Development and testing of High Heat Flux Components for ITER

Mario Merola

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Talk outline

- The ITER Divertor
- Reference geometry for the High Heat Flux Components
- Technology development
- Non-destructive testing
- Acceptance criteria
- Present and future plans

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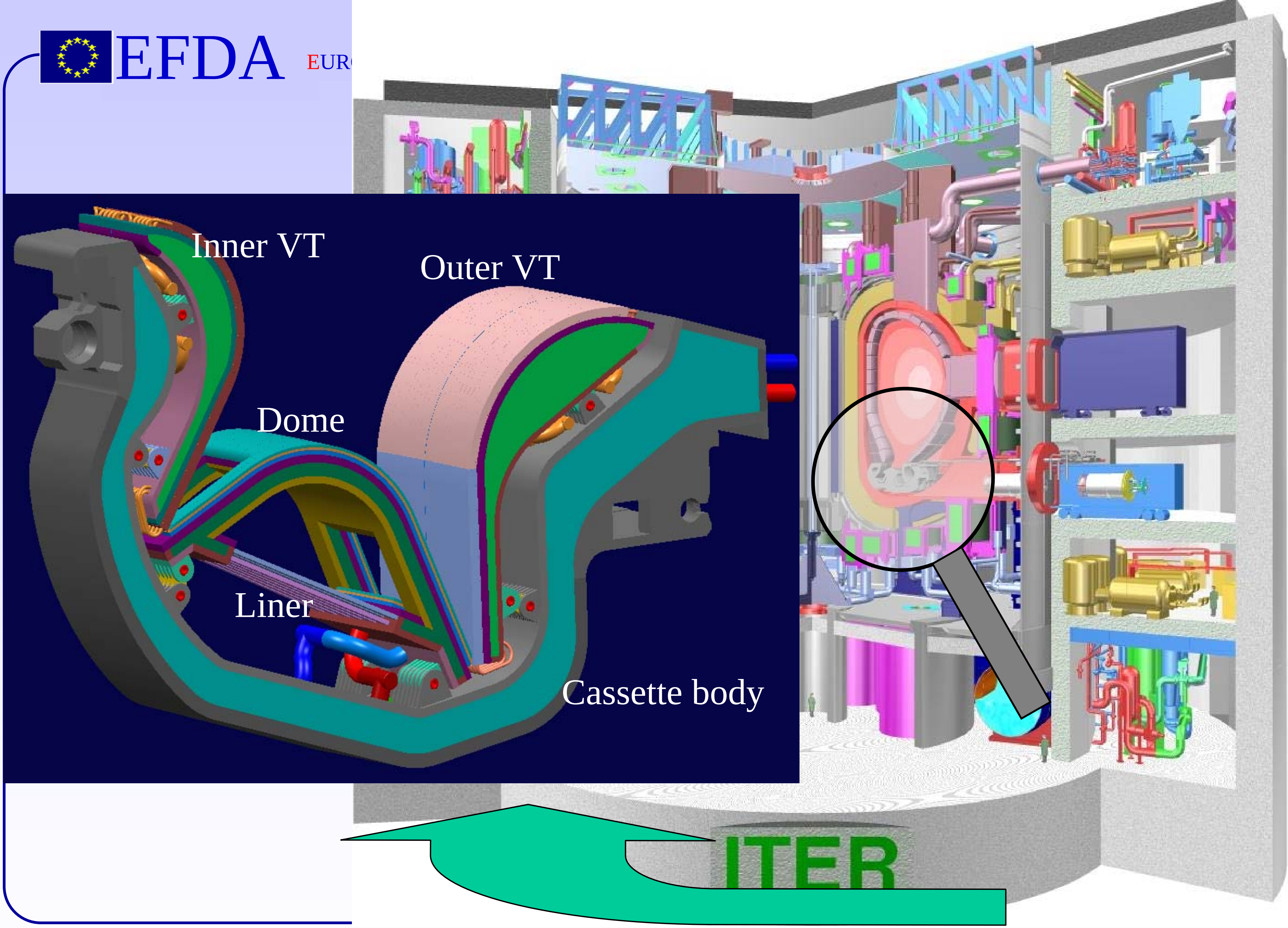
EFDA EUR



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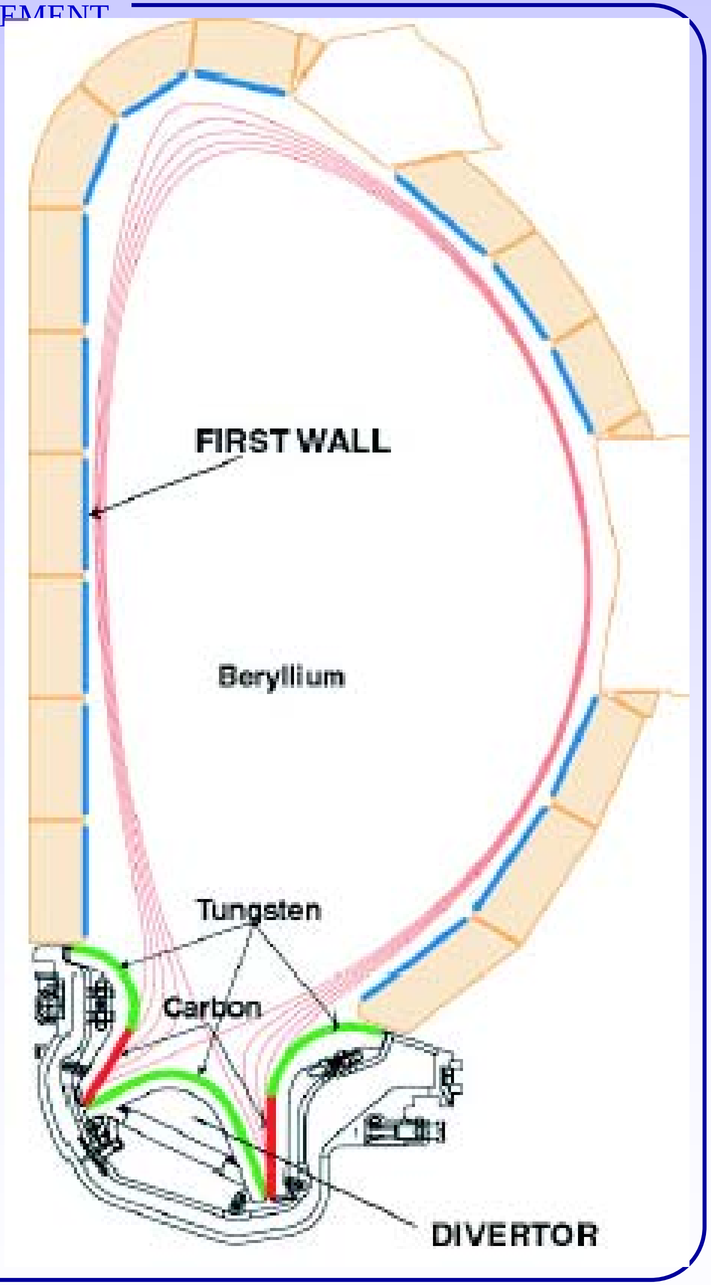
The main function of the divertor system is to exhaust the major part of the alpha particle power as well as helium and impurities from the plasma



Beryllium

- Low atomic number
- Oxygen gettering capability
- Absence of chemical sputtering
- High thermal conductivity

CFC

- Longest lifetime
- Absence of melting
- Excellent thermal shock resistance
- Very high thermal conductivity
- Low atomic number

CFC Material

Thermal Conductivity at RT (W/mK)

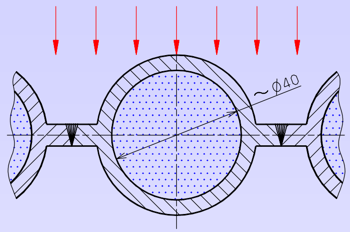
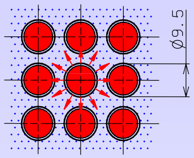
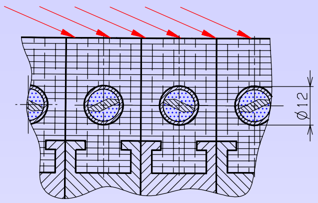
Direction	X	Y	Z
NB31	323	117	115
Concept 2	340	113	78

Tensile Strength at RT (MPa)

NB31	130	30	19
Concept 2	113	35	8

Tungsten

- Lowest sputtering
- Highest melting point
- High thermal conductivity
- No concerns over tritium inventory

HIGH HEAT FLUX COMPONENTS	FOSSILE FIRED BOILER WALL (ABB)	FISSION REACTOR (PWR) CORE	ITER DIVERTOR
DESIGN			
HEAT FLUX - average MW/m^2 - maximum MW/m^2	 0.2 0.3	 0.7 1.5	 3 – 5 10 – 20
Max heat load MJ/m^2 Lifetime years Nr. of full load cycles Neutron damage dpa Structure material	- 25 8000 - Ferritic-Martens. steel	- 4 10 10 Zircaloy - 4	10 3 3000 0.2 CuCrZr & CFC/W
Coolant - pressure MPa - temperature °C - velocity m/s - leak rate g/s	Water-Steam 28 280-600 3 <50	Water 15 285-325 5 <50(SG)	Water 4 100 – 150 9 – 11 $<10^{-7}$

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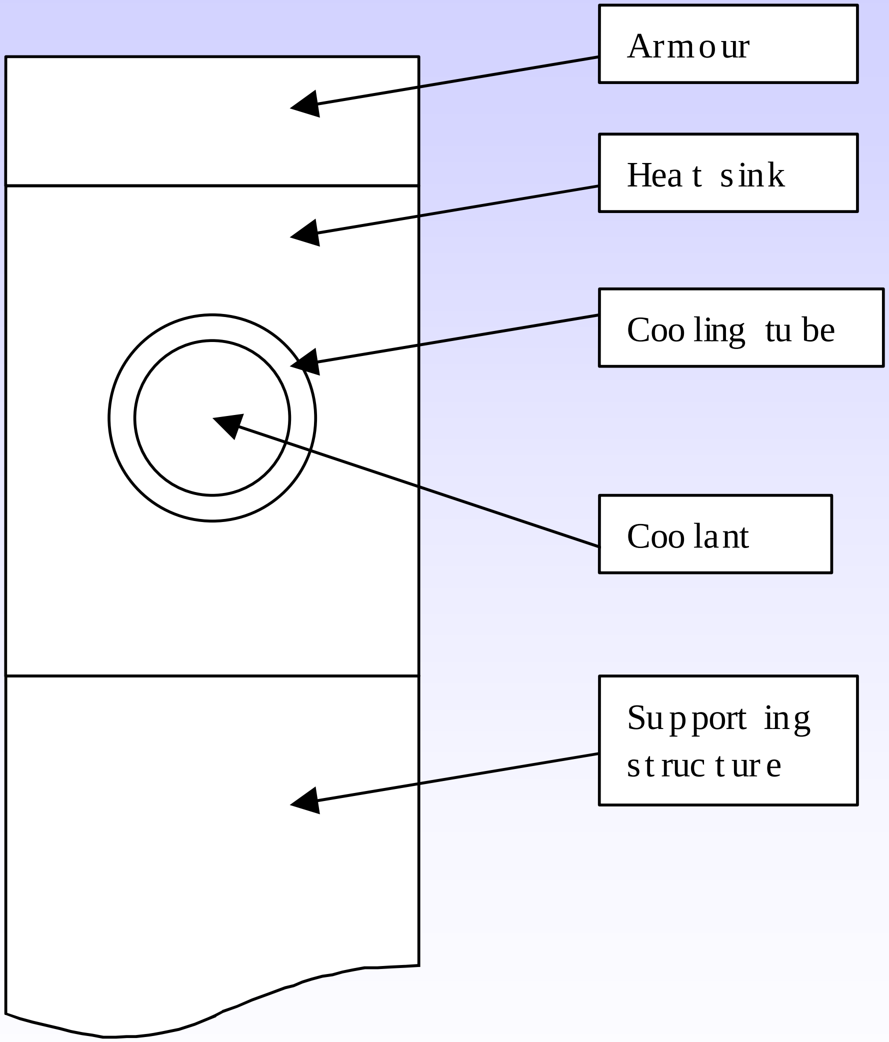
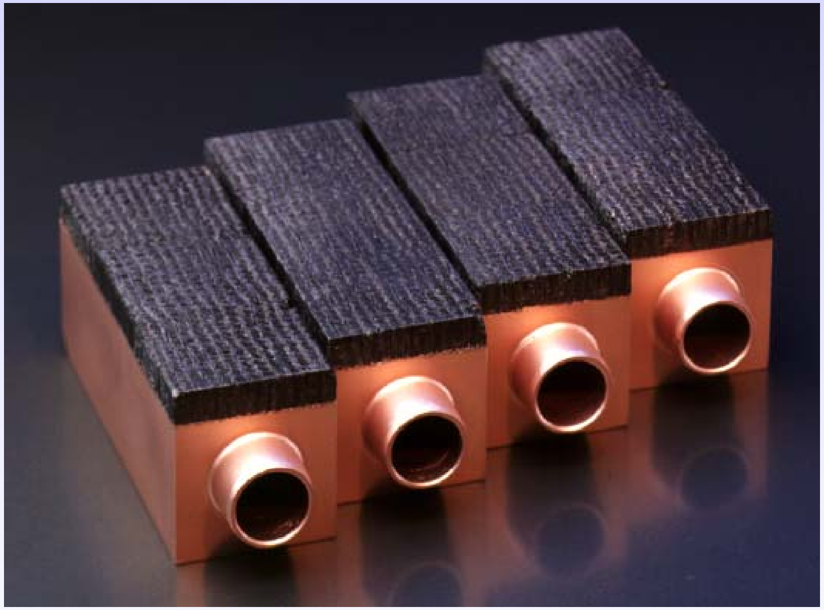
Definitions

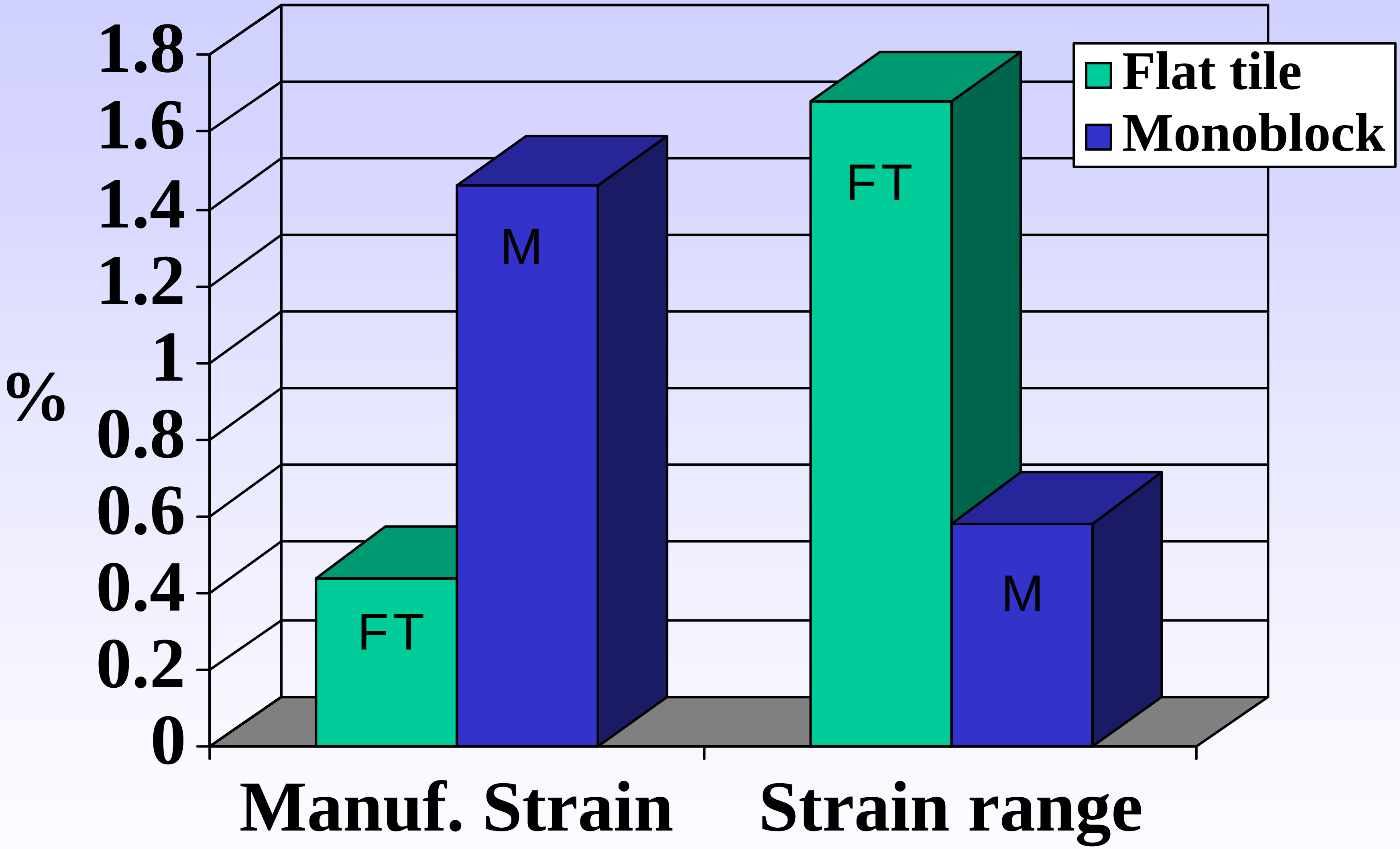


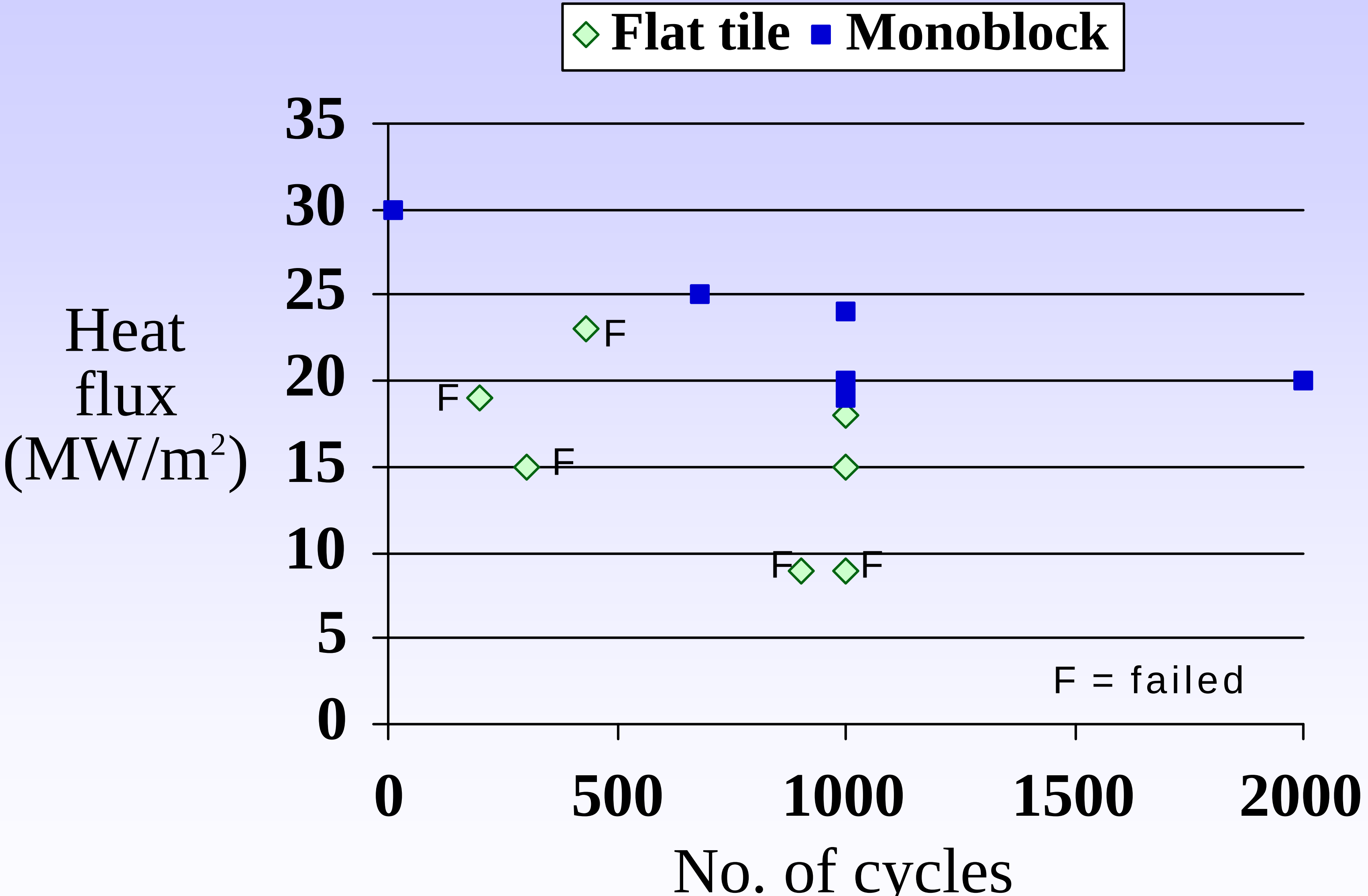
Possible PFC geometries

Monoblock



Flat tile

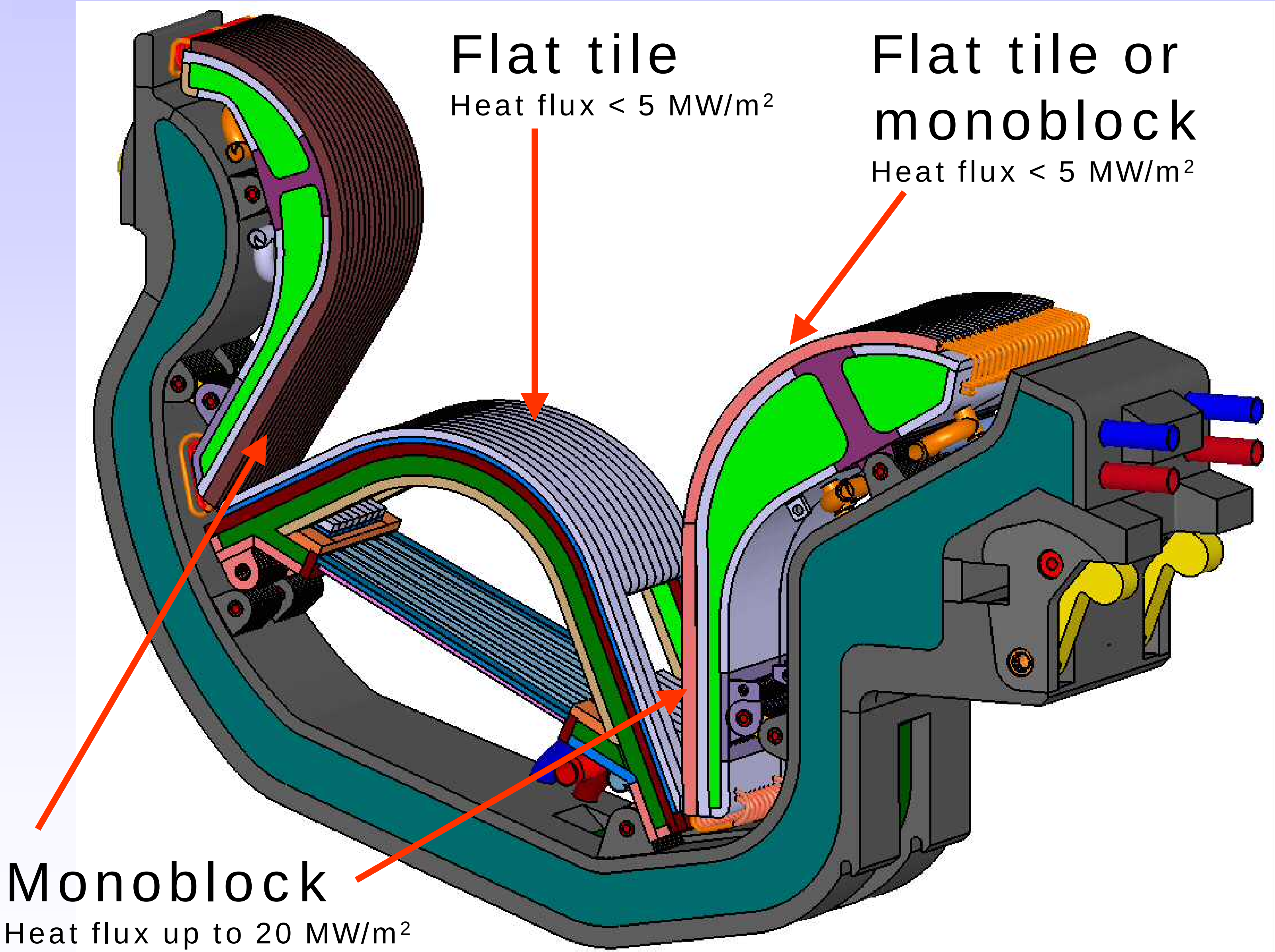

1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
%
Flat tile
Monoblock
FT
M
FT
M
Manuf. Strain
Strain range


Flat tile
Monoblock
Heat flux (MW/m2)
35
30
25
20
15
10
5
0
F
F
F
F
F
F = failed
0
500
1000
1500
2000
No. of cycles

Conclusion

Manufacturing of flat tile components is easier than monoblocks

Thermal fatigue performances of monoblock components are superior than those of flat tiles


Flat tile
Heat flux < 5 MW/m²
Flat tile or monoblock
Heat flux < 5 MW/m²
Monoblock
Heat flux up to 20 MW/m²

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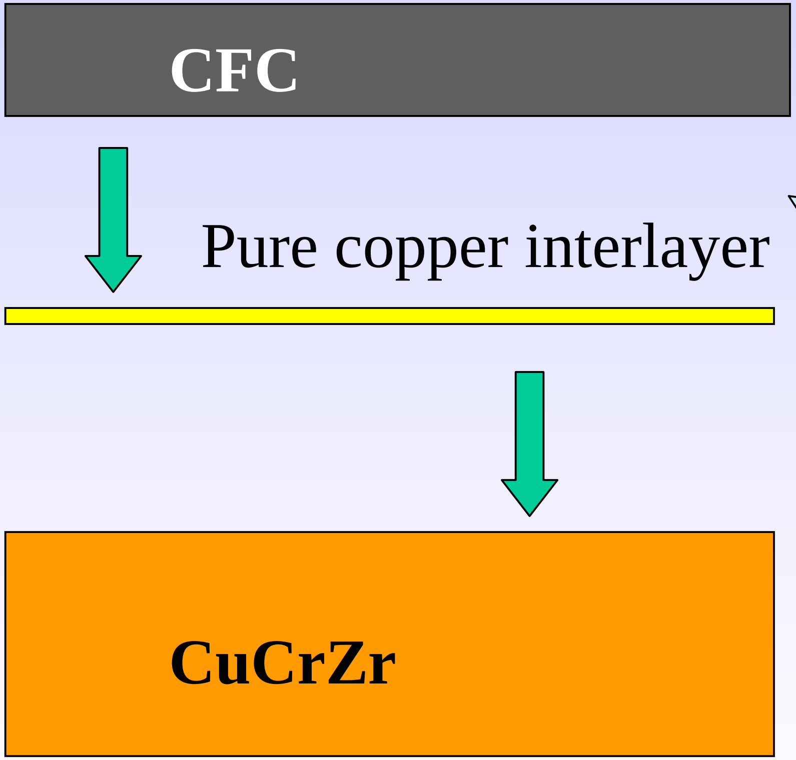
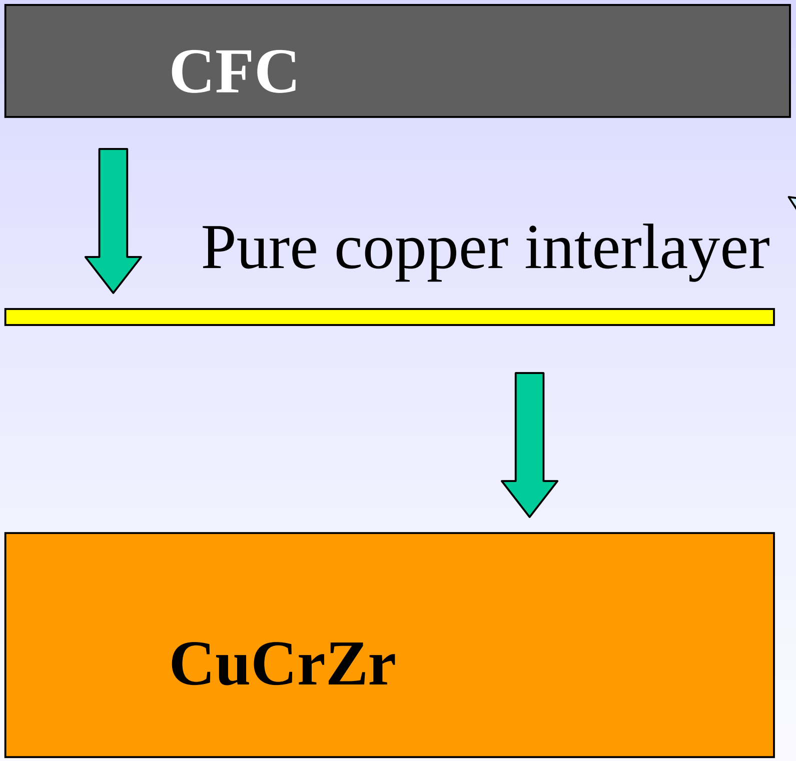
Armour to heat sink joints



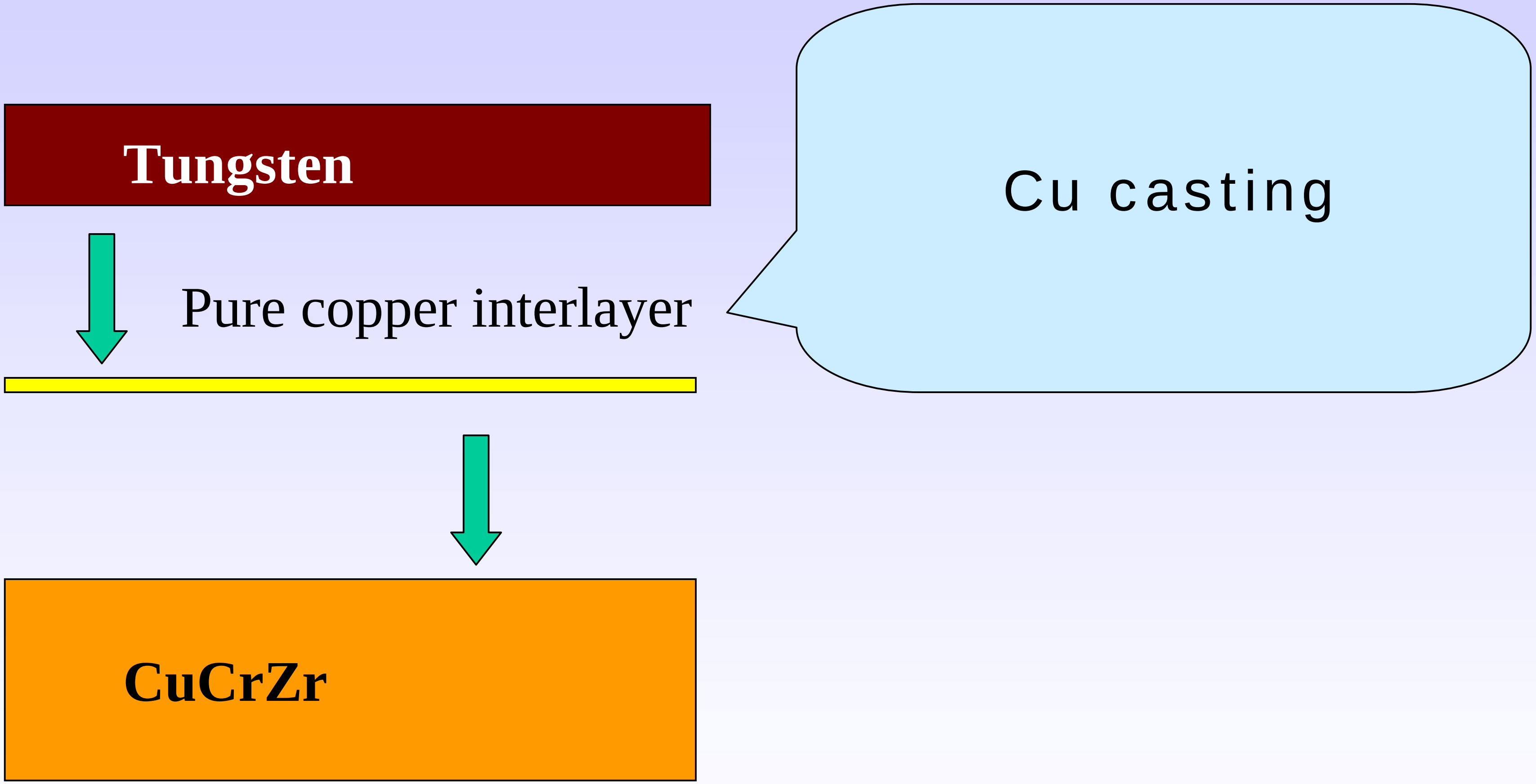
- Copper does not wet carbon
- Wetting agents may lead to the formation of brittle intermetallics or compounds with a low melting point
- Large thermal expansion mismatch

Armour to heat sink joints

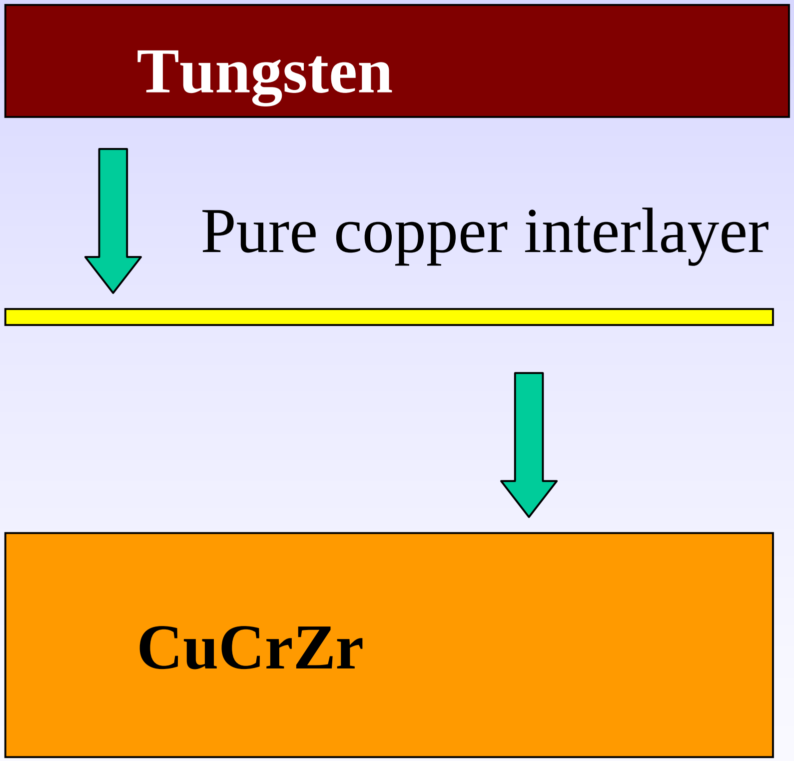


- AMC
- Direct casting
- Pre-brazed casting
- Brazing
- GMP

Armour to heat sink joints

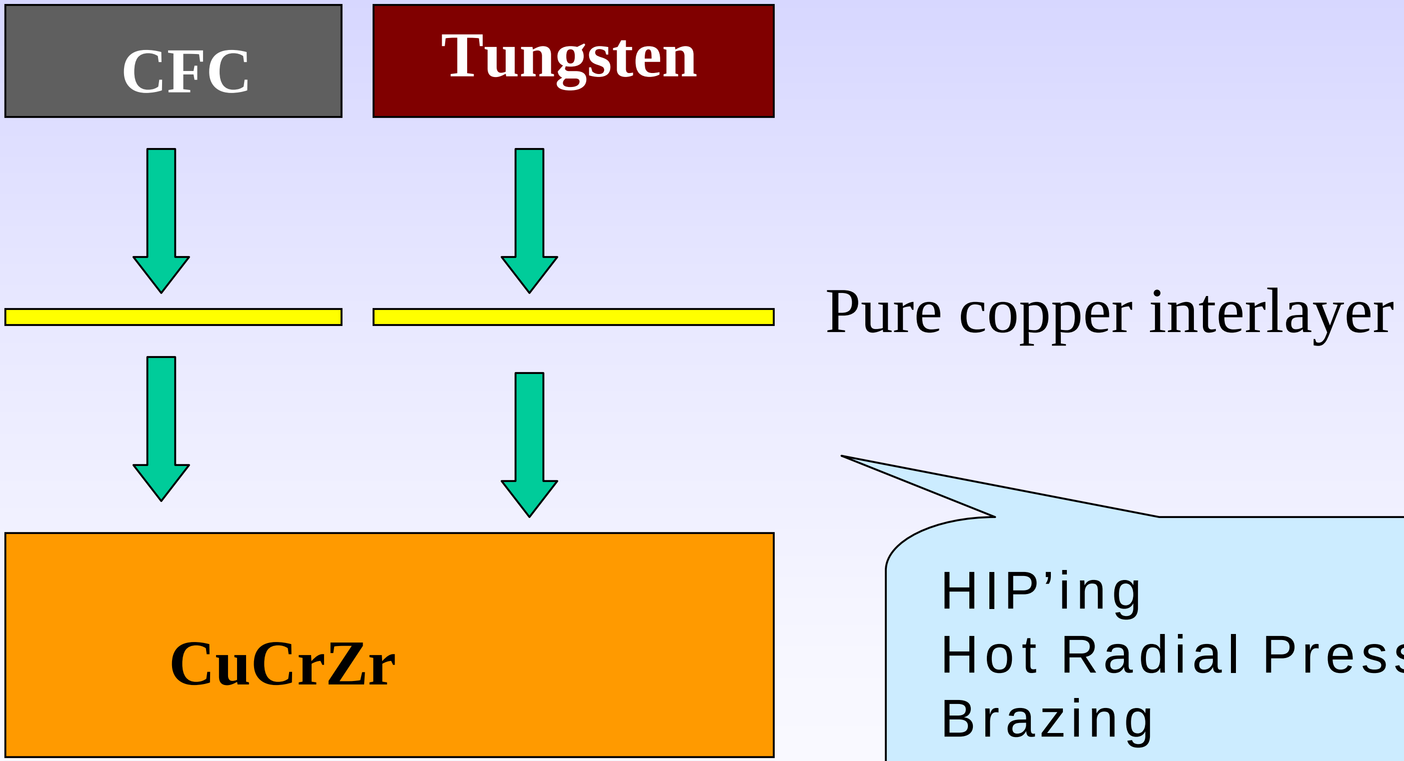


Armour to heat sink joints



Casting Cu onto W requires adequate experience to ensure a good wetting of W and to prevent the formation of bubble in the cast Cu

Armour to heat sink joints



HIP'ing
Hot Radial Pressing
Brazing
EB welding

CuCrZr: a "difficult" material

It reaches an optimum in strength after a thermo-mechanical treatment involving:

1) first a solution annealing at high temperature (>980 C) to dissolve the alloying elements (Cr, Zr)
2) then a water quench to keep the alloying elements in supersaturated solid solution at room temperature
3) finally an ageing treatment at intermediate temperatures (475 C, 3 hrs) to decompose the supersaturated solid solution into a fine distribution of precipitates.

CuCrZr: a “difficult” material

The manufacturing route shall be carefully defined.

Thermal excursions above the ageing temperature can overage the alloy with a significant decrease of strength.

Thermal excursions above the solution annealing temperature can lead to a significant decrease of the thermal conductivity, due to the dissolution of precipitates.

First manufacturing strategy

- Starting point: CuCrZr in the SA status
- The ageing heat treatment is performed at the same time of the HIP joining process

↓

What is the maximum allowable HIP cycle in terms of temperature and time ?

Allowable manufacturing HIP cycle

- Any “ageing” heat treatment below 600 °C gives acceptable mechanical strength

Second manufacturing strategy

- Starting from CuCrZr in any status, the SA heat treatment is performed at the same time of the brazing joining process
- Then the component is “fast cooled”
- Then the ageing heat treatment is applied

What is the required cooling rate to ensure an adequate recovery of the thermal and mechanical properties ?

Allowable manufacturing brazing cycle

- Any “fast cooling” after brazing with a rate > 1 C/s enables an acceptable recovery of the mechanical strength

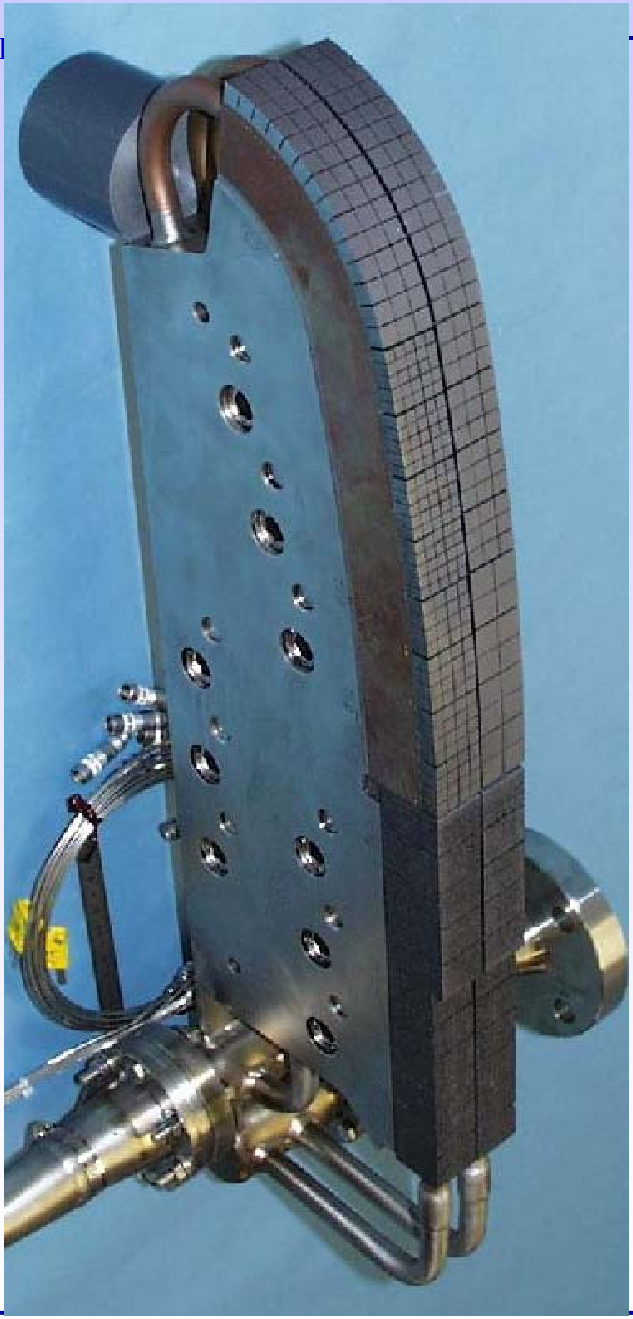
EFDA EUROPEAN FUSION DEVELOP

Vertical Target Medium-Scale Prototype

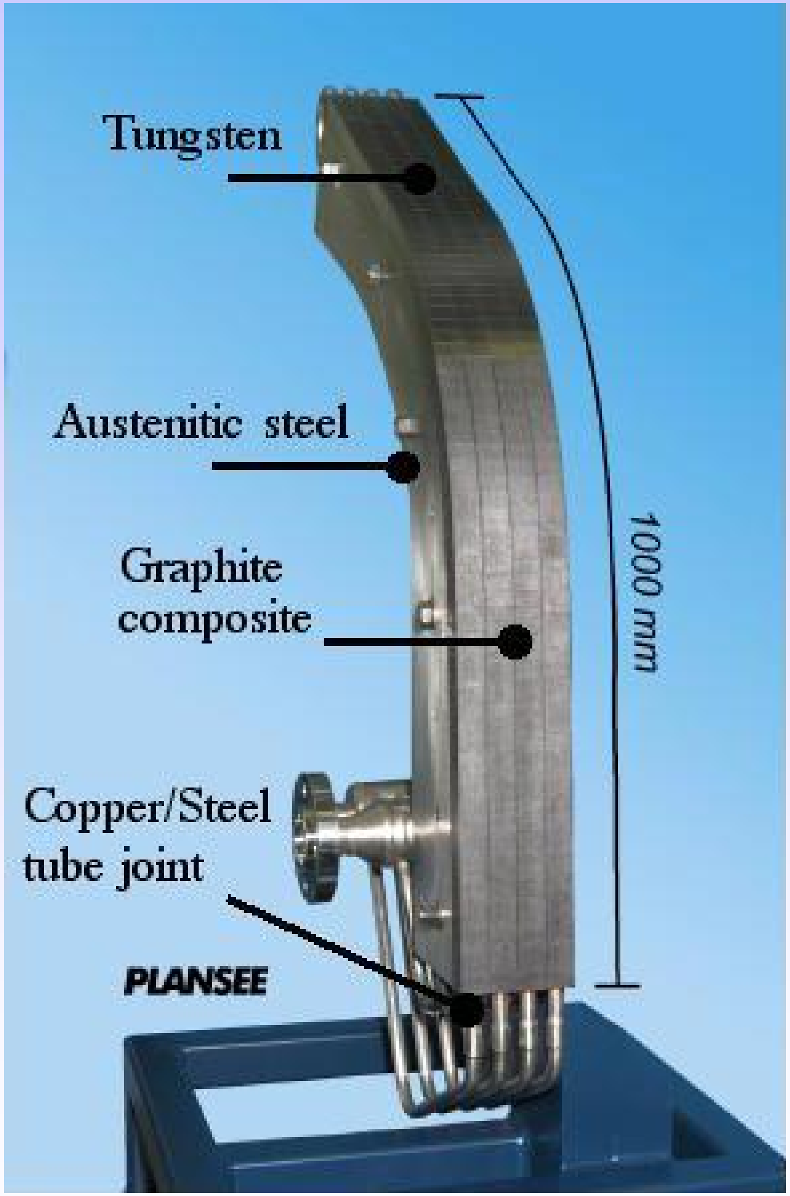
Test results

- W macrobrush:
  15 MW/m^2 x 1000 cycles
- CFC monoblock
  20 MW/m^2 x 2000 cycles
- CHF test > 30 MW/m^2

PLANSEE

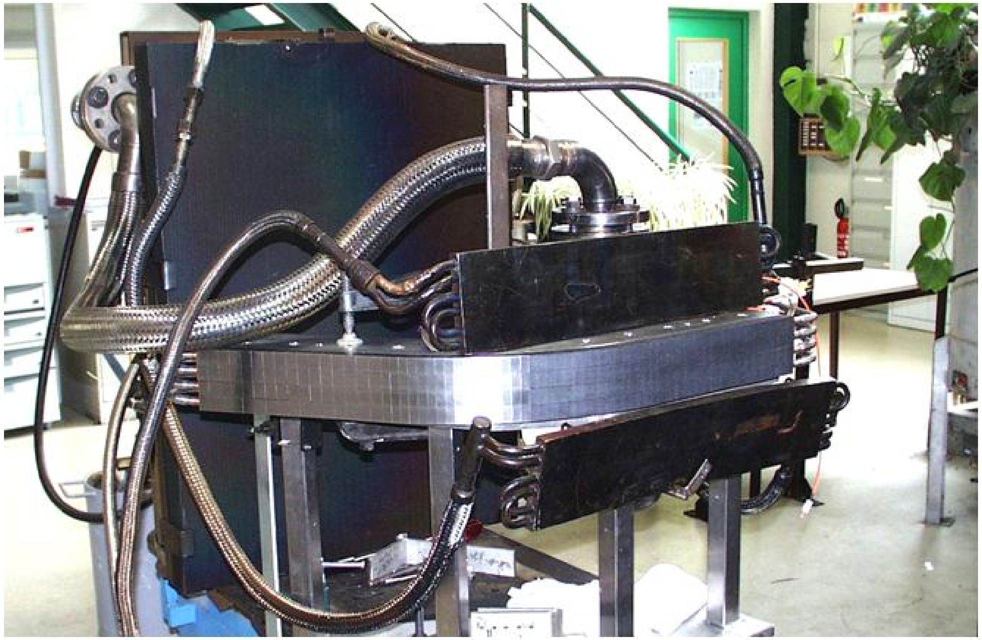


Vertical Target Full-Scale Prototype



PLANSEE

Vertical Target Full-Scale Prototype



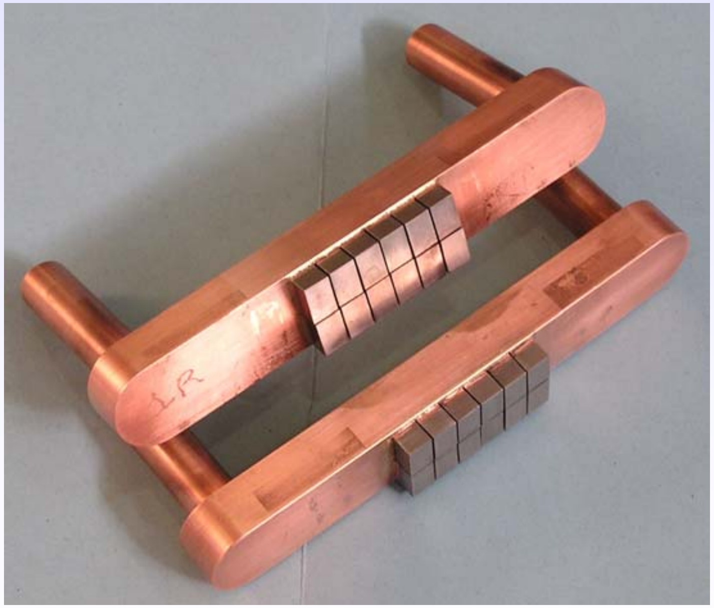
AREVA

- W monoblocks:
  10 MW/m^2 x 1000 cycles

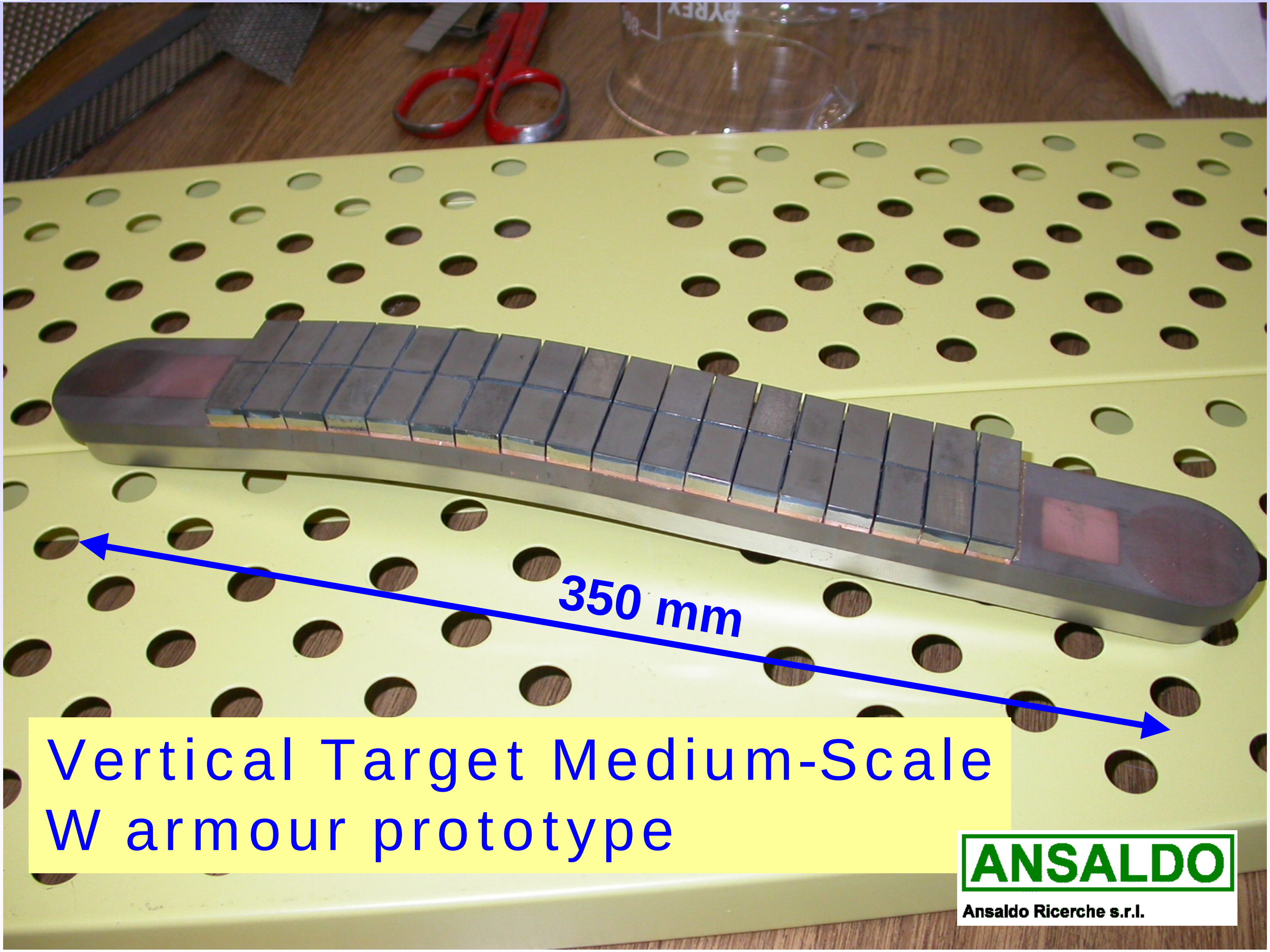
- CFC monoblock
  10 MW/m^2 x 1000 cycles
  20 MW/m^2 x 1000 cycles
  23 MW/m^2 x 1000 cycles

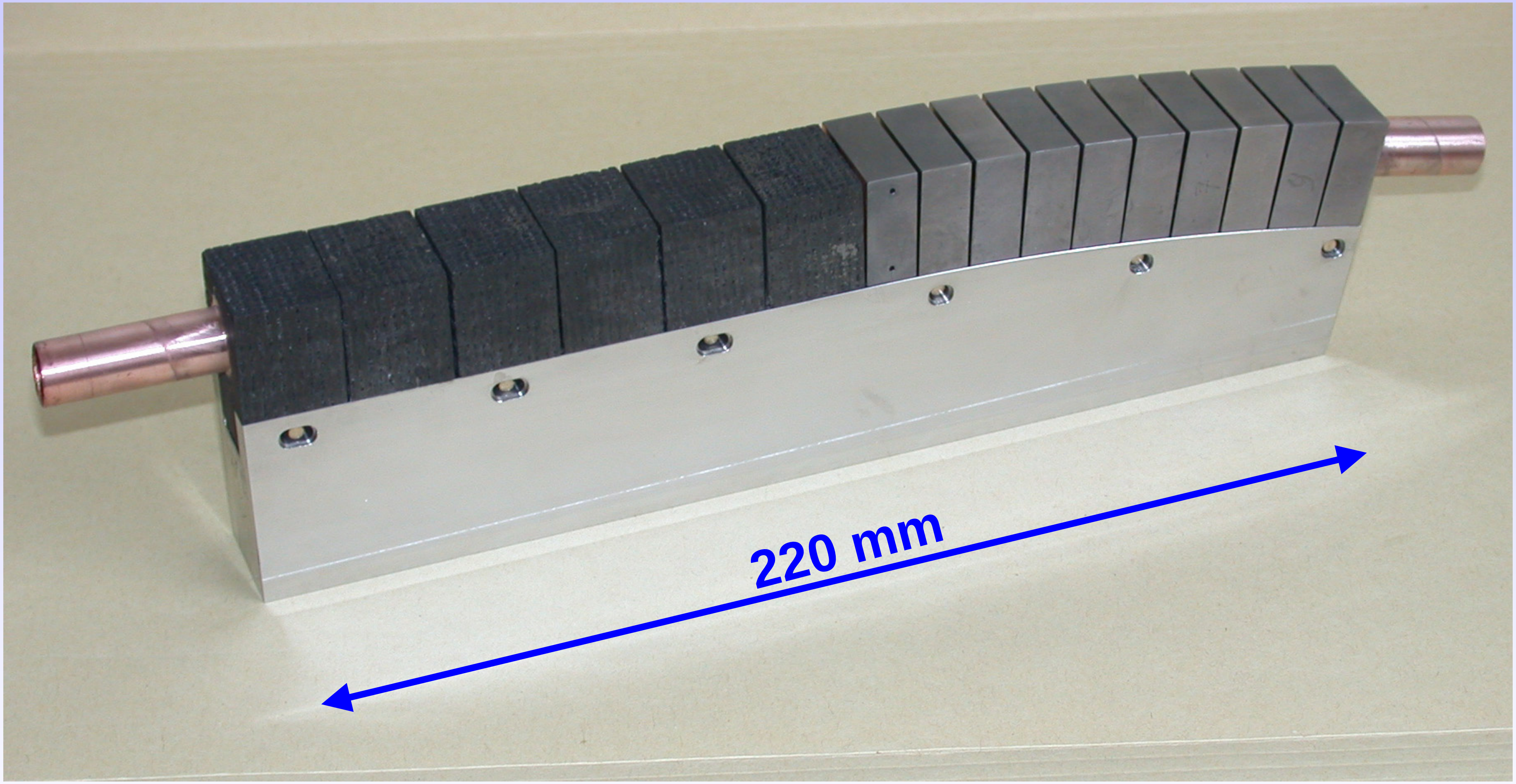
Vertical Target components with W armour

10 MW/m^2 x 1000 cycles
16 MW/m^2 x 1000 cycles
21 MW/m^2 x 1000 cycles



Vertical Target component with W armour

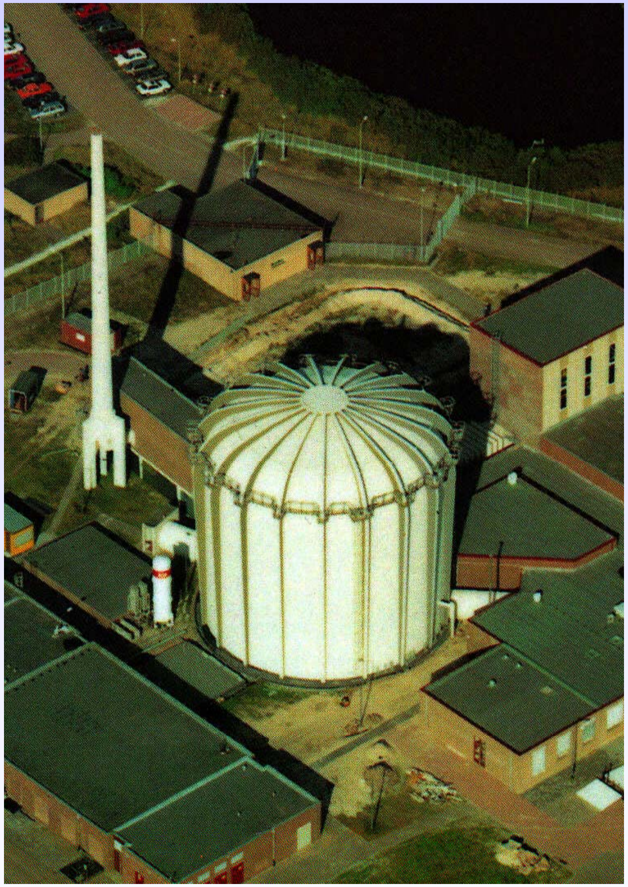

350 mm
Vertical Target Medium-Scale
W armour prototype
ANSALDO
Ansaldo Ricerche s.r.l.



Vertical Target Medium-Scale Prototype

ENEA

Neutron-Irradiation Experiments PARIDE 1 - 4



High Flux Reactor
Petten, Netherlands

PARIDE 1:

- temperature: 350°C
- target fluence: 0.5 dpa

PARIDE 2:

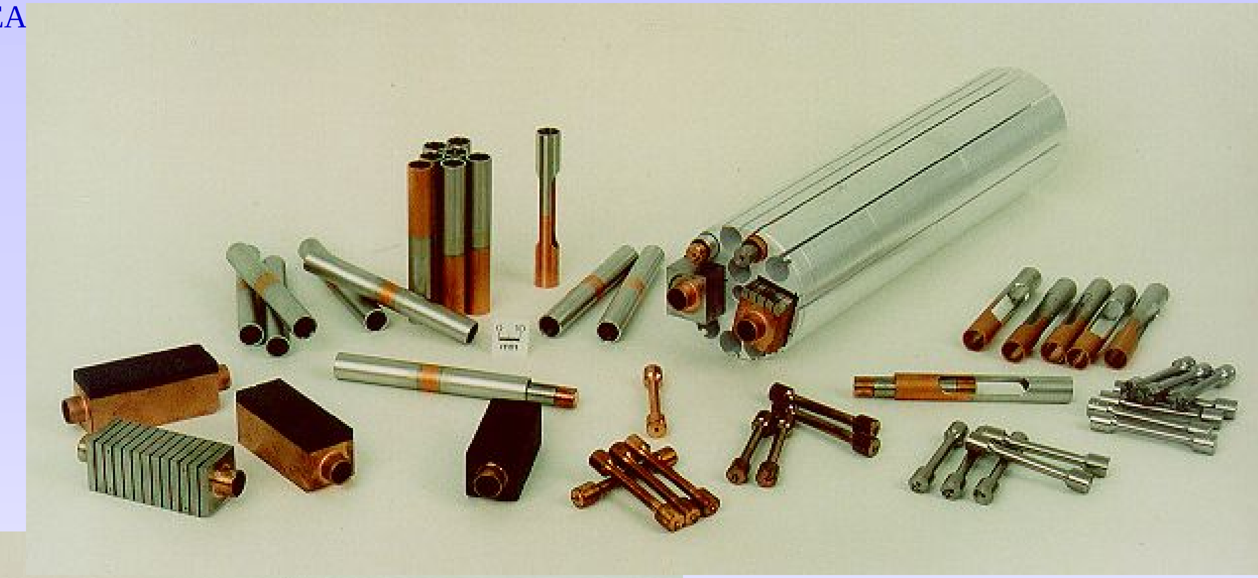
- temperature: 700°C
- target fluence: 0.5 dpa

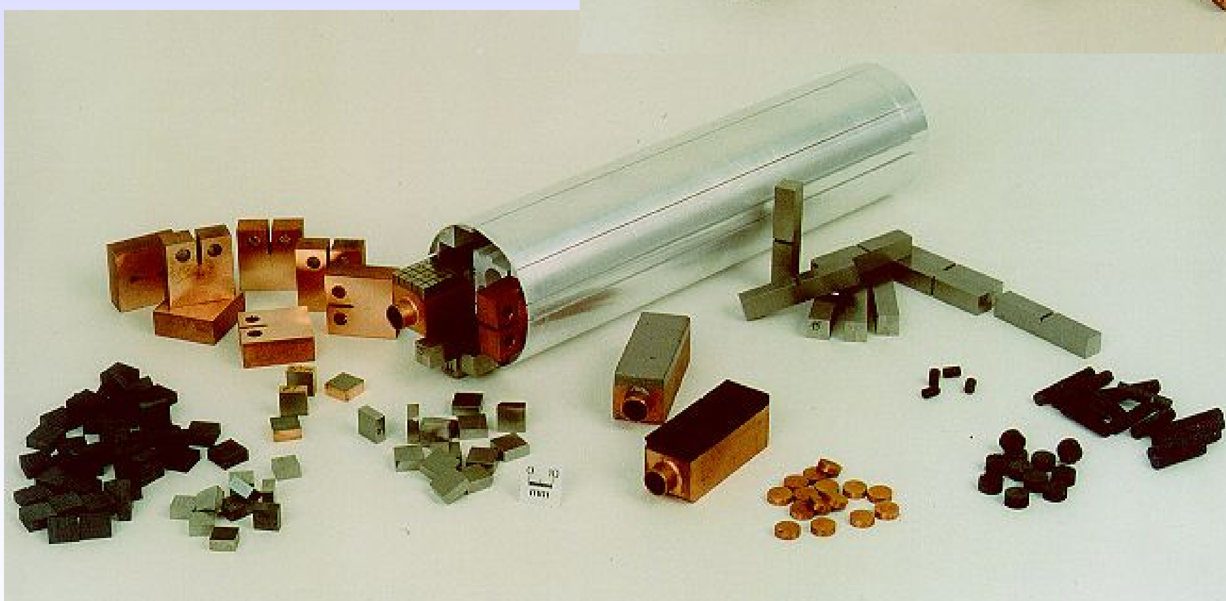
PARIDE 3:

- temperature: 200°C
- target fluence: 0.2 dpa

PARIDE 4:

- temperature: 200°C
- target fluence: 1 dpa



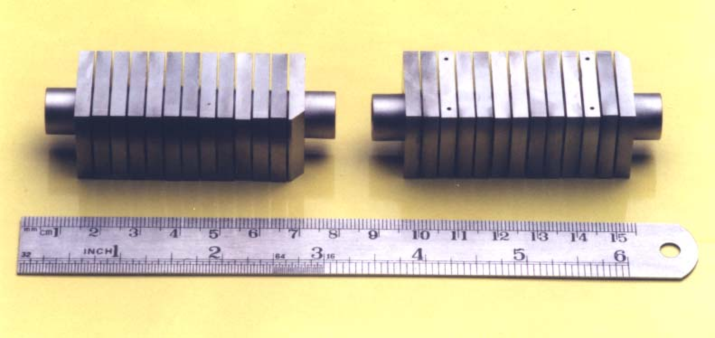


Forschungszentrum Jülich
in der Helmholtzgemeinschaft
EURATOM-Association

Testing of Tungsten Mock-Ups

Unirradiated
- 1000 cycles x 14 MW/m² – no failure

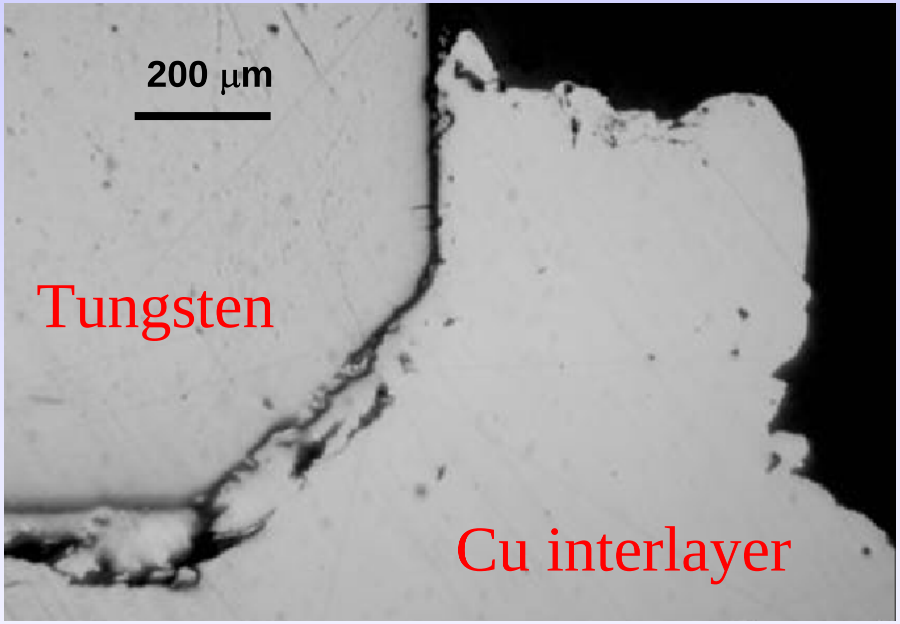
200°C, 0.1 and 0.5 dpa in tungsten
- Failure limit: 10 MW/m²



Unirradiated
- 1000 cycles x 20 MW/m² – no failure

200°C, 0.1 and 0.5 dpa in tungsten
- Successfully tested up to 18 MW/m²

Thermal fatigue testing of a tungsten macrobrush mock-up irradiated in the PARIDE 3 experiment



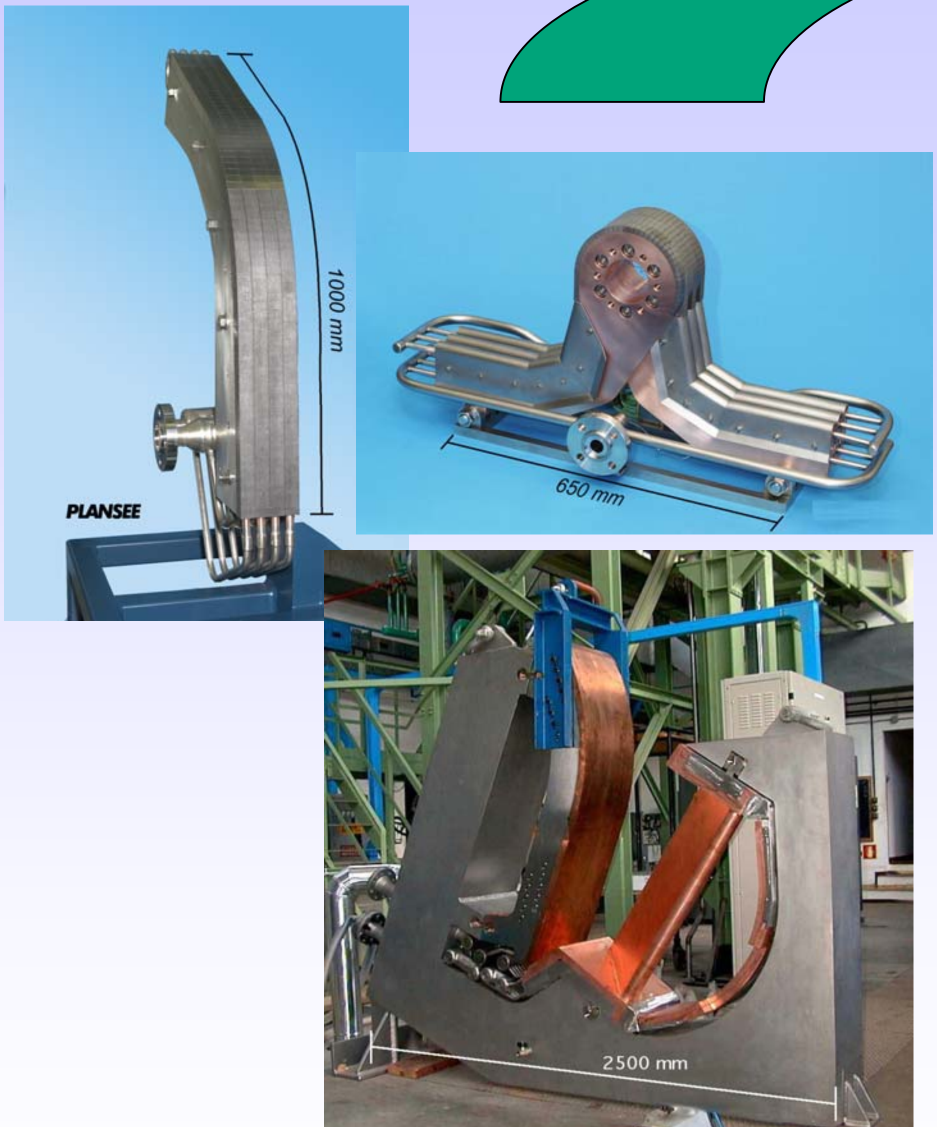
Irradiation condition:
200°C – 0.1 dpa (in W)

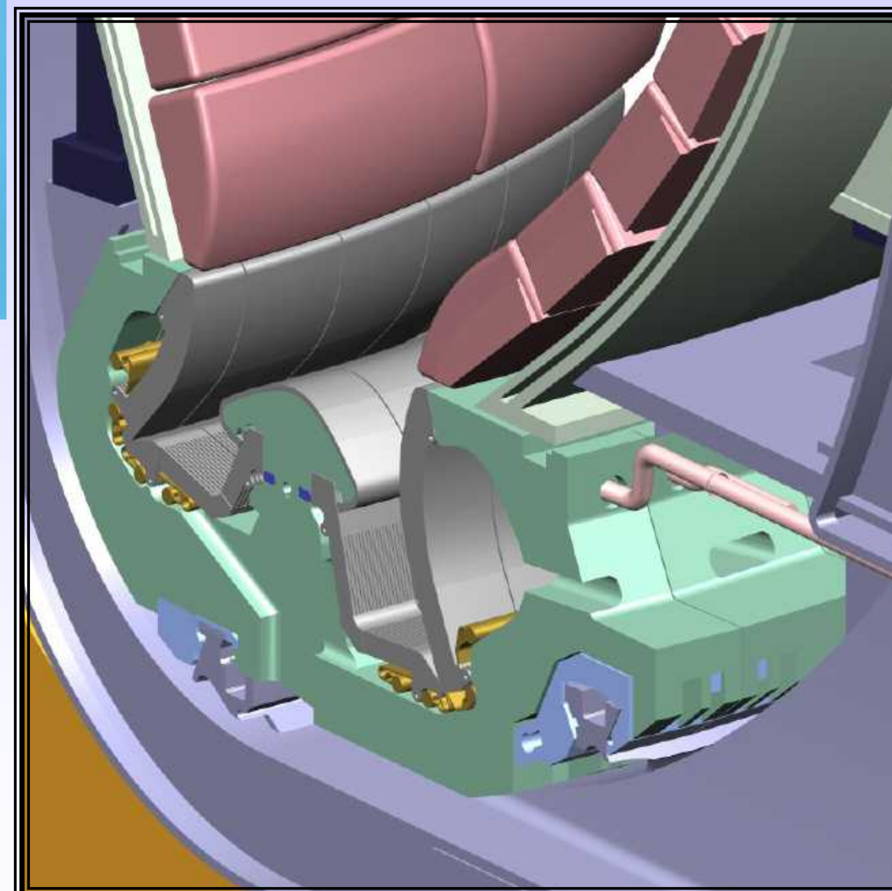
High heat flux test:
1000 cycles at 10 MW/m^2

Irradiation of W armoured mock-ups

The irradiated pure Cu interlayer leads to a reduction of the high heat flux performances in a flat tile geometry.

The monoblock solution seems not to be affected by this problem.


1000 mm
PLANSEE
650 mm
2500 mm



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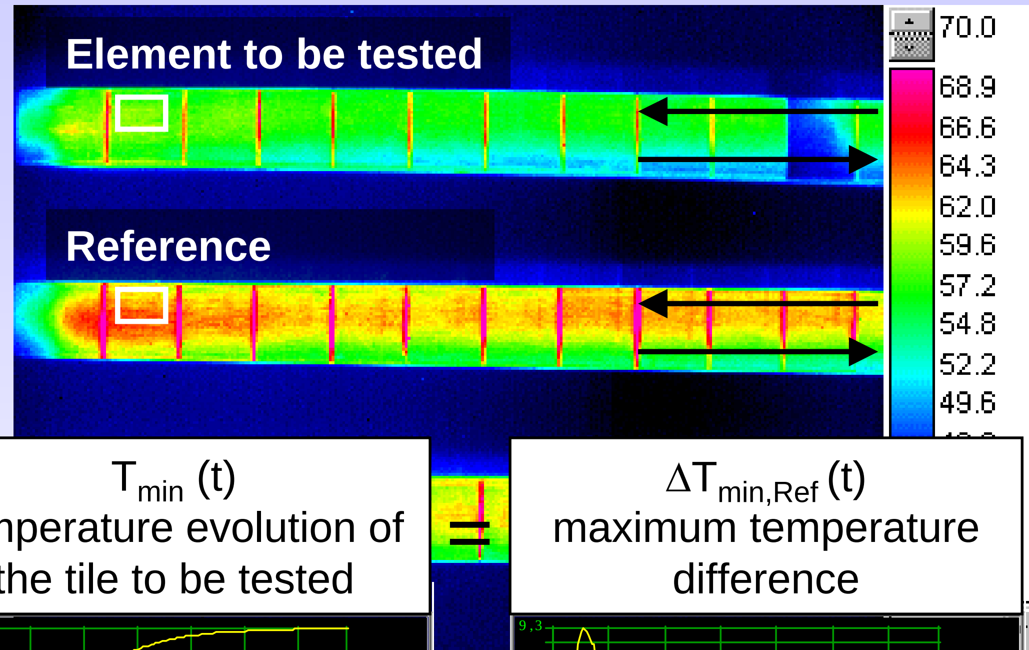
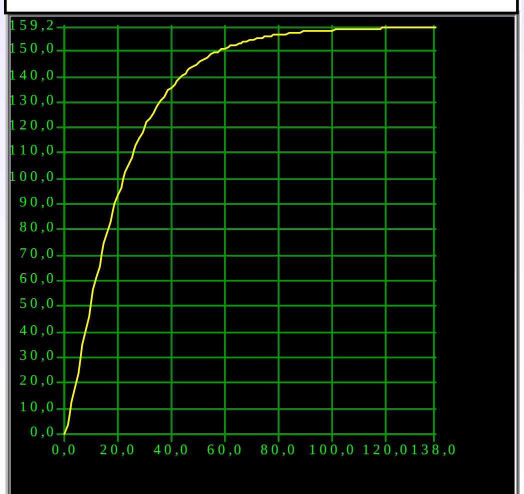
Non-Destructive Testing

- Infrared thermography
- Ultrasonic inspections

Transient Thermography Inspection



$T_{min,Ref}$ (t)
temperature evolution of the reference tile



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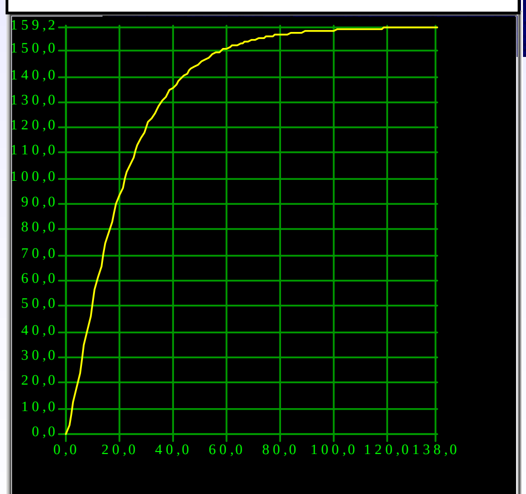
T_{min} (t)
temperature evolution of the tile to be tested



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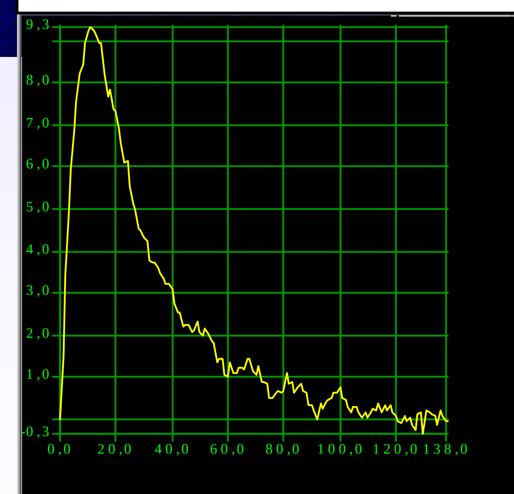
$\Delta T_{min,Ref}$ (t)
maximum temperature difference



Non-Destructive Testing

- Infrared thermography proved to be an essential inspection technique for the CFC/Cu joint
- Ultrasonic inspections have also been successfully applied on the CFC/Cu joint but their effectiveness of depends on the manufacturing technologies
- Ultrasonic inspections is the preferred method to inspect metallic joints (W/Cu and Cu/CuCrZr)

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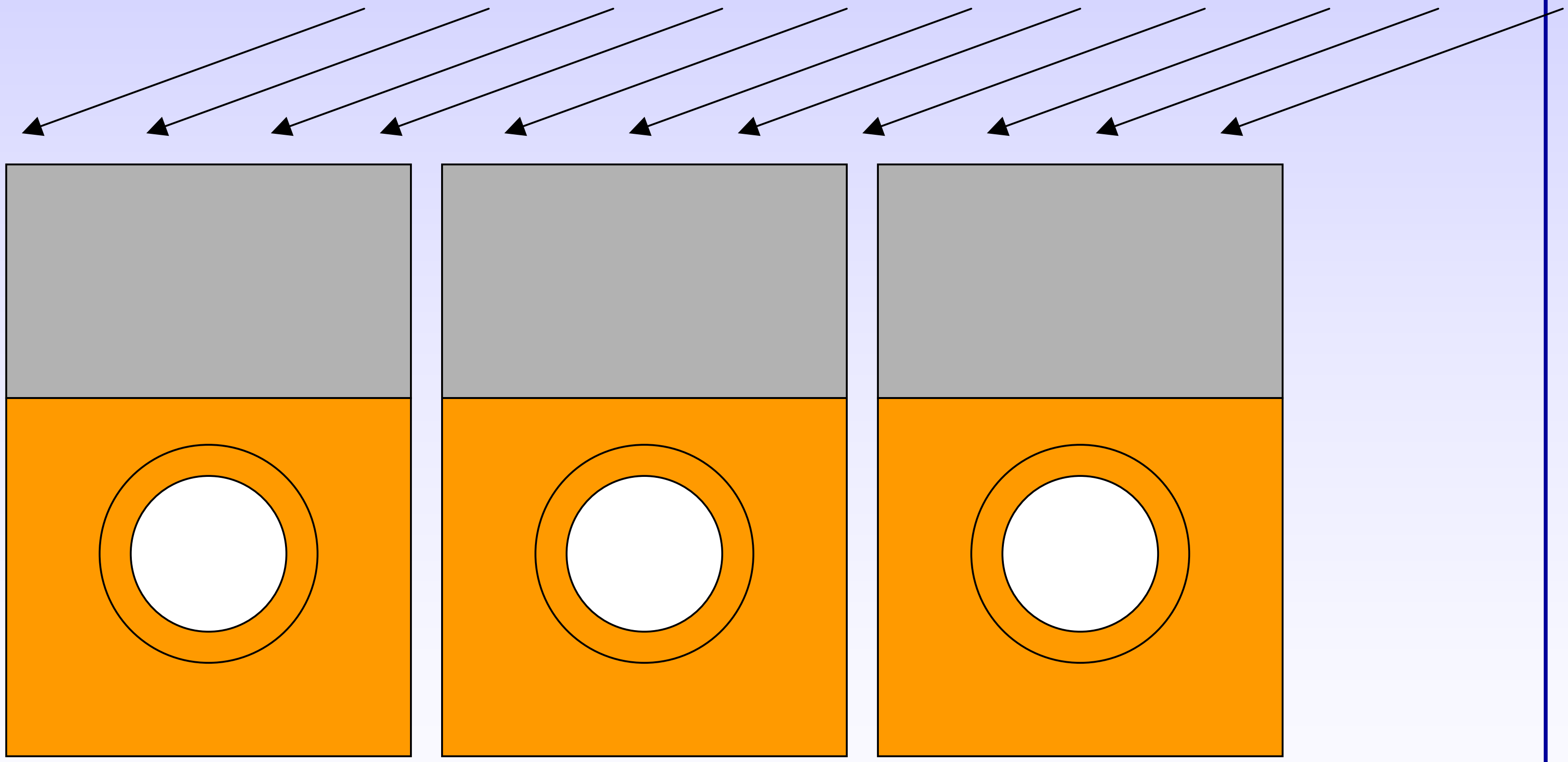
Scope of the activity

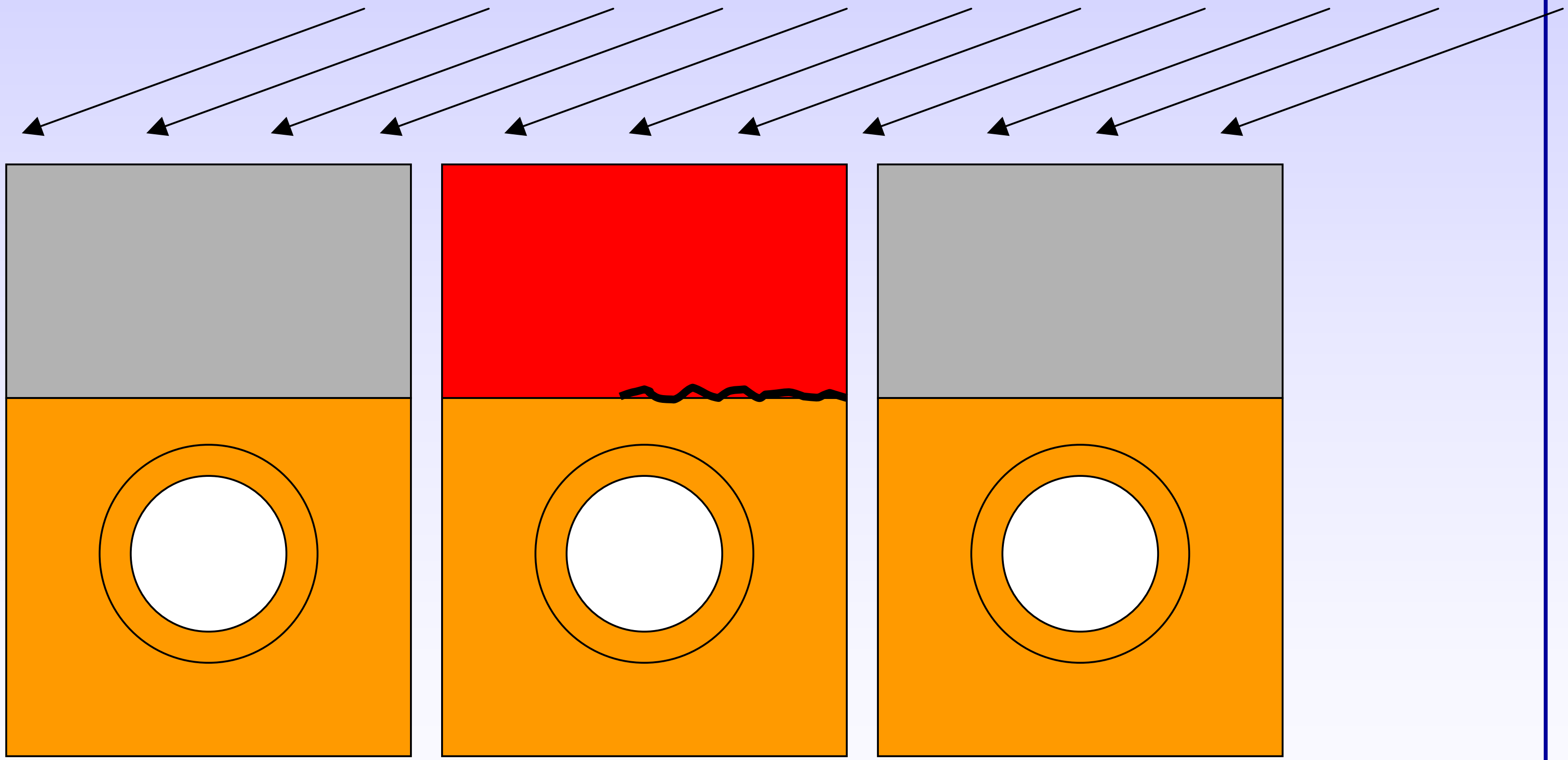
- To provide an analytical and experimental basis for the definition of acceptance criteria for the divertor PFCs

- To correlate this defect with the non-destructive testing evidence

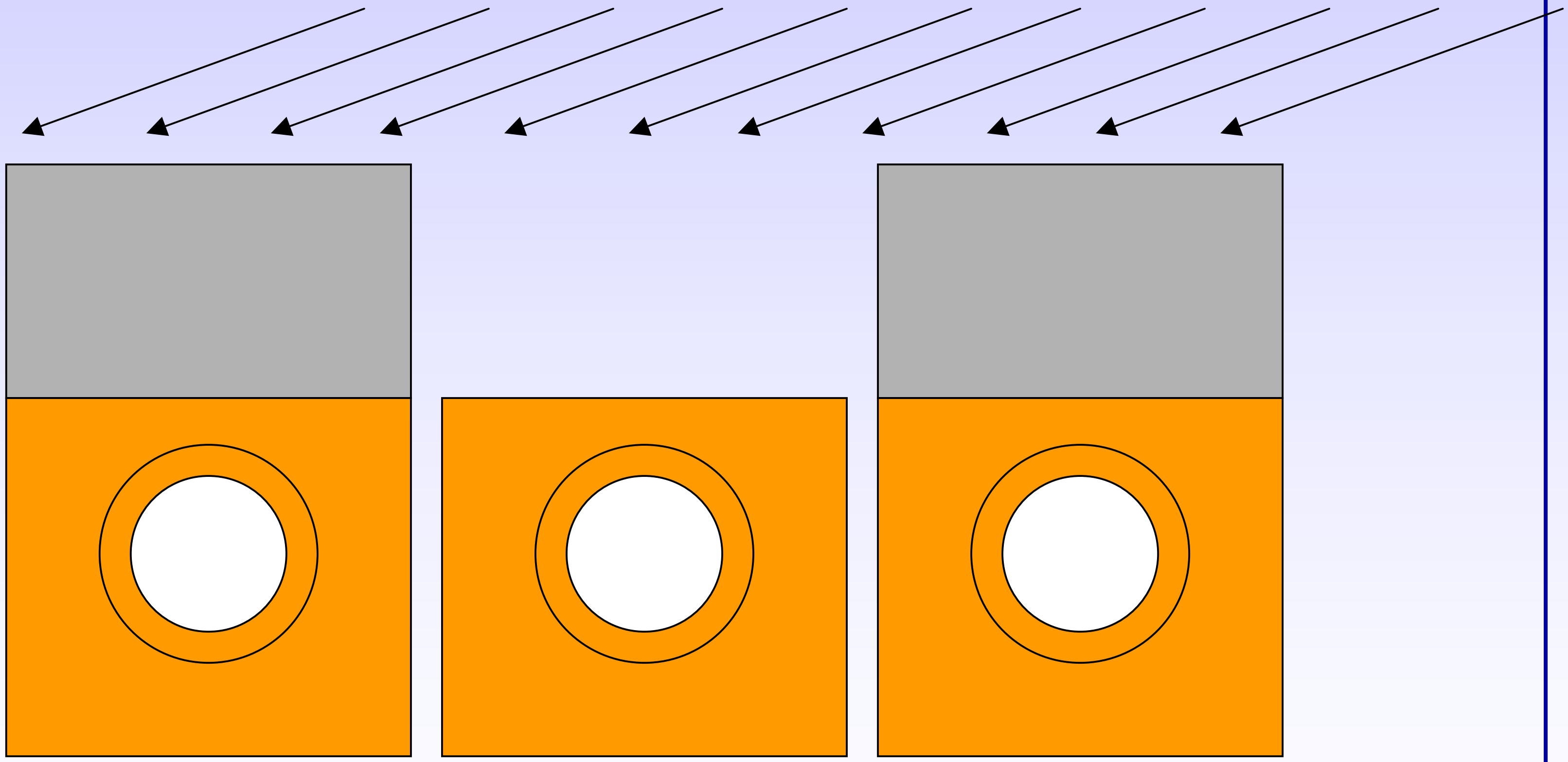
Failure of a flat tile



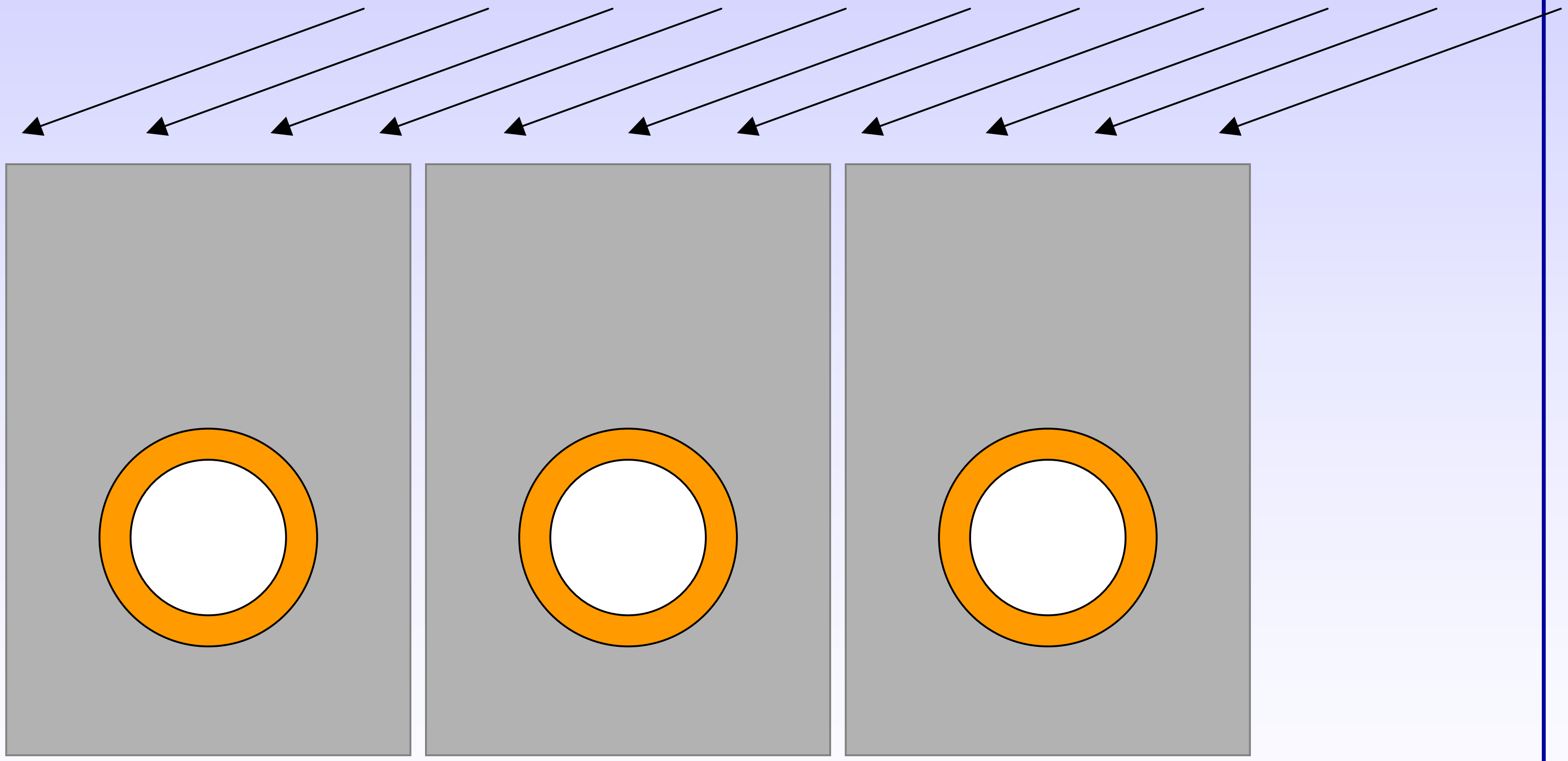
Failure of a flat tile



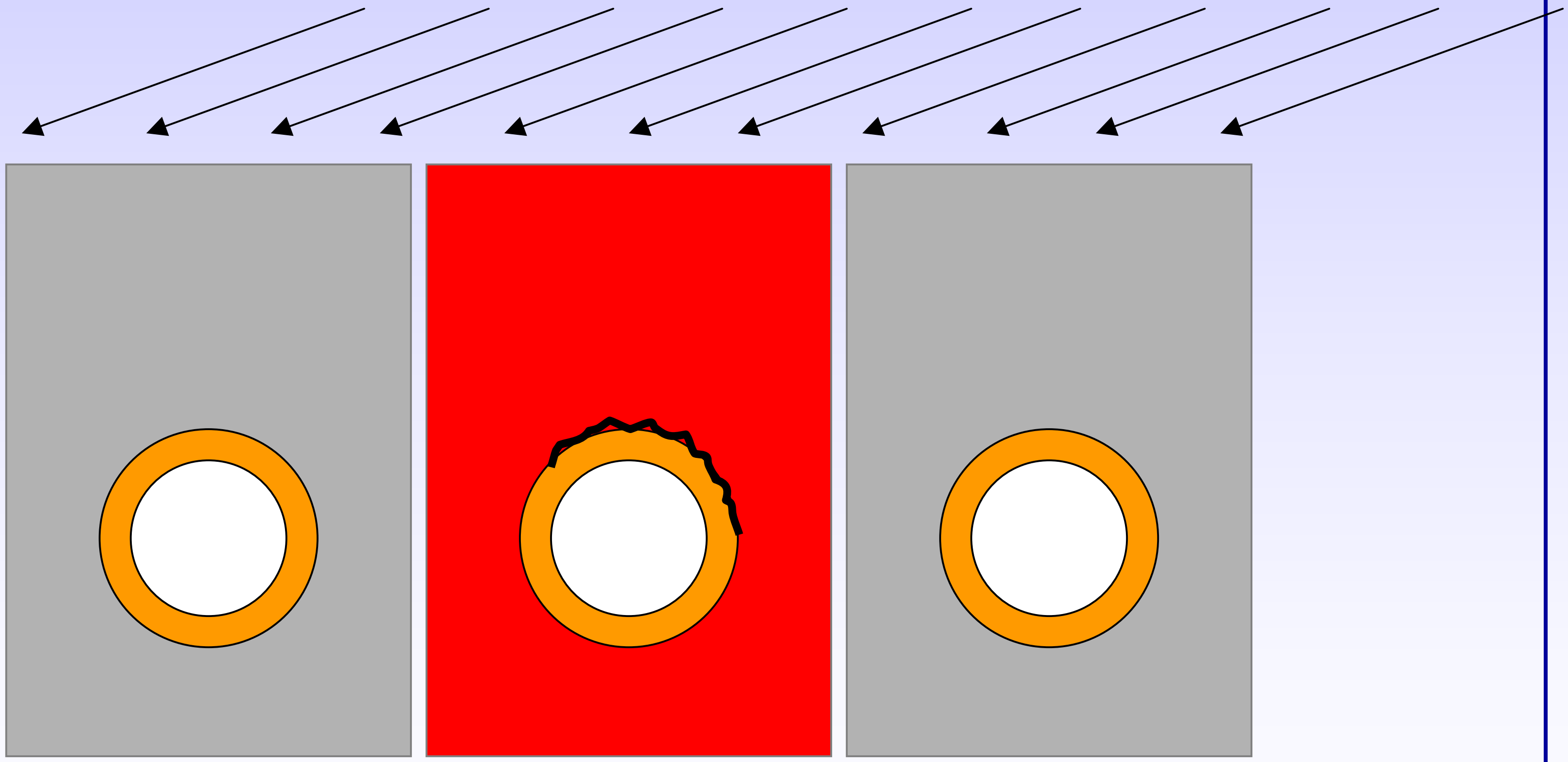
Failure of a flat tile



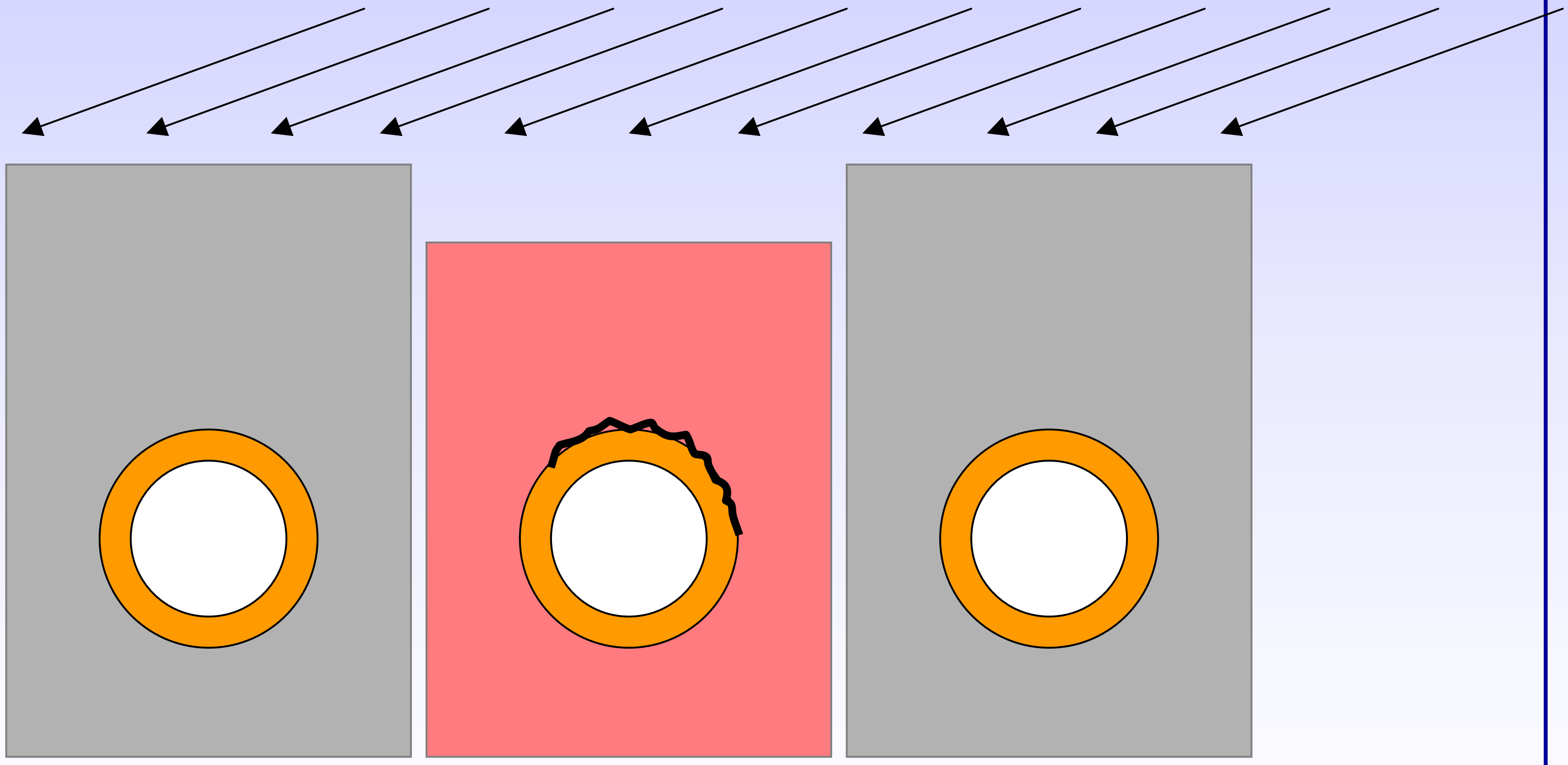
Failure of a monoblock



Failure of a monoblock



Failure of a monoblock



Thermography Acceptance Criteria

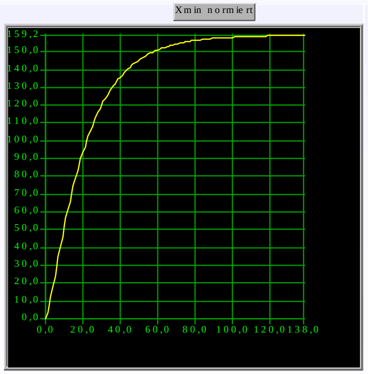
Statistical approach

In order to screen out defects that might lead to a CHF event or too high erosion the following tentative infrared acceptance values are proposed for discussion:

Less than 50% of the CFC monoblocks can have a DT > 4.0 °C

Less than 5% of the CFC monoblocks can have a DT > 8.0 °C

No CFC monoblocks shall be accepted with a DT > 10.0 °C



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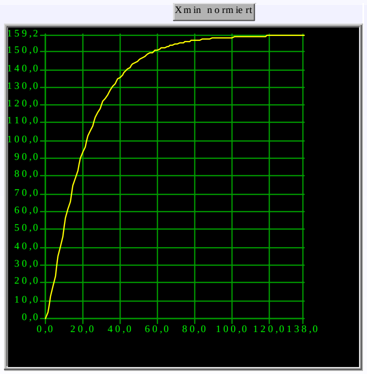

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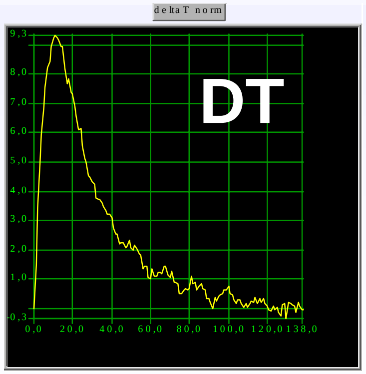

Planned activities

Manufacturing of more than 100 mock-ups with artificial defects

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High heat flux test of mock-ups with artificial defects

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Non-destructive and destructive examinations of mock-ups

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Final definition of the divertor acceptance criteria

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Present and future plans in the divertor area

- Completion of the on-going activities
- Optimisation of the existing HHF technologies and CFC materials
- Promoting competitions among industries
- Development of repairing methods
- Design supporting analysis
- Study of the effects of ELMs
- Diagnostic integration
- NDT methods during ITER procurement