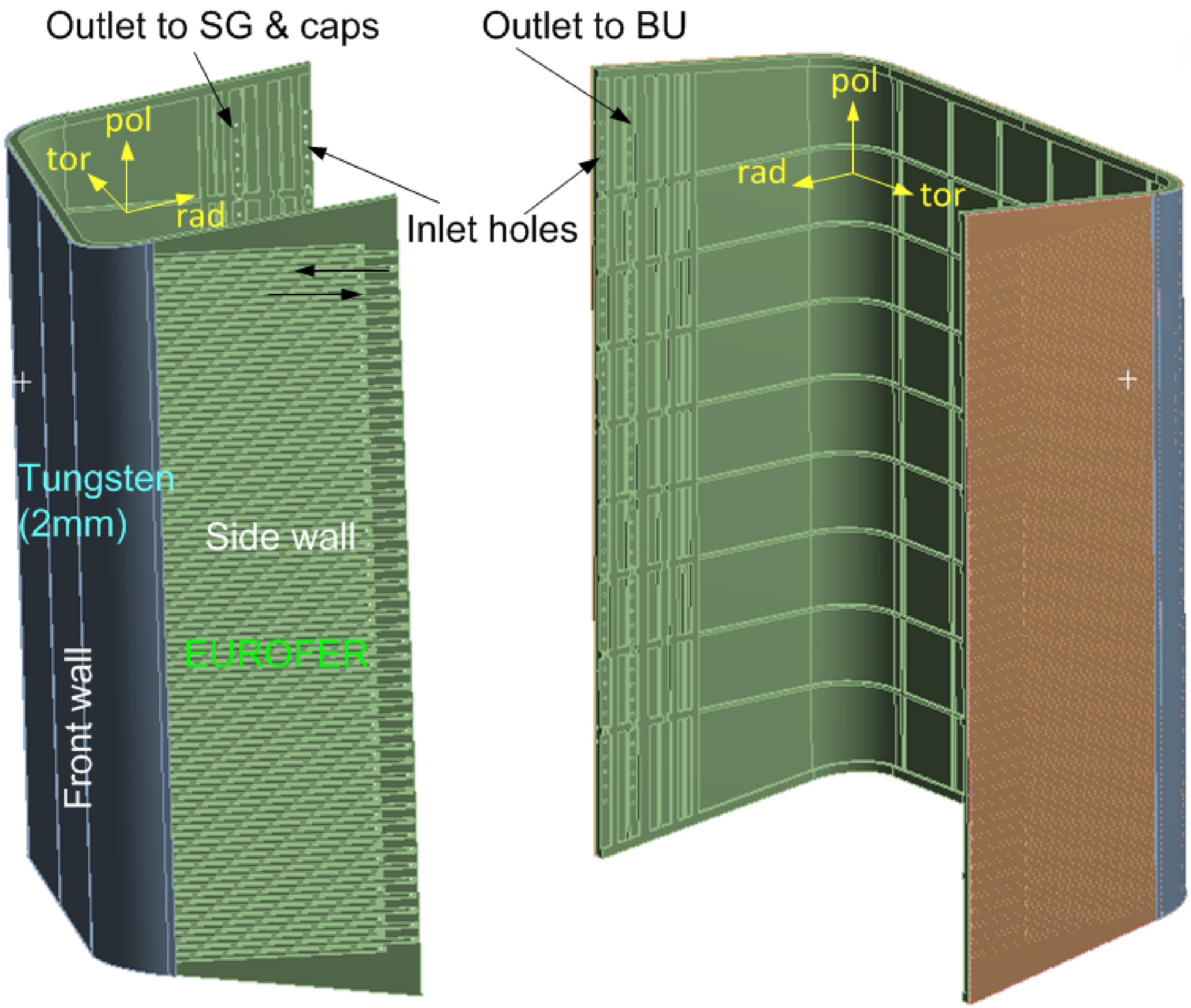




Breeder unit (BU)

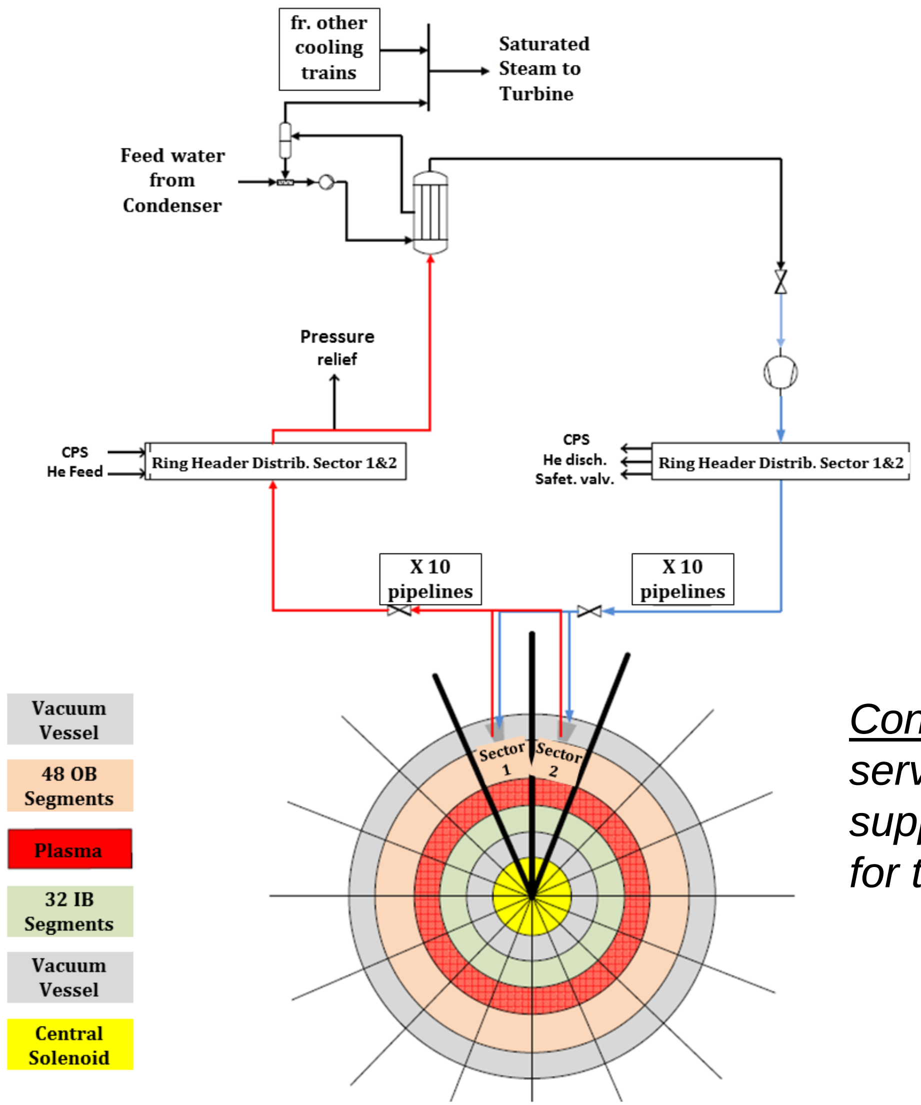
** EUROfusion WPBB (work package breeding blank*

FW of OB_4



95 FW channels:
47 (FW1) & 48 (FW2) in counter flow

Primary heat transport system (PHTS) *



Configuration 2014: *one PHTS loop serves 2 sectors. Each sector is supplied by 2 independent cooling loops for the redundancy.*

** EUROfusion WPBB*

Main design data of OB_4

Parameter		value
Fluid		He
Surface heat flux on the FW (MW/m²)	front wall	0.5
	BU to front wall	0.06
	BU to side wall	0.035
Neutron power (MW)		5.142
Mass flow rate $\dot{m}$ (kg/s)		6.323
Pressure at inlet (MPa)		8.0
Temperature (°C)	inlet	300
	outlet	500
Material	W thickness (mm)	2.0
	EUROFER to W (mm)	3.0
FW	Cross section (mm x mm)	15 x 10
	No. of channels	95

LOFA

Causes

- Circulator seizure
- Malfunction of valves
- Clogging in cooling channels
- Instrumentation & Control failure

↓

Possible consequences

- Increase of temperature and pressure in the blanket & PHTS
- Reaching the critical conditions of the materials
- Failure of the FW => in-vessel LOCA

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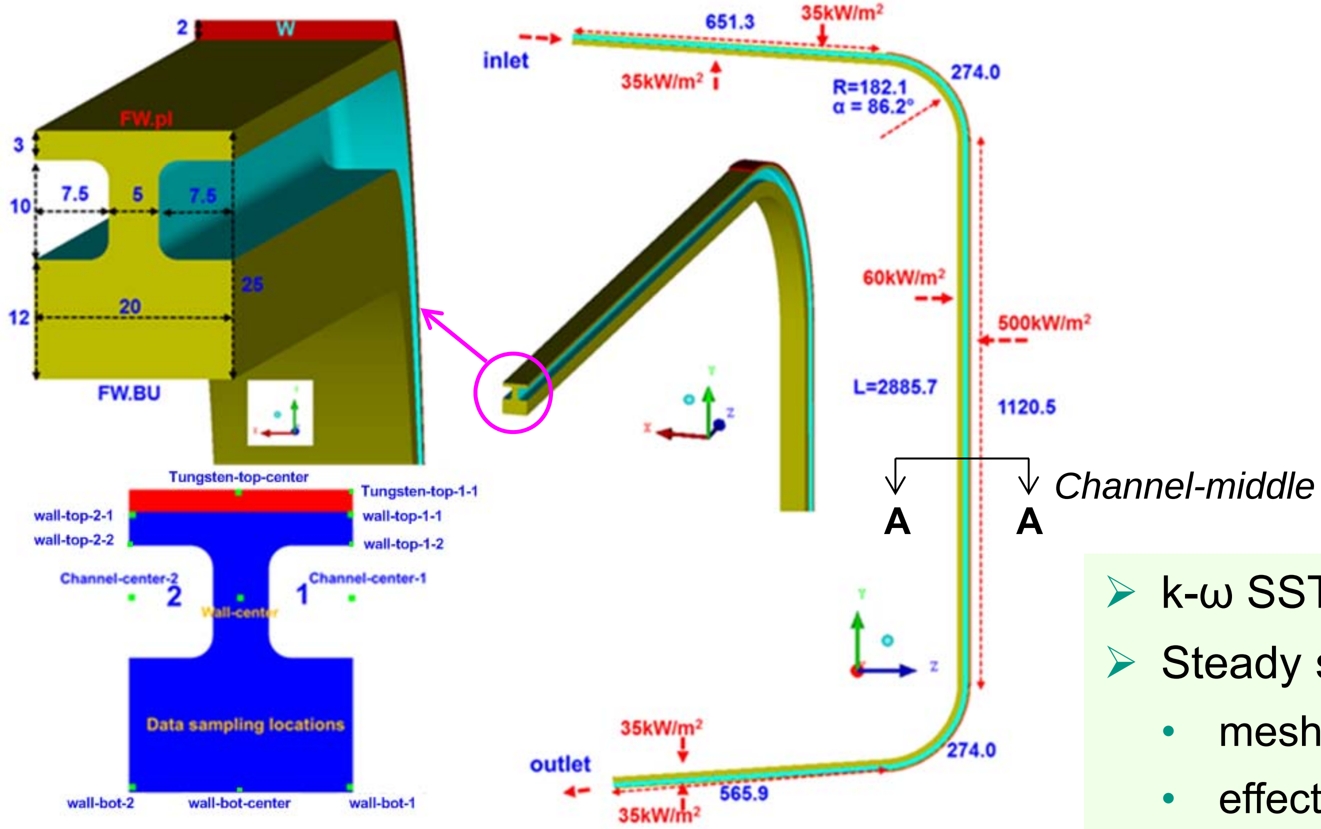
Mitigation

- Cooling circuit redundancy
- Circulator redundancy
- Plasma shutdown

CFD simulation (ANSYS CFX V15)

❑ FW channel geometry and numerical model



- k-ω SST model
- Steady state *
  - mesh sensitivity
  - effect of the surface roughness
- Coarse mesh (y+=14)
- Transient for LOFA

** Y. Chen: "Transient Analyses on The cooling channels of the DEMO HCPB blanket", Fusion Engineering and Design, in press, 2016.*

CFD simulation (ANSYS CFX V15)

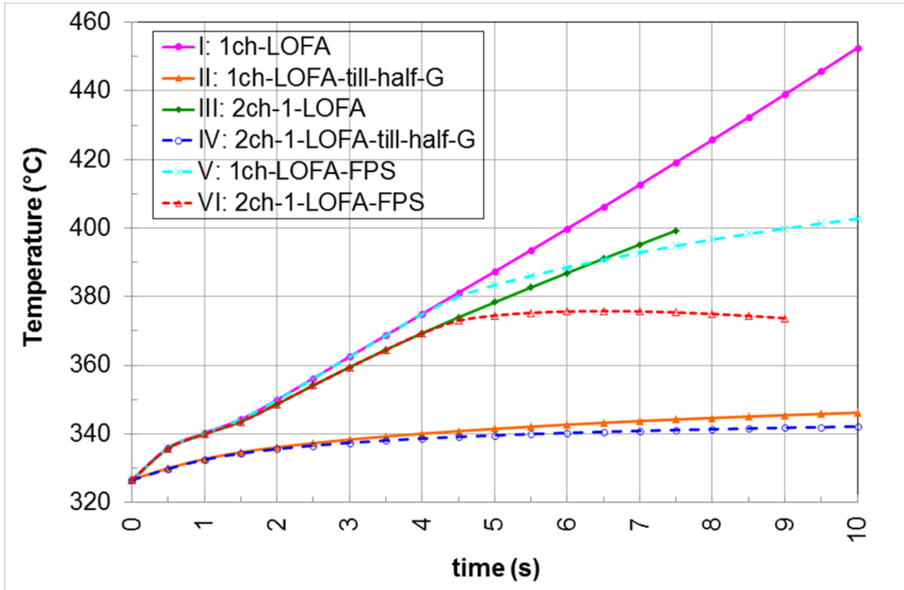
❑ LOFA scenarios

Scenarios (CFX)	Cooling circuit redundancy	Circulator redundancy	FPS	$\dot{m}$ (g/s) ($\dot{m}_0$ = 66.6 g/s)	Pressure decrease
I: 1ch-LOFA	no	no	no	$\dot{m}_0$ to 0	0.2MPa
II: 1ch-LOFA-till half G	no	yes	no	$\dot{m}_0$ to $G_0/2$	
III: 2ch-1-LOFA	yes	no	no	$\dot{m}_0$ to 0	
IV: 2ch-1-LOFA-till-half-G	yes	yes	no	$\dot{m}_0$ to $\dot{m}_0/2$	
V: 1ch-LOFA-FPS	no	no	yes	$\dot{m}_0$ to 0	
VI: 2ch-1-LOFA-FPS	yes	no	yes	$\dot{m}_0$ to 0	

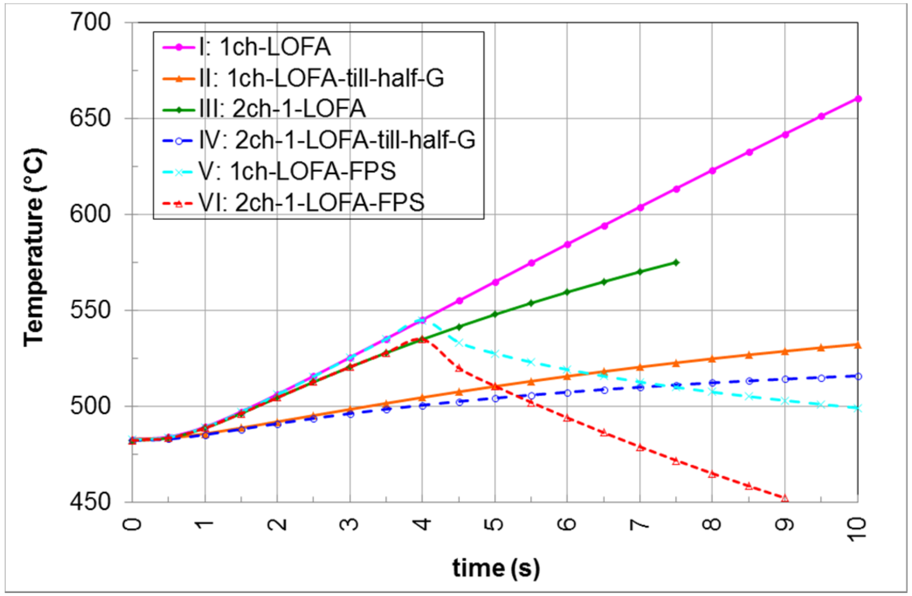
- *Fast plasma shutdown (FPS) is activated at 4s after the LOFA. Plasma disruption is not considered.*
- *The mass flow rate and inlet pressure are assumed to decrease exponentially,* at a pace $1/t^2$.

CFD simulation (ANSYS CFX V15)

- LOFA results



He temperature channel-center-1 (channel-middle)



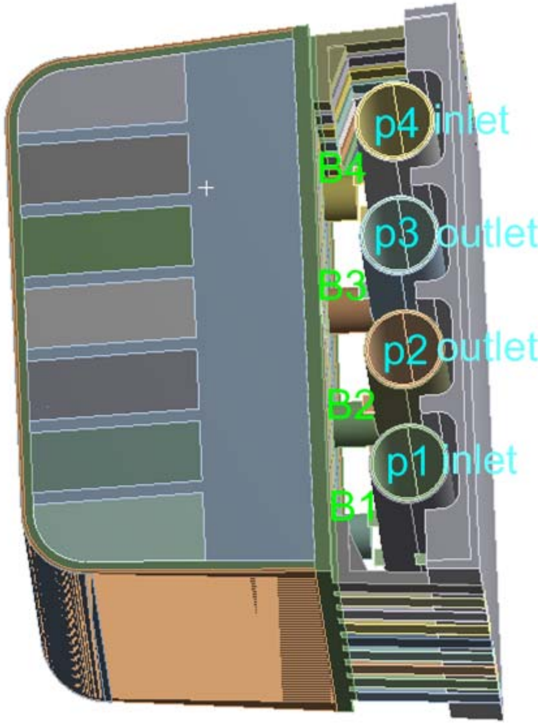
FW temperature wall-top-1-1 (channel-middle)

Simulation with system code

- RELAP5-3D (V4.2.1)
  - Best-estimate transient simulation of light water reactor coolant systems during postulated accidents
  - Cope with controlled steady state and cyclic operation
  - Model of gas compressor
  - Helium as working fluid
  - Modelling of all components (helium circulator, economizer, electrical heater, cooler, filter, piping, mixers, valves and the test section) in the cooling circuit and control mechanisms.
  - Application for ITER HCPB TBM, HCS, HELOKA-HP & -LP in normal operation & accidents.

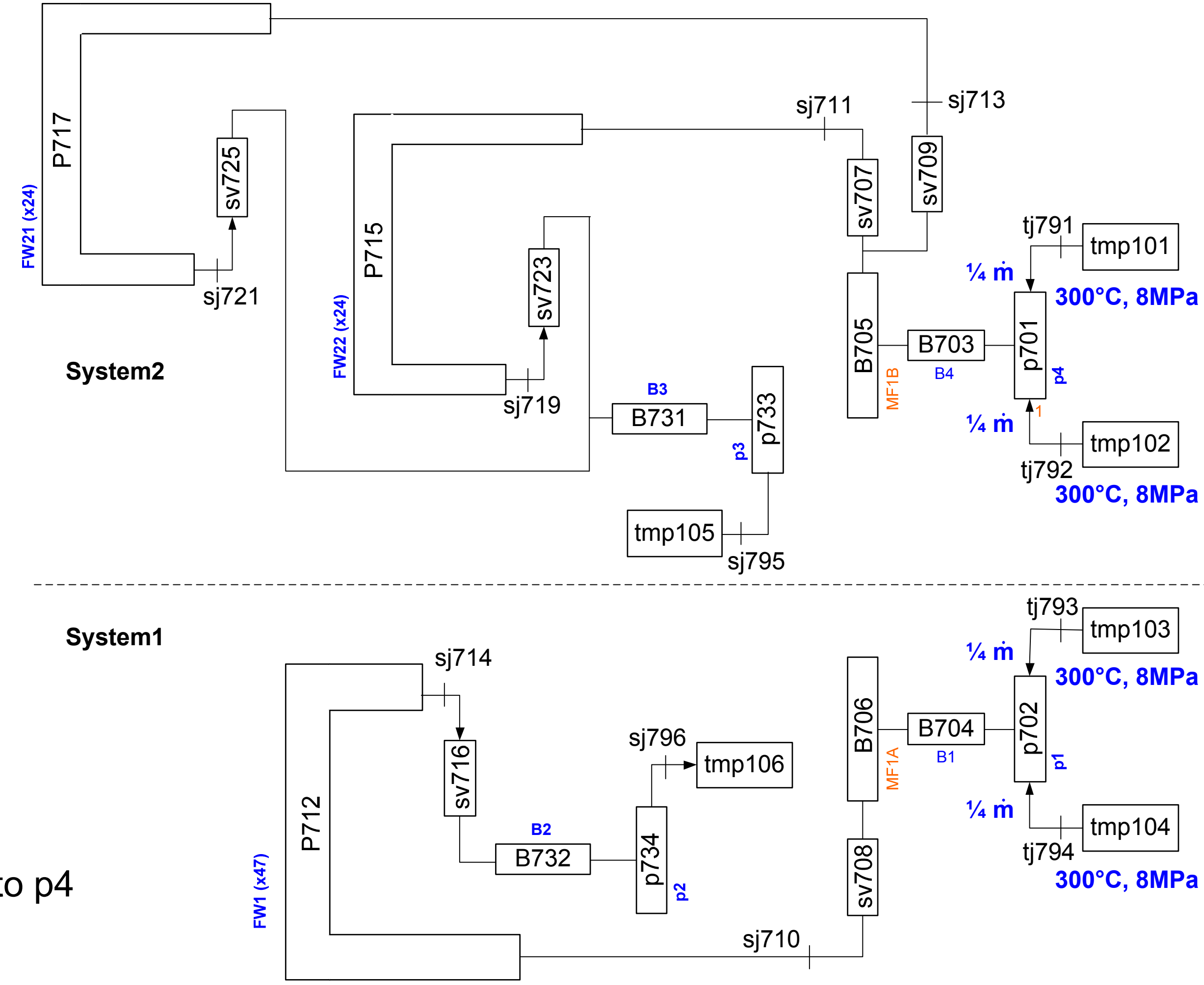
Simulation with system code

- ❑ Modelling



FW inlet: B1 connected to p1 & B4 to p4
SG&cap outlet: B2 to p2
BU outlet: B3 to p3

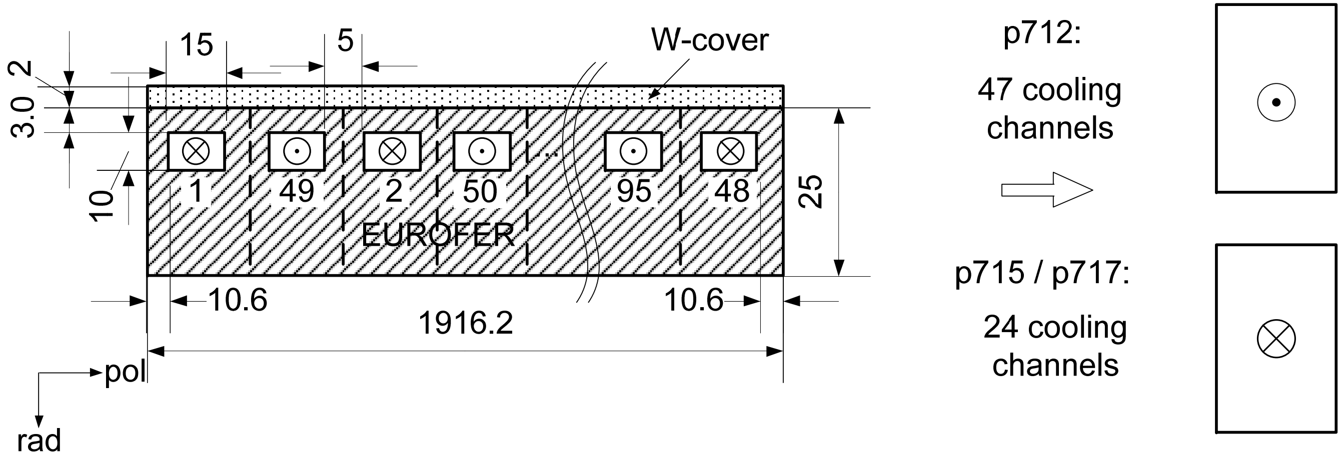
Inlets & outlets of module OB_4



Modelling in 2 systems

Simulation with system code

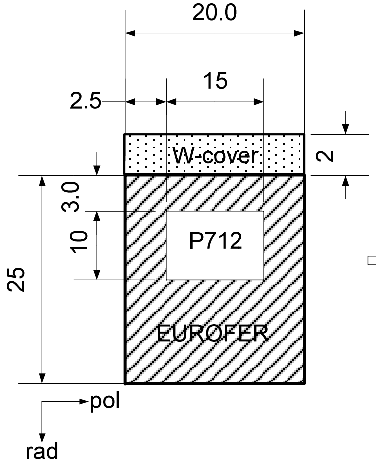
- Modelling



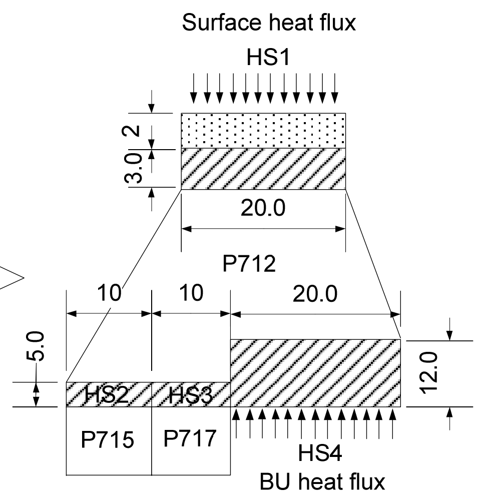
Cooling channels of the FW (dimensions in mm)

HS modelling for the front wall (dimensions in mm)

Surface heat flux, nuclear heating and decay heat assumed as 1.7% of the full power in the heat structure (HS) for the FW. Power ramps up to the full power within 60s.



Real unit cell



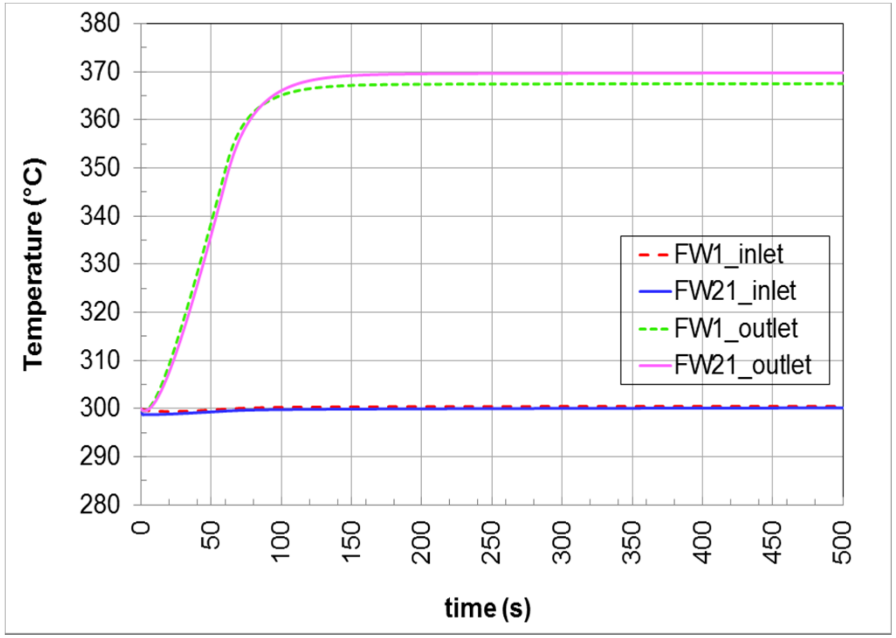
modelled unit cell

Simulation with system code

- ❑ Steady state (500s)

Parameter	RELAP5-3D		CFX single channel
	FW1	FW21	
T_outlet (°C)	367.5	369.8	370.1
T_FW (°C)	497.0	502.0	453.0
T_W (°C)	554.0	559.0	522.0
dp (MPa)	0.111	0.109	0.086
dp/L (MPa/m)	0.0375	0.0357	0.0374
V_outlet (m/s)	76.7	75.5	77.0
HTC_HS1 (W/m²K)	4254	4182	6166
Channel L (m)	*2.9529*	*3.0520*	*2.8857*

Comparison of the results at the steady state



He temperature

Simulation with system code

LOFA scenarios

<table>
<tr><th>Scenarios (RELAP5-3D)</th><th>Cooling circuit redundancy *</th><th>Circulator redundancy</th><th>Soft plasma shutdown</th><th>$\dot{m}$</th><th>Pressure decrease</th><th>HTC</th></tr>
<tr><td>A</td><td>yes</td><td>no</td><td>no</td><td colspan="3" rowspan="2">from scenario III (CFX)</td></tr>
<tr><td>B</td><td>yes</td><td>no</td><td>yes</td></tr>
<tr><td>C</td><td>yes</td><td>no</td><td>no</td><td>$\dot{m}_1$ to 0 within 1s</td><td>0.2MPa</td><td rowspan="5">calculated</td></tr>
<tr><td>D</td><td>yes</td><td>no</td><td>yes</td><td>$\dot{m}_1$ to 0 within 1s</td><td>0.2MPa</td></tr>
<tr><td>E</td><td>yes</td><td>yes</td><td>no</td><td>$\dot{m}_1$ to 50% within 1s</td><td>0.1MPa</td></tr>
<tr><td>F</td><td>no</td><td>yes</td><td>yes</td><td>$\dot{m}_1$ & $\dot{m}_2$ to 50% within 1s</td><td>0.1MPa</td></tr>
<tr><td>G</td><td>yes</td><td>yes</td><td>yes</td><td>$\dot{m}_1$ to 50% within 1s</td><td>0.1MPa</td></tr>
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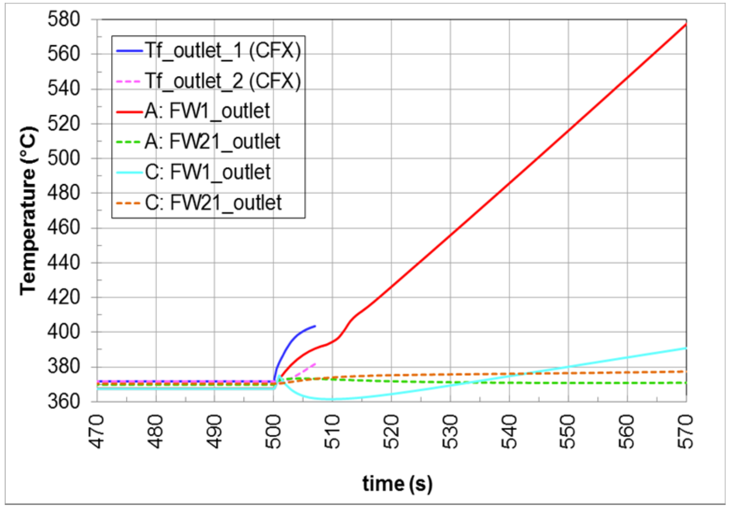
* LOFA in system 1.

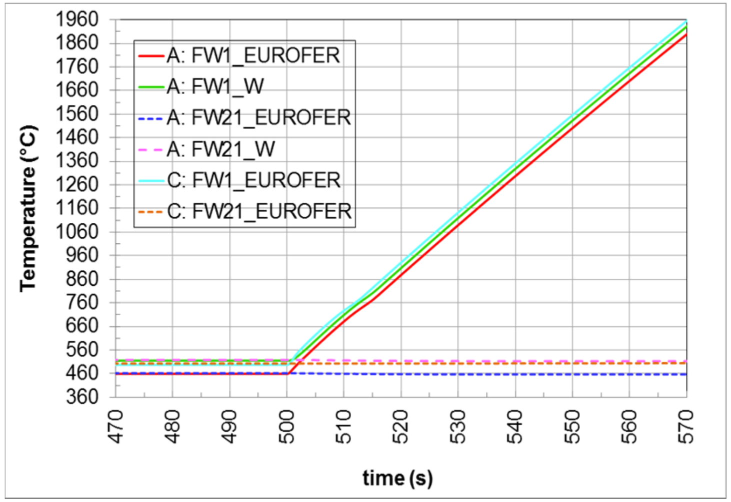
No plasma disruption, soft plasma shutdown in 60s from ITER.

Simulation with system code

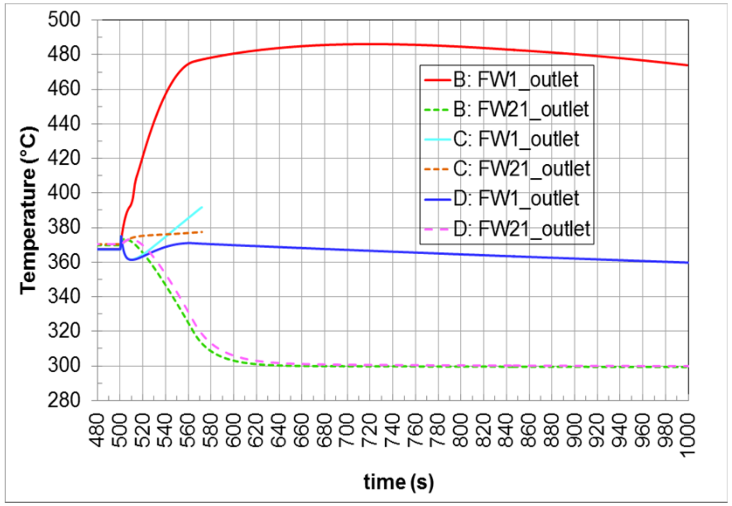
- LOFA results



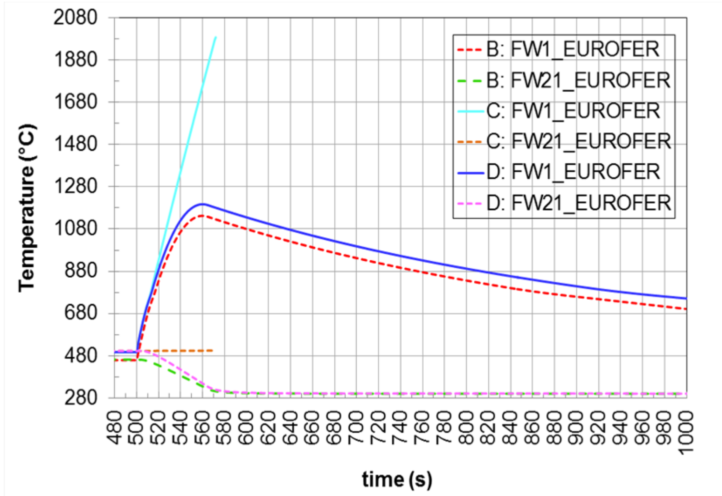
CFX, A, C: He temperature



A, C: HS1 at the outlet volume of the front wall



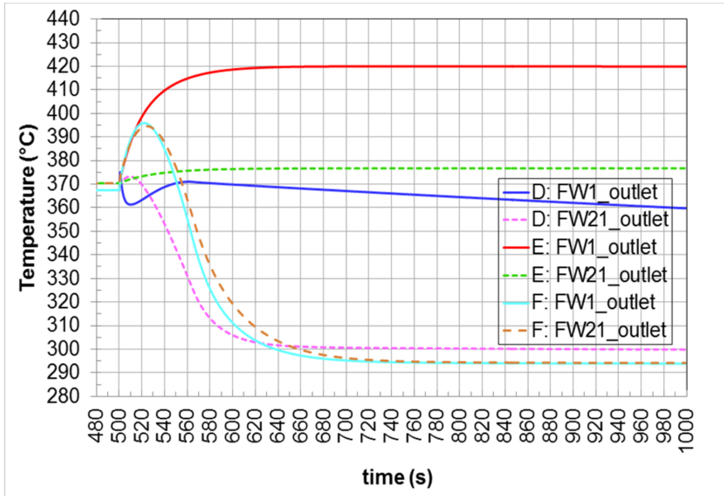
B, C, D: He temperature



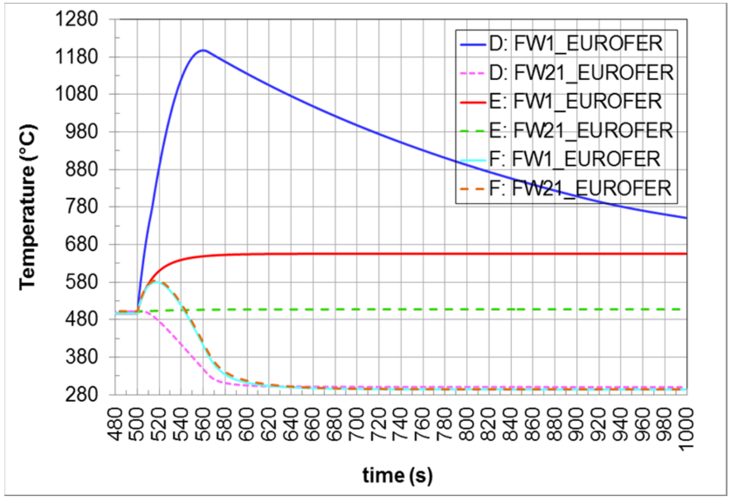
B, C, D: HS1 at the outlet volume of the front wall

Simulation with system code

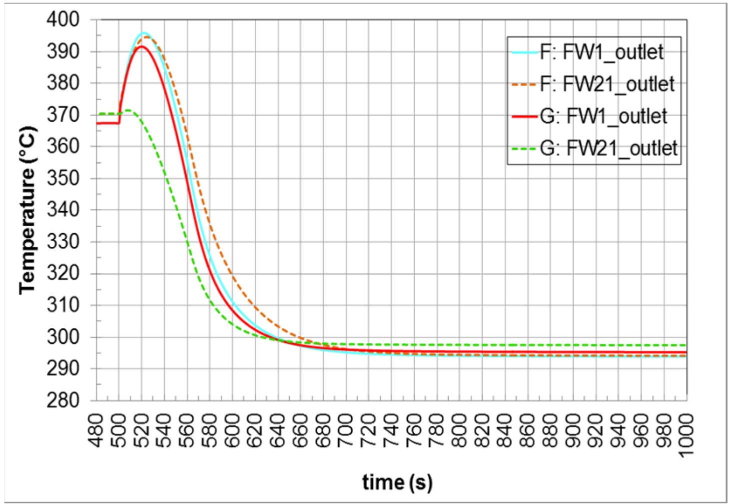
- LOFA results



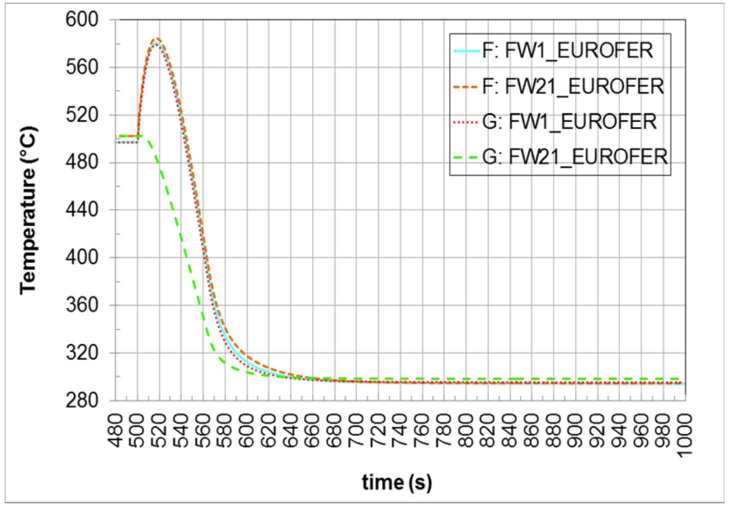
D, E, F: He temperature



D, E, F: HS1 at the outlet volume of the front wall



F, G: He temperature



F, G: HS1 at the outlet volume of the front wall

Summary of the scenarios

Nr.	Cooling circuit redundancy	Circulator redundancy	FPS / soft plasma shutdown	T_FW vs. T_limit (550°C)	Scenario
1	no	no	no	T_FW > T_limit in 4s	CFX I
2	yes	no	no	T_FW > T_limit in 5.5s T_FW > T_limit in 4s, 2s	CFX III & RELAP A, C
3	no	yes	no	T_FW < T_limit within 10s	CFX II
4	no	no	yes	T_FW < T_limit within 10s	CFX V
5	yes	yes	no	T_FW < T_limit within 10s T_FW > T_limit in 6s	CFX IV & RELAP E
6	yes	no	yes	T_FW < T_limit within 9s T_FW > T_limit in 4s, 2s	CFX VI & RELAP B, D
7	no	yes	yes	max. T_FW: 585°C T_FW < T_limit in the long term	RELAP F
8	yes	yes	yes	max. T_FW: 579°C T_FW < T_limit in the long term, 50% FW is affected.	RELAP G

Conclusion

- LOFA scenarios have been investigated for the FW of DEMO HCPB blanket concept using CFD and system codes. Transient time for 3D-CFD simulation is very limited due to high CPU time.
- Steady state
  - The RELAP5-3D results are well comparable with the CFD results (He temperature, pressure drop & velocity).
  - The FW temperature of the RELAP calculation is ~44°C higher than it from the CFX due to the 1D-HS modelling in RELAP.

Conclusion

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- LOFA
  - No mitigation: T_FW increases up to the structure melting point rapidly.
  - One mitigation action in priority: *FPS, circulator redundancy, cooling circuit redundancy.*
  - Two mitigation actions: *plasma shutdown is mandatory.*
  - Three mitigation actions: *T_FW < T_limit in the long term, 50% FW is affected.*
  - Heat exchange between two systems for the cooling circuit redundancy is not effective enough with the 1D-HS modelling in RELAP.
  - Soft plasma shutdown cannot stop the temperature increase at the beginning of the shutdown.
- Temperature behaviour considering the plasma disruption following the FPS in DEMO should be studied.
- Future work for the FW integrity: structural analysis to withstand the thermal-mechanical and electro-magnetic loads following loading categories and criteria.