Second Technical Meeting on Long-Pulse Operation of Fusion Devices at IAEA Headquarters in Vienna, Austria from 14–18 October 2024
15th of October 2024

Technological developments for the W7-X and JT-60SA metallic actively cooled divertors

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This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.

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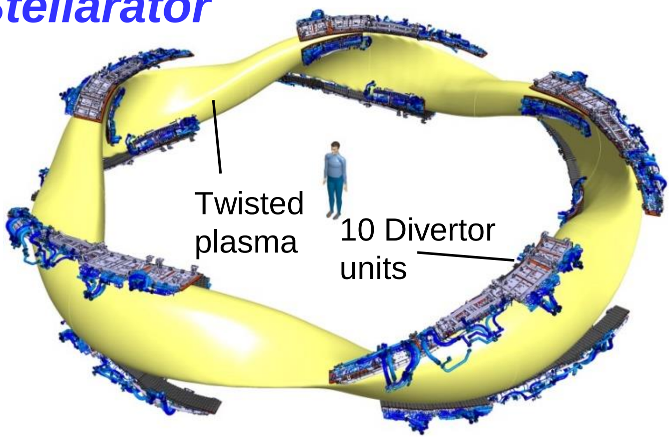
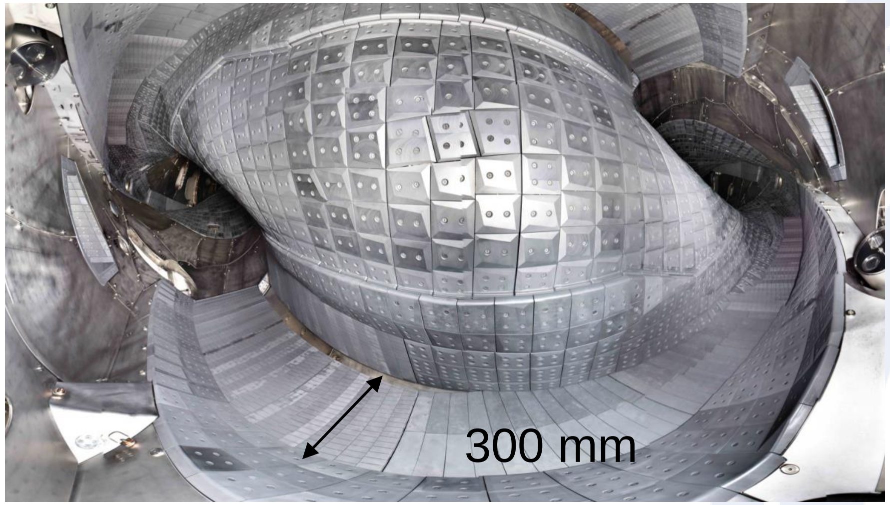
   - 2.3 Additive Manufacturing

1. W7-X and JT-60SA water-cooled divertor – Divertor targets

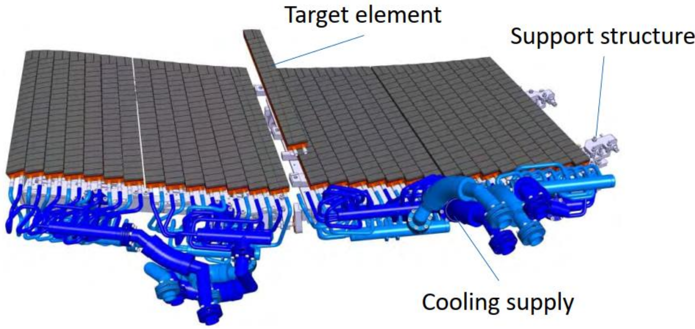
Stellarator



W7-X

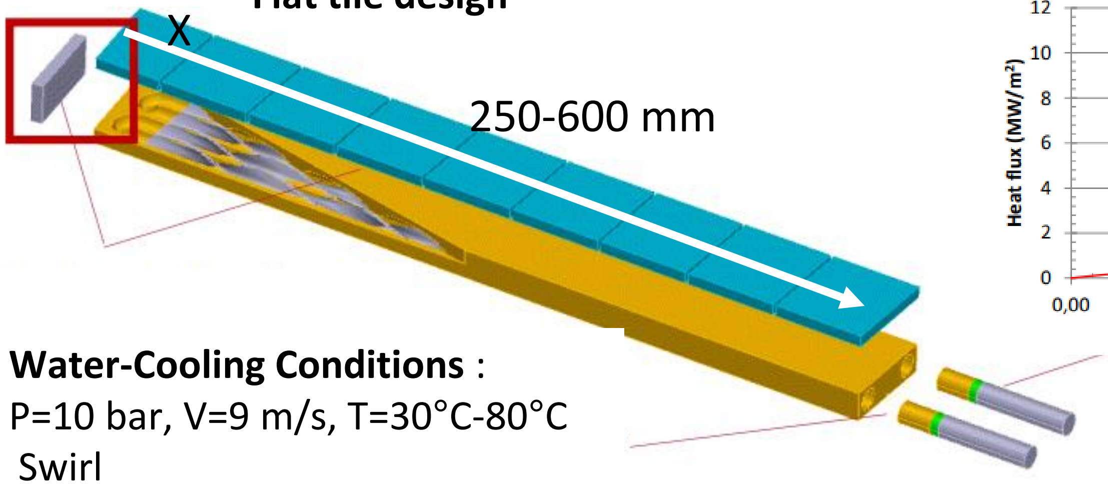


Target modules



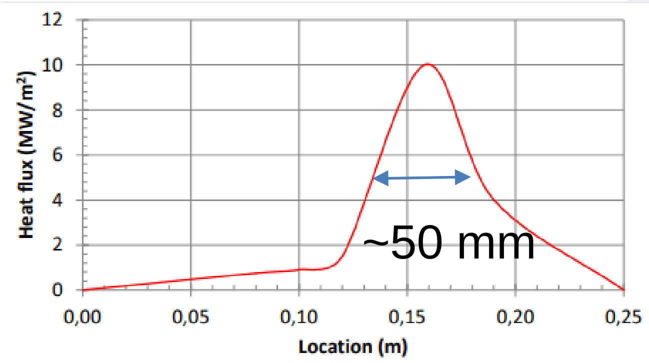
Target element:

Flat tile design



Water-Cooling Conditions :
P=10 bar, V=9 m/s, T=30°C-80°C
Swirl

Steady state heat loads

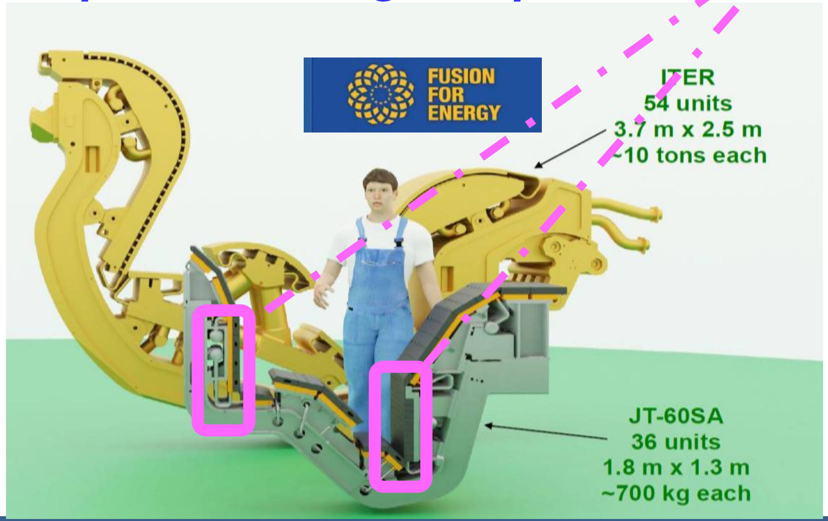


→ To be reactor relevant, W armour material is needed

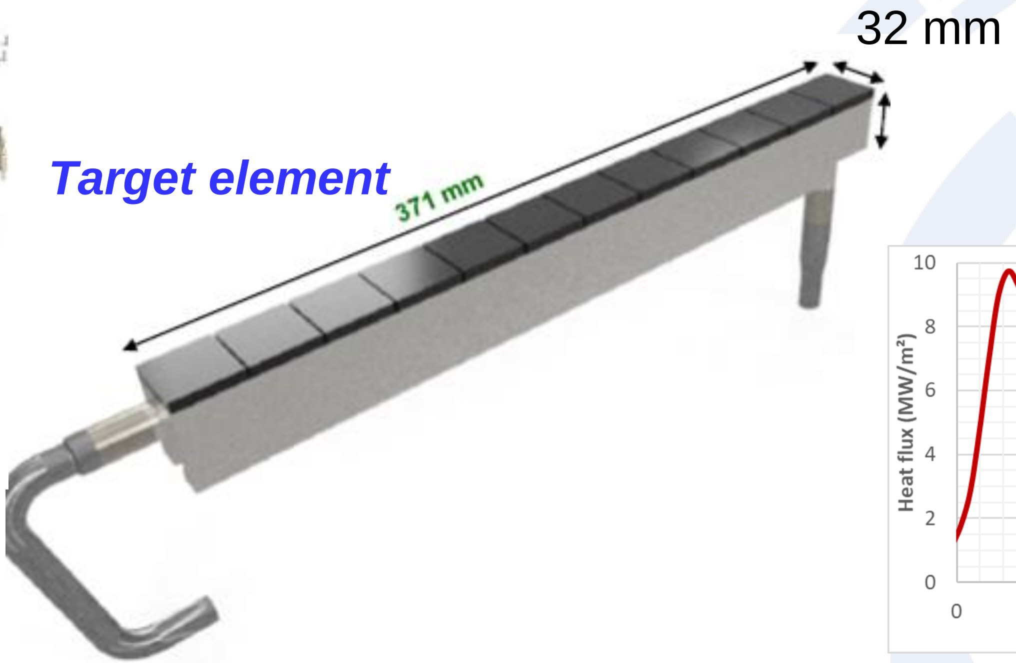
1. W7-X and JT-60SA water-cooled divertor – Divertor targets

→High-beta, inductive and non-inductive operation

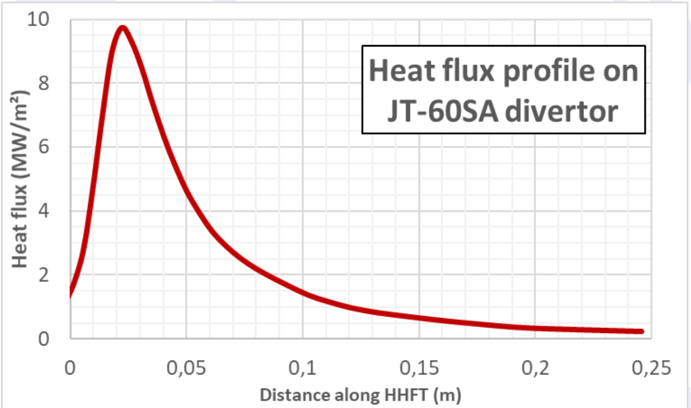
Divertor cassette and plasma facing components



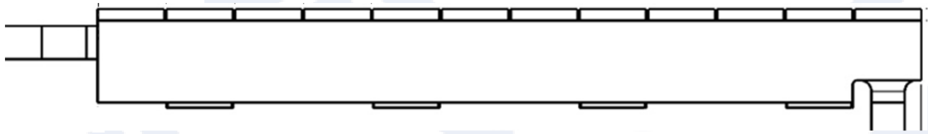
Target element



Steady state heat loads



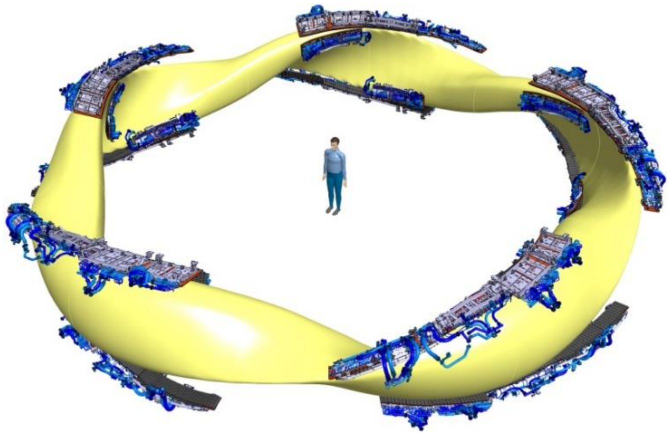
Cooling conditions :
20 bar, 7m/s, 40°C, swirl



→ To be ITER and DEMO relevant, W armour material is needed

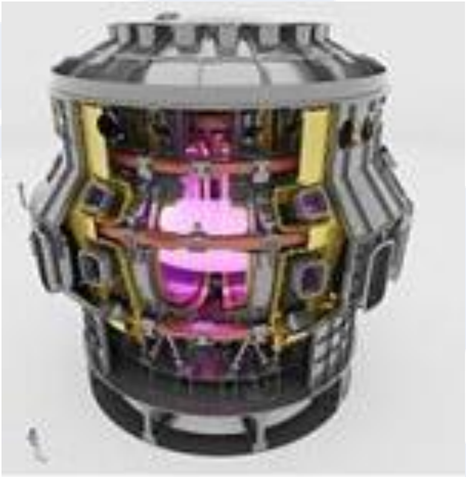
2. W7-X and JT-60SA divertor targets with W armor material

W7-X



- Activities started in 2021 within EUROfusion
- W armor material (to be relevant with European fusion power plant)
- Keep the present cooling system
- Minimize the interfaces changes between the target and the divertor support structure (similar weight…)

JT-60SA



- **Heat loads**

10 MW/m² (Steady state)
No VDE, ELMs…

- **Schedule**

Geometry defined : >2026
Technology qualified: 2026

- **Heat loads**

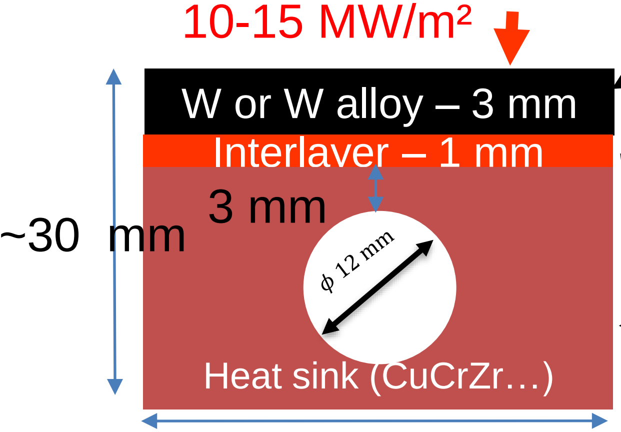
15 MW/m² (Steady state)
ELMs : 10 MJ/m² - 0.2 ms

- **Schedule**

Geometry defined: 2026 (EUROfusion)
Technology qualified: 2027 (EUROfusion)

2.1 Involved materials / Available concepts vs heat load

Flat tile – Circular channel



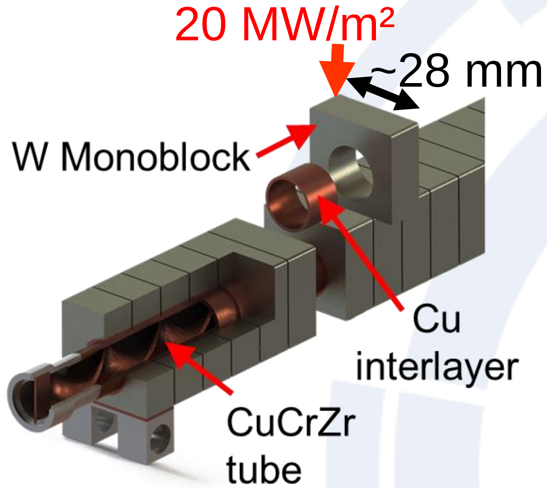
Ductility at RT (alloy),
Transient resistance
Erosion (> 2 mm)

joining feasibility

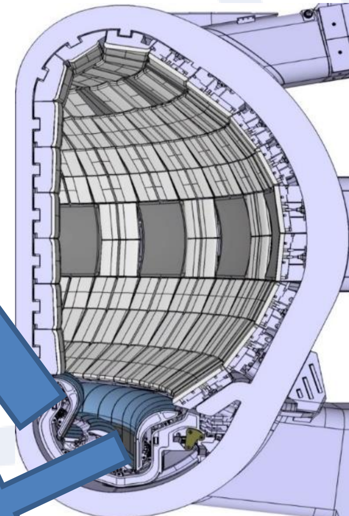
Structural resistance

- Mature fabrication (EAST)
- Developed by MPG for W7-X

Monoblock

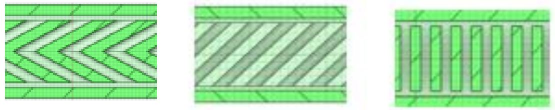


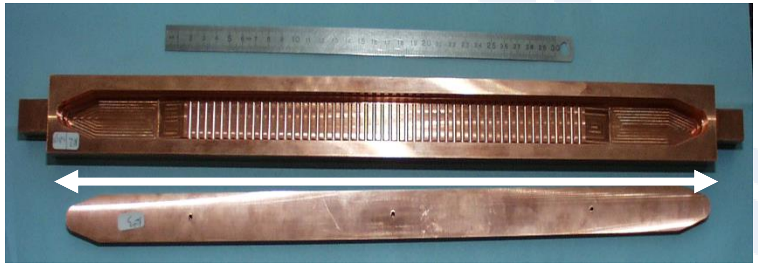
- Mature fabrication (WEST, EAST)
- Developed by F4E for JT-60SA W divertor

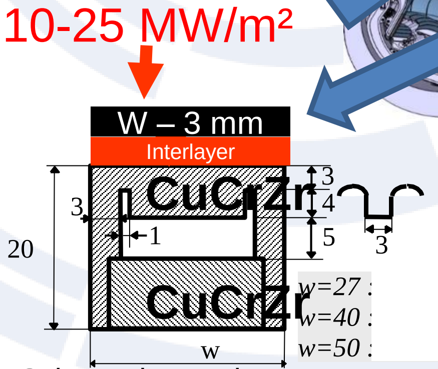


Enhanced : Flat tile – Rectangular + fin channel

- Different fin orientation [1,2]
- Fabrication maturity under investigation
- Developed by EUROfusion as alternative concept







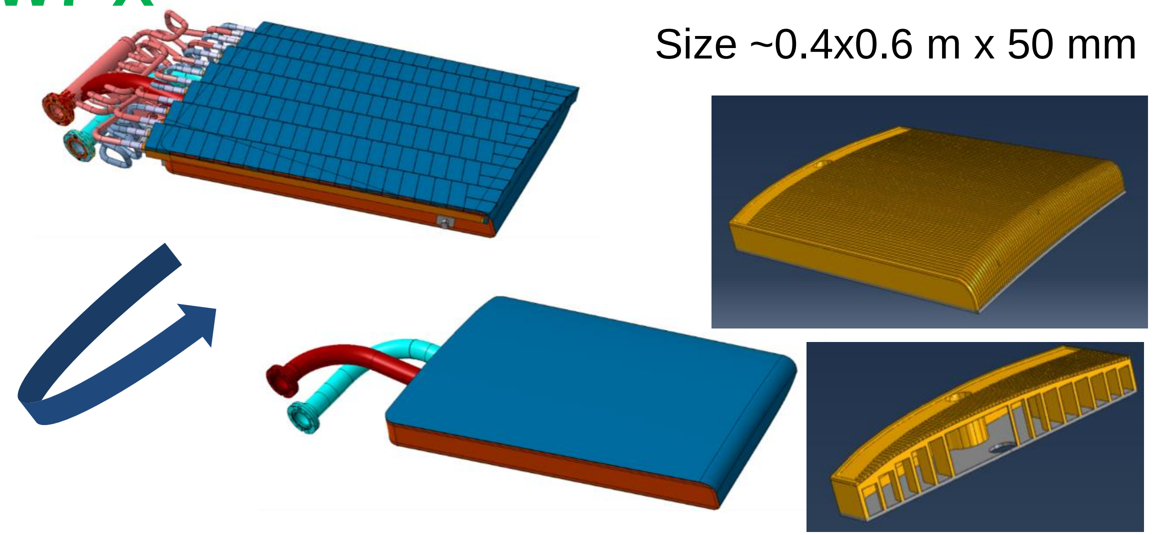
Schematic cut view

[1,2] Ji Hwan et al. (2022), Natthaporn Kaewchootong et al. (2017)

2.2 Choice of developed concepts

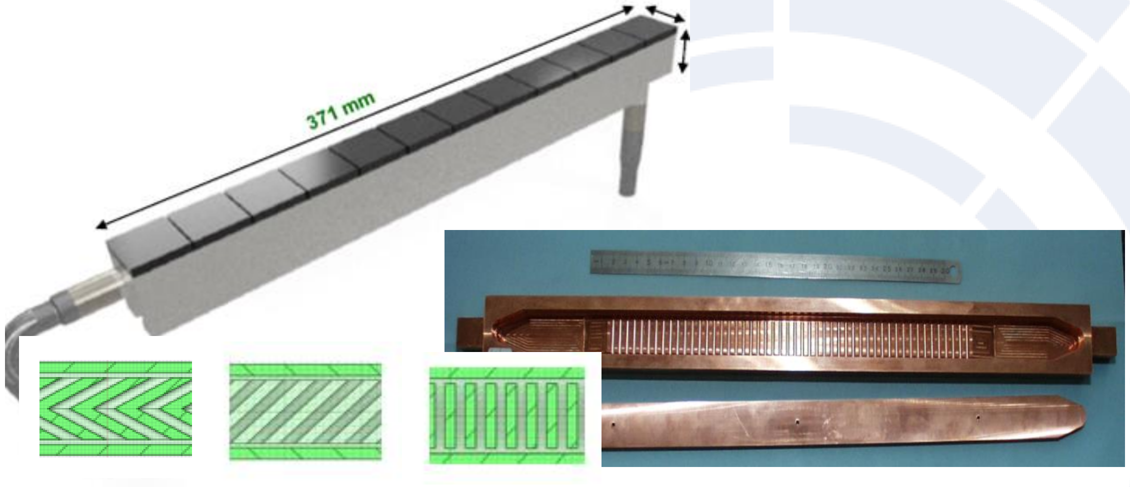
W7-X

Size ~0.4x0.6 m x 50 mm



➔Manifold included in the PFC

JT-60SA (Alternative concept)



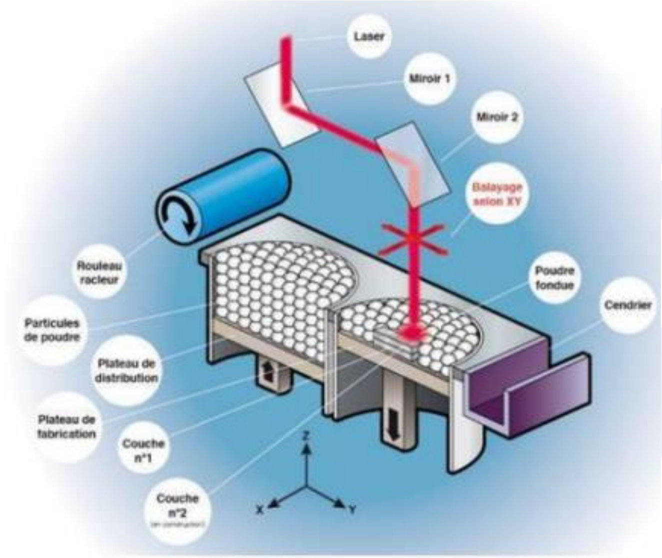
➔By design analysis, the proposed geometries are able to sustain specified heat loads (steady state)
➔The use of additive manufacturing may represent an advantage (reduce the manufacturing steps, evaluate the fin prefered option)
➔ W based amour material joining to CuCrZr: coating, hot isostatic pressing

2.3 Additive manufacturing

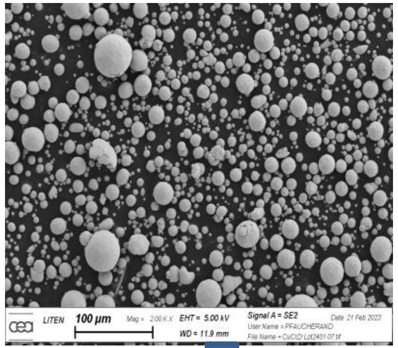
- Laser powder bed fusion

Used when >99% dense parts of medium size (from 1cm^3 up to 1m^3) with internal mm-size channels. Precision~0.1 mm

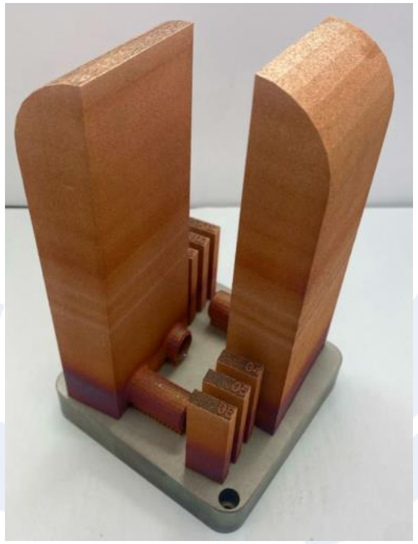
- Steps for qualification
  - Powder properties set to
    - achieve LPBF manufacturing (based on the past experience of the manufacturer)
    - achieve adapted properties on bulk materials (O, Cr, Zr… contents)
  - Bulk materials characterization
  - Mock-up testing and qualification (CuCrZr part)



[Franceschini 2016]



280 mm x 280 mm



98x98 mm

2.3.1 Process parameters – Achieved bulk materials

- Main characterizations
  - Densities (closed porosities)

  → Criteria/goal: Highest as possible

  → Achieved: 99.8 % (W7-X) – 98.2 % (JT-60SA)

  (May be fully densified after one Hot isostatic pressing (HIP))

  - Tightness (Open porosities)

  → Criteria: max. allowable He-leakage rate $1*10^{-9}$ mbar*l/s

  - Thermo-physical and mechanical properties

  → Criteria/goal: Sufficient properties after the complete heat conditions faced by the plasma facing component (manufacturing route + operation)

  (~ITER grade for the JT-60SA project, < ITER grade for the W7-X project)

2.3.2 Hot isostatic pressing (HIP) vessel

- For the HIP at CEA Laboratory (Grenoble), two different modules exists

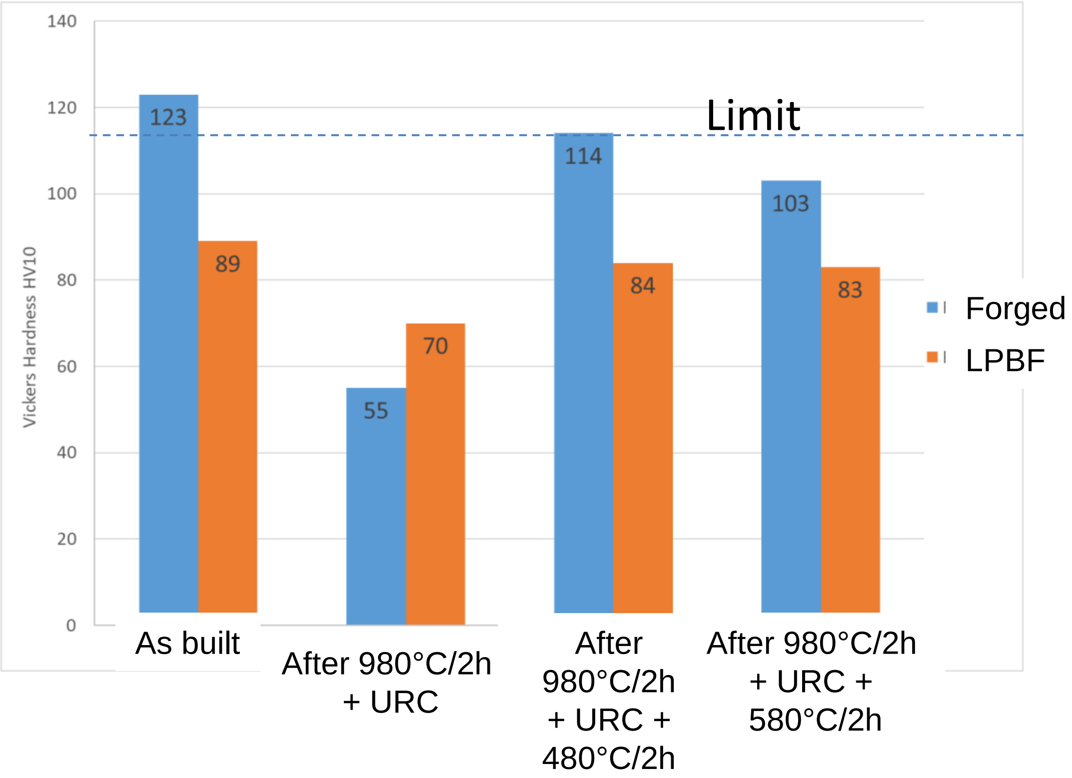
A Uniform Rapid Cooling module (URC) to reach 100°C/min

A Uniform Rapid Quenching module (URQ) to reach 2000°C/min

- Larger HIP vessel with this technology (Φ400mm, H1000mm, ~ 600°C/min) also available (Equipex CALHIPSO)

QIH 21 –URC module	
Max pressure of the vessel (MPa)	207
Max pressure for URC mode(MPa)	163.35
Max temperature (°C)	1400
Max height (mm)	700
Max diameter (mm)	228
Max cooling rate (°C/min)	200
Max work load (kg)	175
Thermal homogeneity(°C)	± 10

2.3.3 Impact of heat treatment on mechanical properties



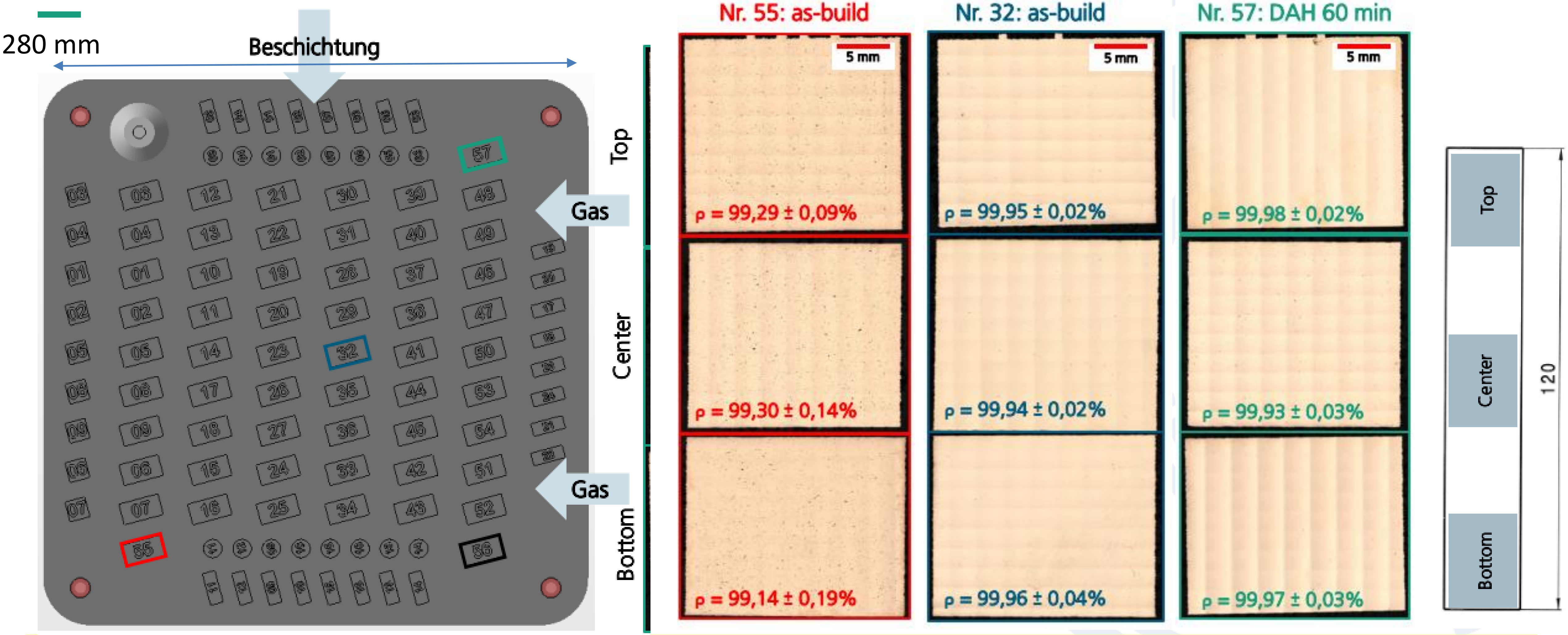
Uniform Rapid Cooling 100°C/min

→ Effect of heat treatment on mechanical properties (already shown in the literature)

→ For the JT-60SA project, heat treatment needs to be optimised

2.3.4 Example of concern for mock-up manufacturing

Density dependence on printing position

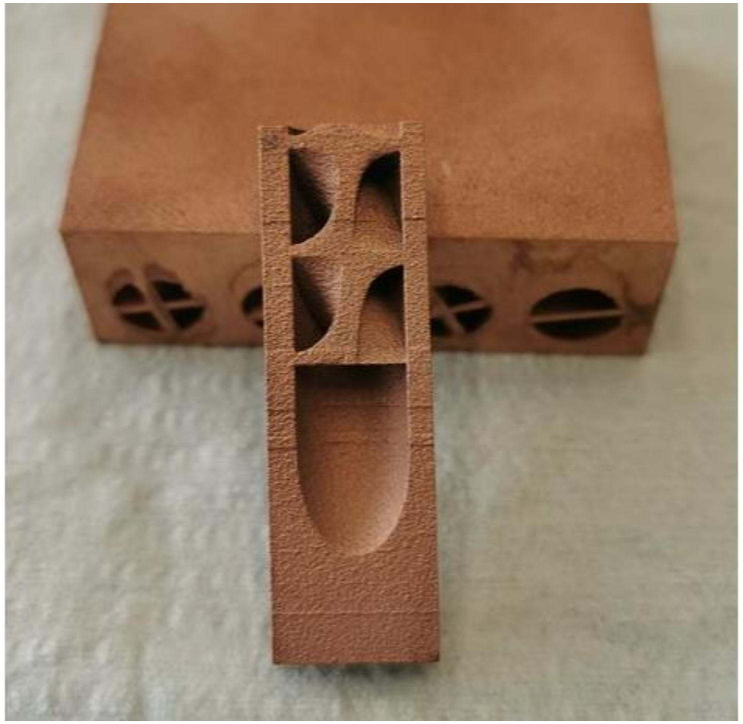


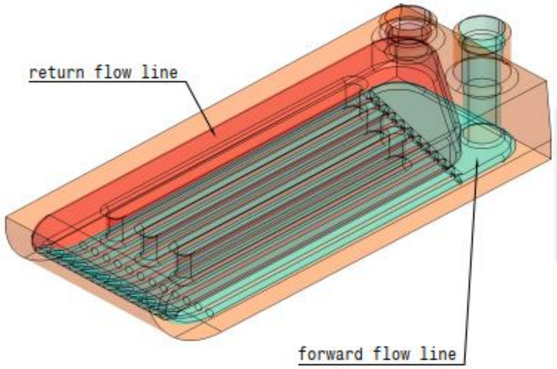
→ Decrease of density in direction of gas flow

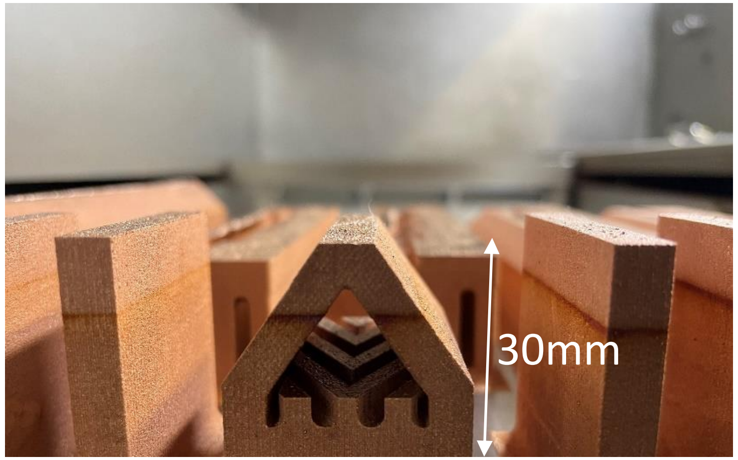
→ No effect of building height / no effect of Direct aged hardening / no effect of powder supply direction

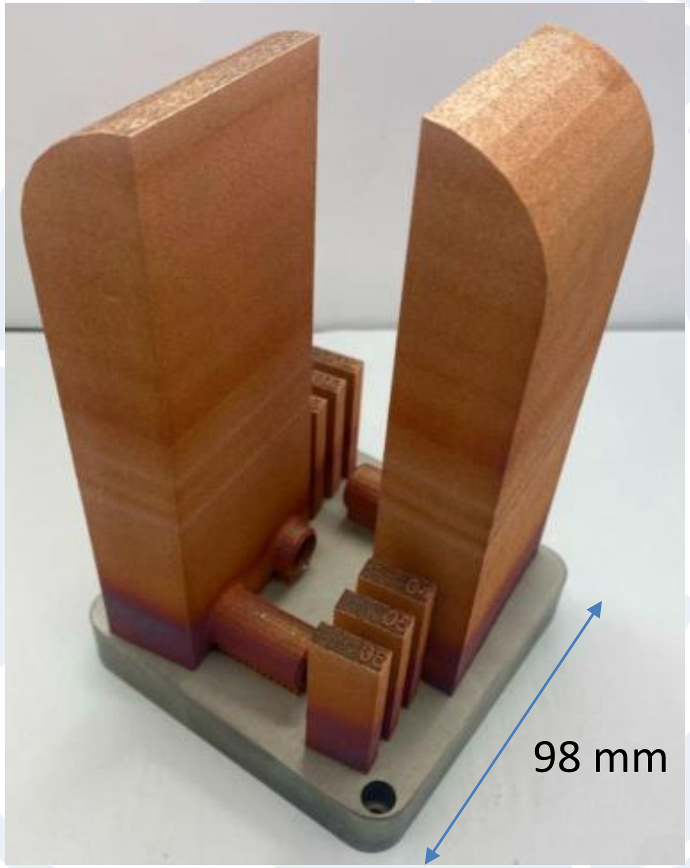
2.3.5 From mock-up point of view

- Heat exchange promoter and fins integrations feasible
- Small mock-ups manufactured to be high heat flux tested







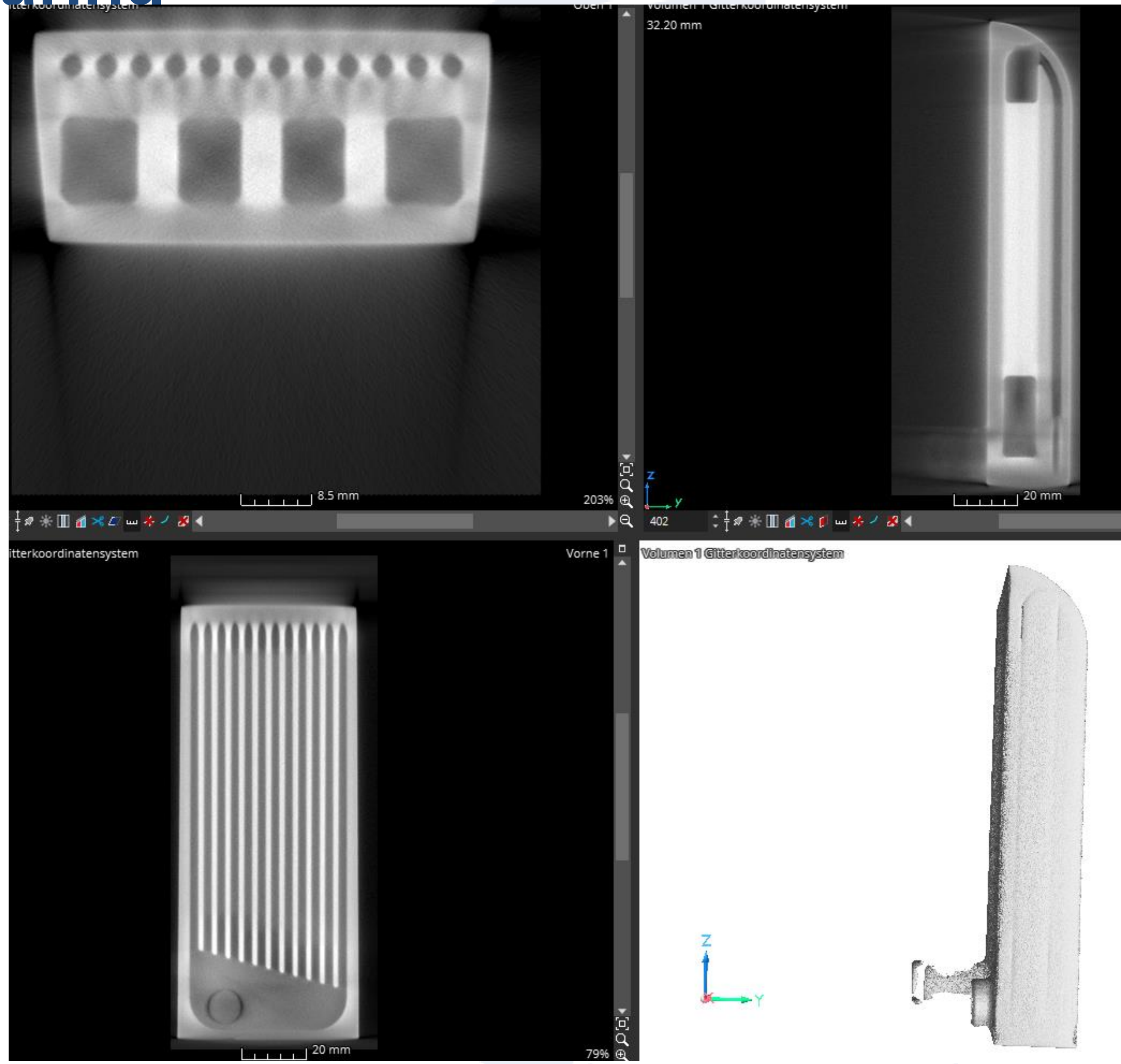


2.3.6 Non-destructive techniques to check the quality after CuCrZr additive manufacturing

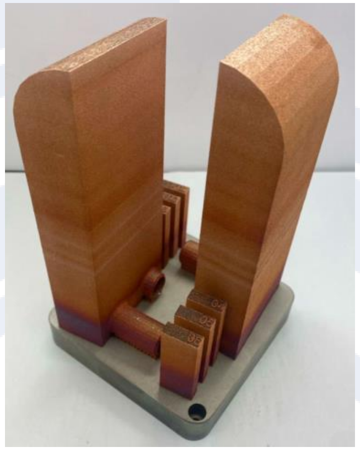
- De-powdering solutions
  - Mechanical shaking
  - Pressurized liquid flow through channels
    - Measuring powder rests in the liquid

- CT-scan mandatory to check the remaining powder
  - 80 µm resolution
  - Max size: ~900 x Ø600 mm
  - Cost depends on resolution

- He leak test mandatory (open porosities)



Conclusions



- Divertor water cooled target with W armor material for W7-X and JT-60SA
  - Installations needed (reactor relevant)
  - Steady state heat loads requirement : 10 MW/m² (W7-X) to 15 MW/m²(JT-60SA)
  - Current designs: Joining with flat interfaces
  - Alternative designs are developed to propose designs able to handle the required heat flux while being manufactured with lower cost
  - Technological developments provide promising results, some optimization still needed (heat treatment…)
  - To understand the hardening mechanisms of CuCrZr – LPBF we propose to perform investigations to determine
    - The density of Cr and Zr hardening nano precipitates (responsible of hardening)
    - The chemical composition of these nano precipitates
    - The grain size and the density of dislocations and their influence on precipitations mechanisms
  - On the complete mock-up, the main qualification test remains the high heat flux testing preceded by non-destructive testing (ultrasonic testing, Infrared thermography testing)

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