From Legacy to Leading-edge: Optimizing Hypervapotron's Cooling for Extreme Heat Flux in Fusion Applications

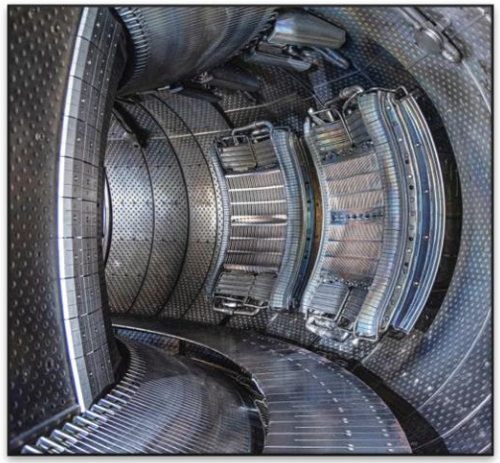
34th Symposium on Fusion Technology

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Aix-en-Provence, France,
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Fundamentals on Plasma Facing Components (PFC)
Current design limit and alternative design



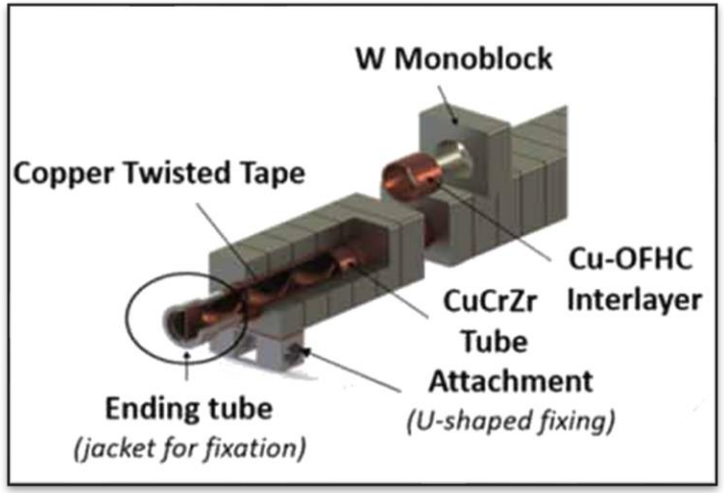
Inside view of WEST tokamak

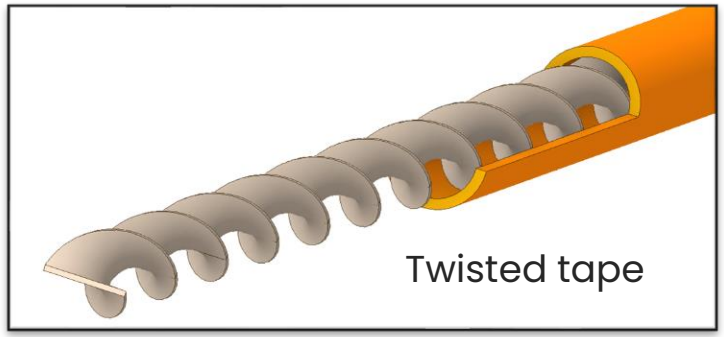
PFC functions and challenge

- **3 roles**: plasma-facing material, transfer heat to coolant, structural attachment
- Most advanced design : **monoblock** with twisted tape (ITER-like), limited to ~25MW/m² (critical heat flux)
- **Challenge**: increase incident heat flux limit for future devices without lifetime decrease

Alternative candidate: hypervapotron (developed since the 1980s), but development limited by manufacturing and modeling difficulties

Monoblock design





Outline

1. **History of hypervapotron: from invention to fusion field**
2. **New manufacturing route**
3. **PFC qualification**
4. **Beyond hypervapotron performances**
5. **Fluid simulation progress in fusion conditions**

A brief history on hypervapotron

1951 Charles Beurtheret (Thomson-CSF) innovation on tetrode (television transmission): **vapotron effect**, based on thermal anisotropy along fins to **create and evacuate vapour burst in steady-state :**

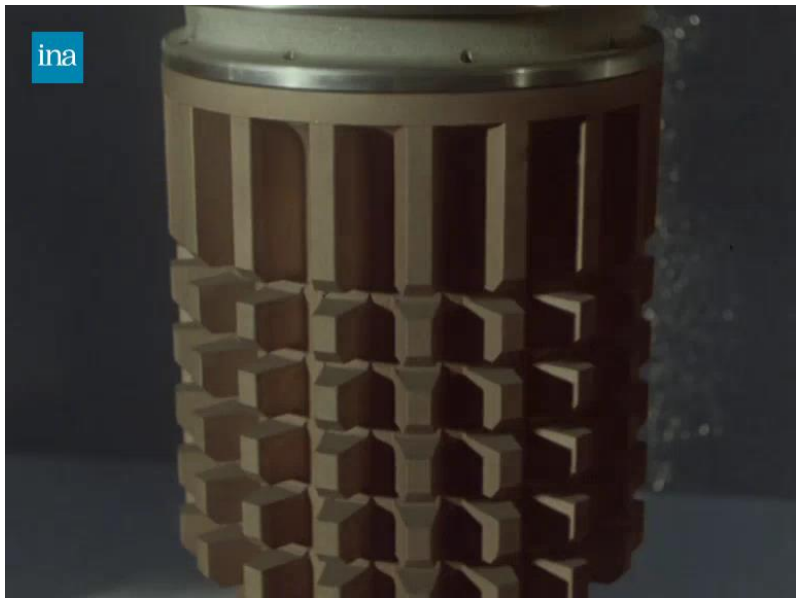
- vapotron (large protrusions - 150W/cm²) – 1950s
- supervapotron (small fins - 500-700W/cm²) - 1960s
- hypervapotron (forced flow perpendicular to the fins +1000W/cm² *"with a wide margin of safety"*) – 1970s

Main characteristics : low pressure water, low flow rate, high thermal efficiency



TH467 – 1955 Vapotron | TH543 - 1959 Supervapotron | TH590 – 1974 Hypervapotron

https://lampes-et-tubes.info/tt/Thomson-CSF_Vapotron_cooling_techniques.pdf



https://www.ina.fr/ina-eclaire-actu/video/afe07000086/radio-electronique

From anode to plasma facing components

Route from RF anodes to fusion PFC is not clear (maybe through physicist/engineers from the CERN where HV tetrodes are largely used in the early 80s)

From 1986, JET operates ~300 elements (flat NBI scrapper) : 10 000s stress cycles at full power load of 10 MW/m² (Falter et al., 1996 Fusion Technology)

Soon after, **publications** in the fusion field starts increasing, but total stays low

As of today, publications show a limited understanding of the internal mechanism

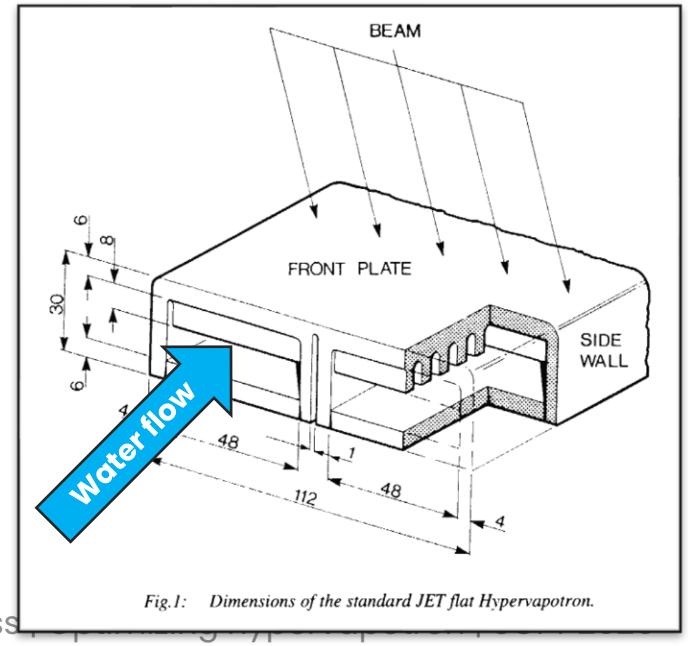
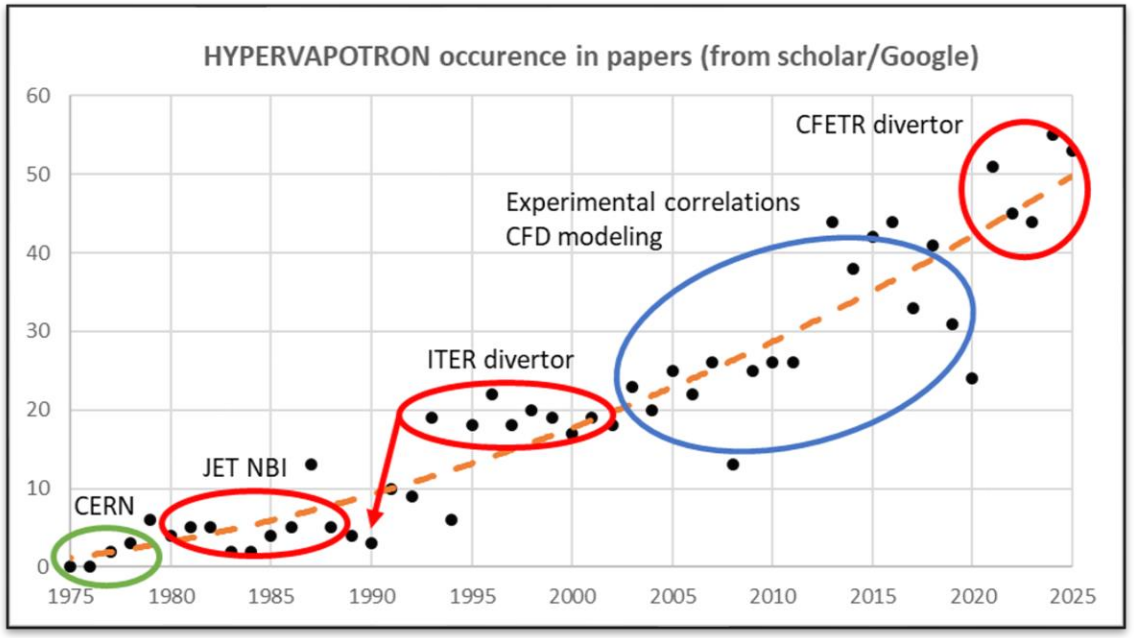


Fig.1: Dimensions of the standard JET flat Hypervapotron.

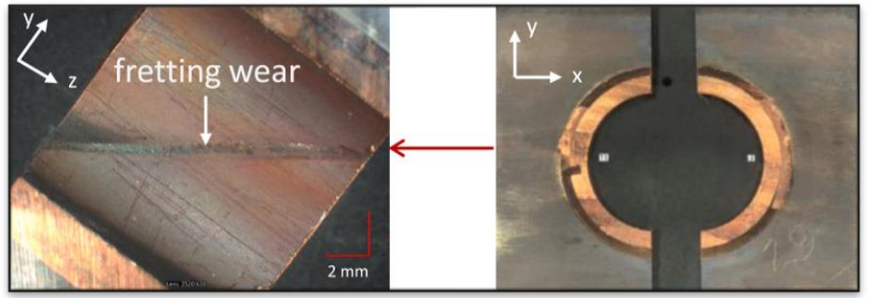


Expected advantages over monoblock design

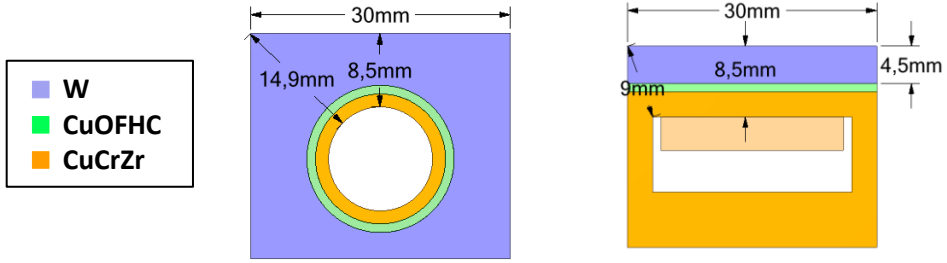
By design, hypervapotron is **insensitive to twisted tape fretting** and associated tube damages, as shown in the last years

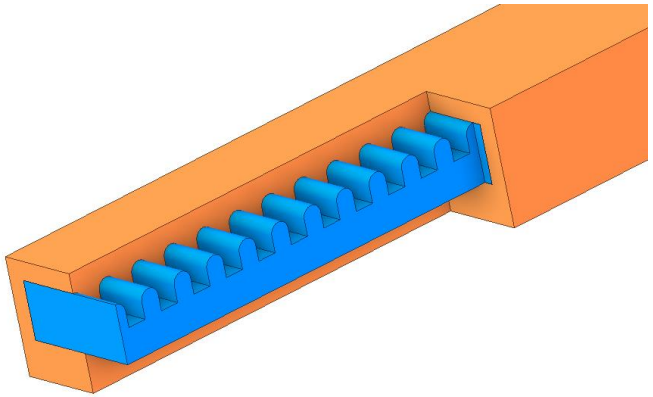
As **boiling is very efficient to remove heat flux** (latent heat of vaporization), hypervapotron is by design more efficient for a similar hydraulic diameter

Rectangular channel geometry is more adapted to armour material: edges closer to the channel (temperature lower) and interface is flat (joining and qualification are easier)



S. Baydoun et al., 2026 Wear





Internal view of an HV design – coolant volume in blue

Pressure drop could be in the same range, to be assessed with the final geometry

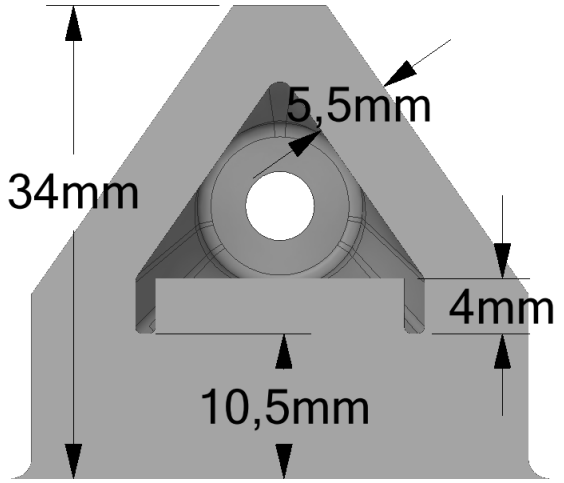
For similar geometries, hypervapotron design may be advantageous, with a caveat on pressure drop

The game changer : additive manufacturing

Laser Powder Bed Fusion (LPBF) has transformed from a prototyping tool into a cornerstone industrial technology

CEA/LITEN, pioneer in producing CuCrZr heat sink with LPBF [1], adapted their process:

- CuCrZr powder within fusion standard (chemical composition and powder properties)
- **Triangular channel shape adopted to avoid collapse of the part**



Produced CuCrZr material main properties [2]:

- relative density 98.5 to 99.4%
- thermal conductivity ~40% standard value
- hardness 90% standard value
- anisotropic microstructure with columnar grains

Thermal treatment after manufacturing is required


LPBF hypervapotron, triangular shape

[1] Salvan et al., 2021 Materials Science and Engineering
[2] Dias Aleixo et al., 2025 Nuclear Material & Energy

Hot Isostatic Pressure (HIP) as a two-in-one process: joining and heat treatment



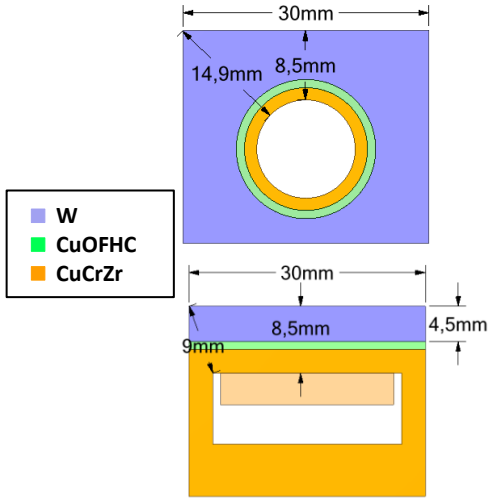
Qualified HIP W/Cu/CuCrZr/316L (monoblock):

1. *HIP (CuCrZr/316L) 1040°C 0,5h*
2. *Solution Annealing 980°C 1h + Fast cooling (>60°C/min)*
3. *HIP (W/Cu/CuCrZr)/ageing 580°C/2h*

Proposal: include solution annealing step in first HIP

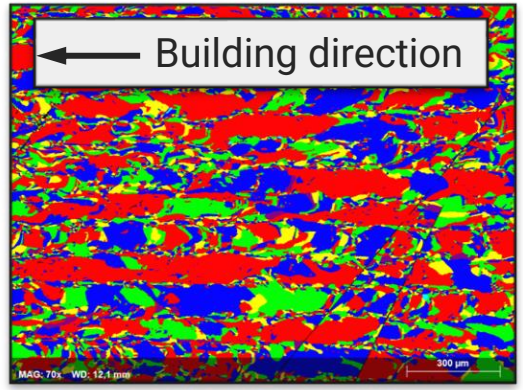
Adaptation of the standard 2-cycles process for joining:

1. *HIP (CuCrZr/316L) 980°C/2h + Fast cooling (>60°C/min)*
2. *HIP (W/Cu/CuCrZr) ageing 580°C/2h*



Only possible with the **use of a HIP device with Uniform Rapid Cooling** (cooling up to 110°C/min)

Density and thermal conductivity recovered but LPBF CuCrZr microstructure resistant to grain growth: **anisotropy remains**

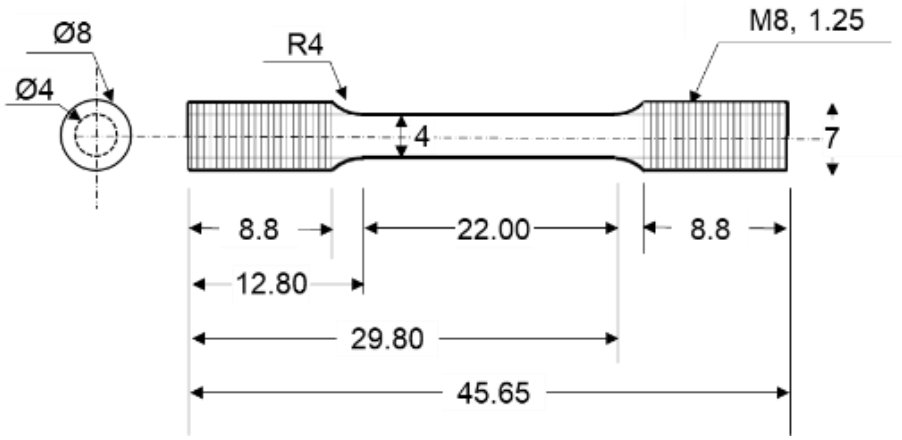


P.-E. Frayssines et al., HIP 2025

Two processes with one device: CuCrZr thermal treatment and material joining

Material properties after thermal treatment: in line with standard fusion specifications

	YS 20°C	YS 250°C	UTS 20°C	UTS 250°C	ΔL/L 20°C	ΔL/L 250°C
Building	180	164	298	242	32	25
Cross building	169	154	274	225	36	32
Min ITER specs [1]	**150**	**125**	**260**	**200**	**15**	**14**



Tensile tests following ISO 6892-1 : 2019 / ASTM E8/E8M (∅ 4mm specimens)

Building direction (vertical) and **cross building direction** (horizontal) are tested

Material slightly non isotropic (~10%), in line with grain orientation and in spite of thermal treatment

Results are in agreement with reference specs(ITER) regarding strength, tensile strength and total elongation at room and high temperature

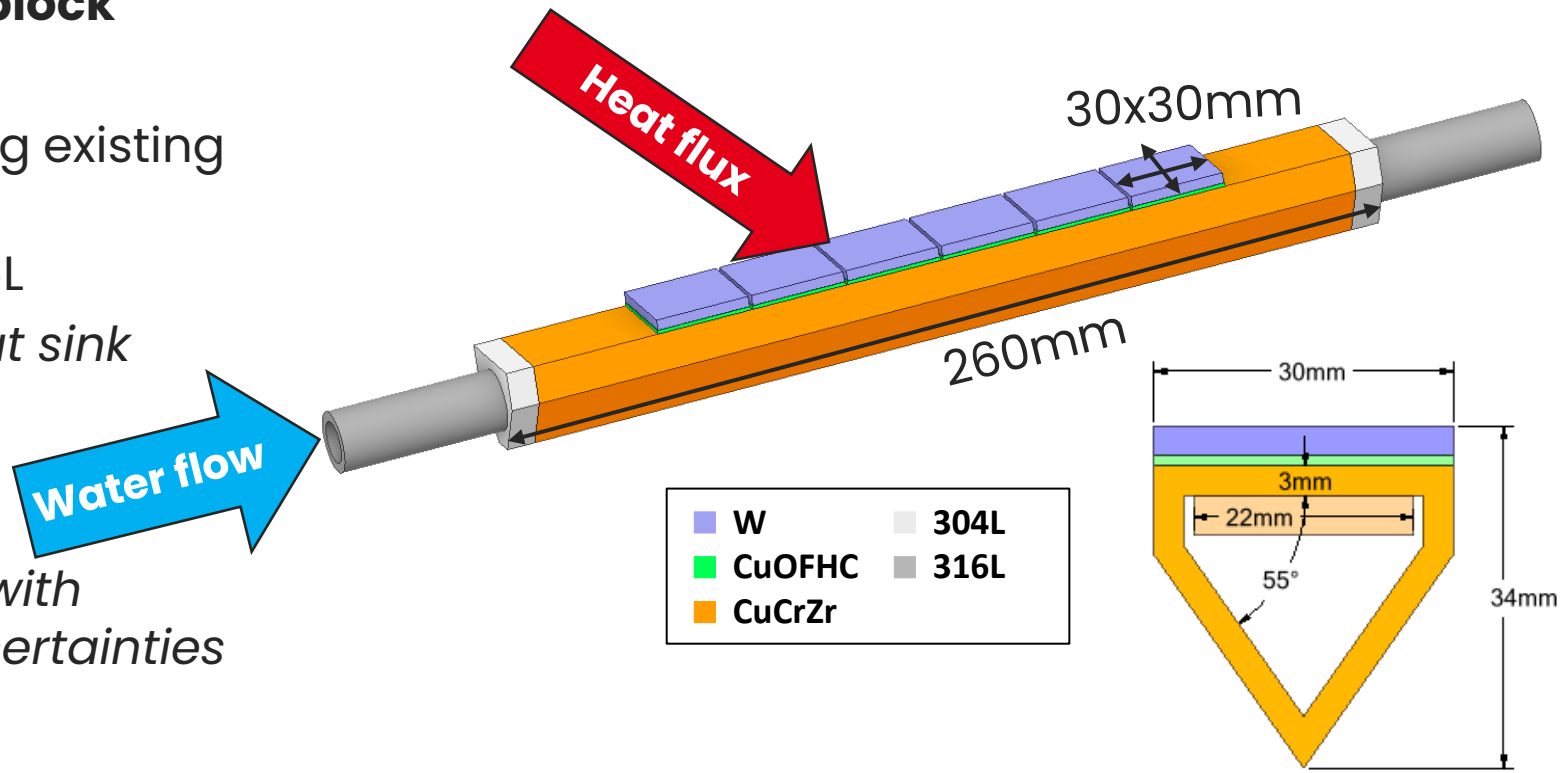
[1] M. Sardo et al., 10.1016/j.nme.2025.101993

Toward an enhanced PFC for divertor

Currently under procurement, **JT-60SA W divertor target is reference case**
Hydraulic conditions are different to ITER reference: 40°C / 20 bar / 7 m/s

Eurofusion project to produce **medium scale mock-ups** (using the LPBF+HIP route) and **compare performances to monoblock**

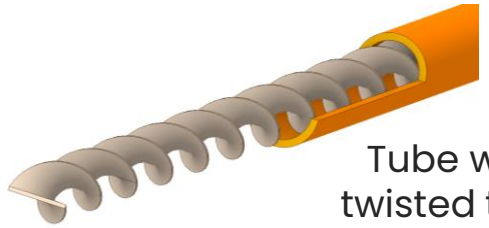
- Heat sink with hypervapotron
- Hypervapotron designed using existing ad-hoc correlations*
- Inlet/outlet tubes made of 316L
- *W tiles covering a CuCrZr heat sink*



**correlations based on experiments, with limited validity domain and large uncertainties +- 30% heat transfer prediction [1]*

[1] Lim and Park, 2021 Physica Scripta

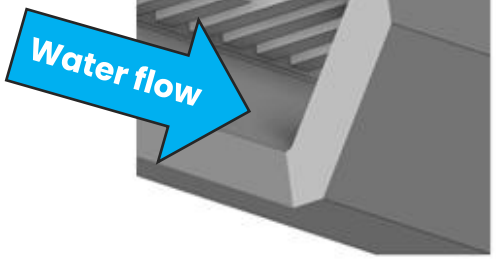
Pressure drop comparison
Hypervapotron design well adapted



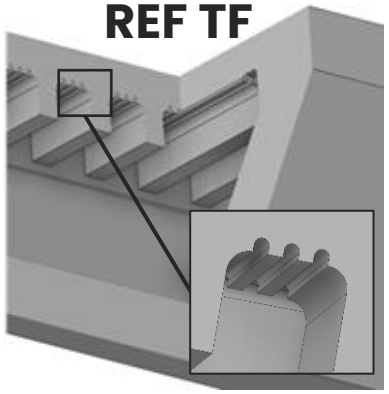
Tube with twisted tape

Same hydraulic diameter for tube with twisted tape and triangular hypervapotron

REF

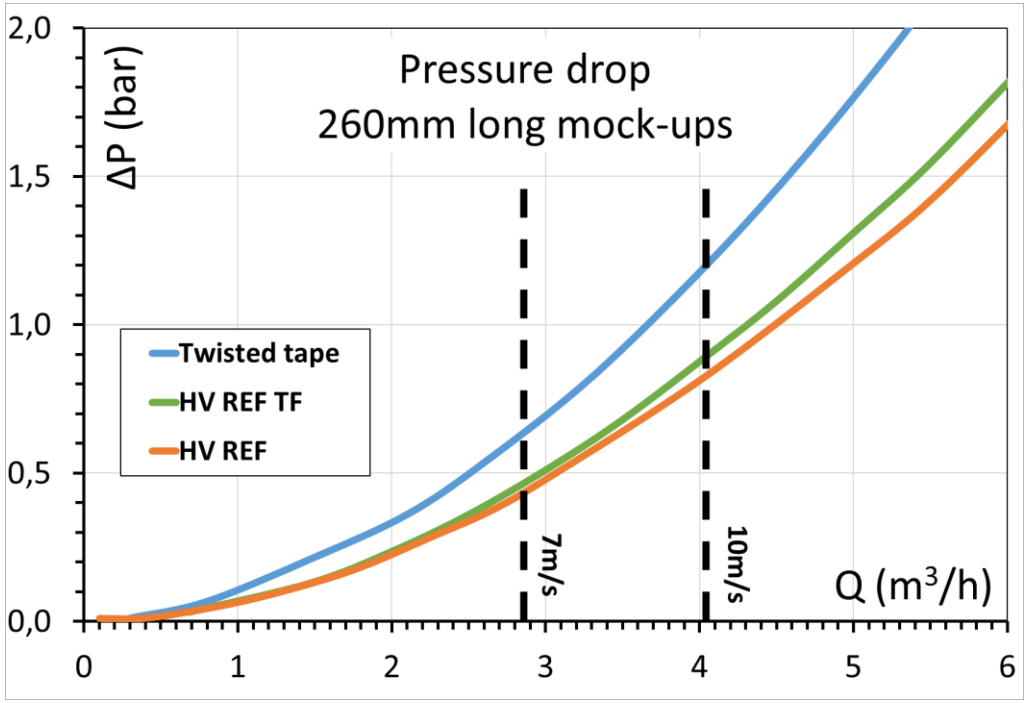


REF TF



Two hypervapotron designs are compared with twisted tape:

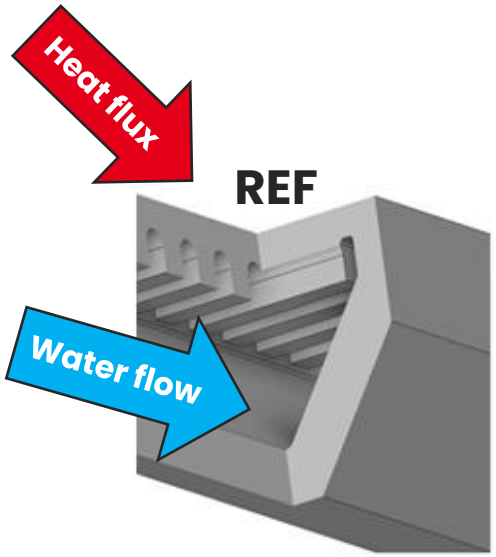
- **REF**erence design, close to the original JET hypervatpotron
- **REF**erence with **T**ransverse **F**ins design



Hypervapotron has lower pressure drop than twisted tape, up to 35% in the divertor regime (7 to 10 m/s) for original hypervapotron

[1] Dias Aleixo et al., 2025 Nuclear Material & Energy

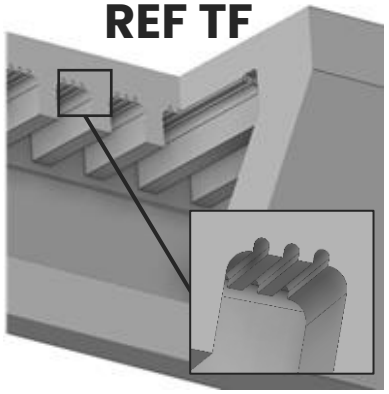
High heat flux tests in HADES facility
Hypervatron design thermally efficient



2 hypervapotrons heat sink (only CuCrZr) tested in steady-state (15 s), **stepped heat flux** up to CuCrZr max temperature (~800°C) or start of boiling

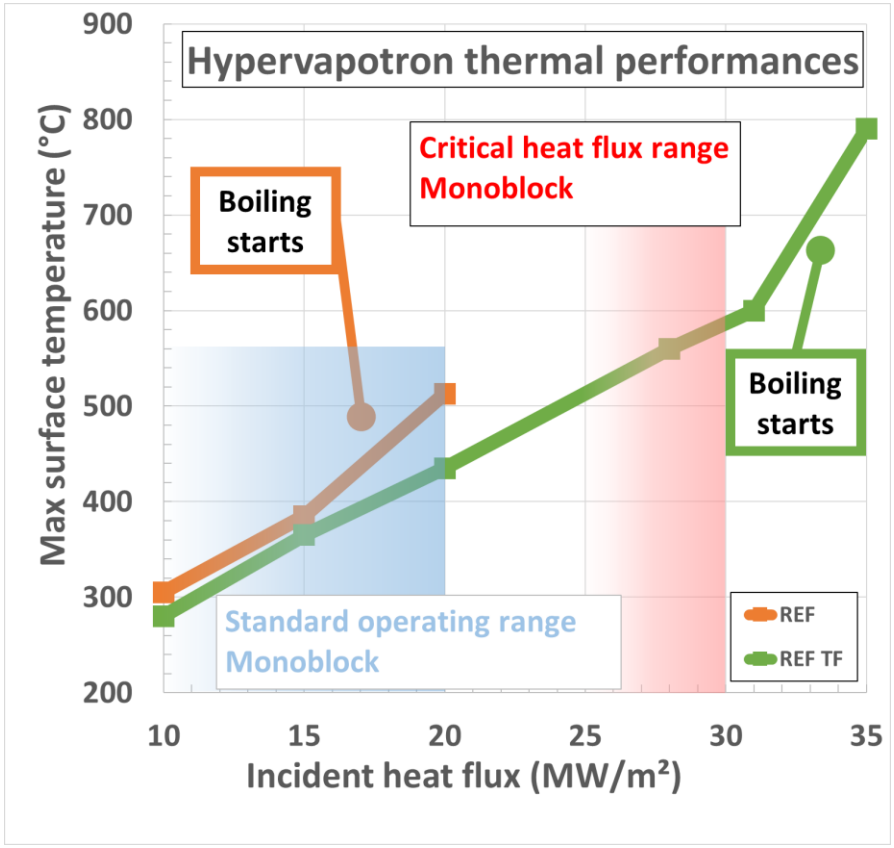
Surface temperature measured by IR camera, including **local emissivity** measurement

Boiling assumed from pressure perturbation and noises



Reference design similar thermal limits than monoblock

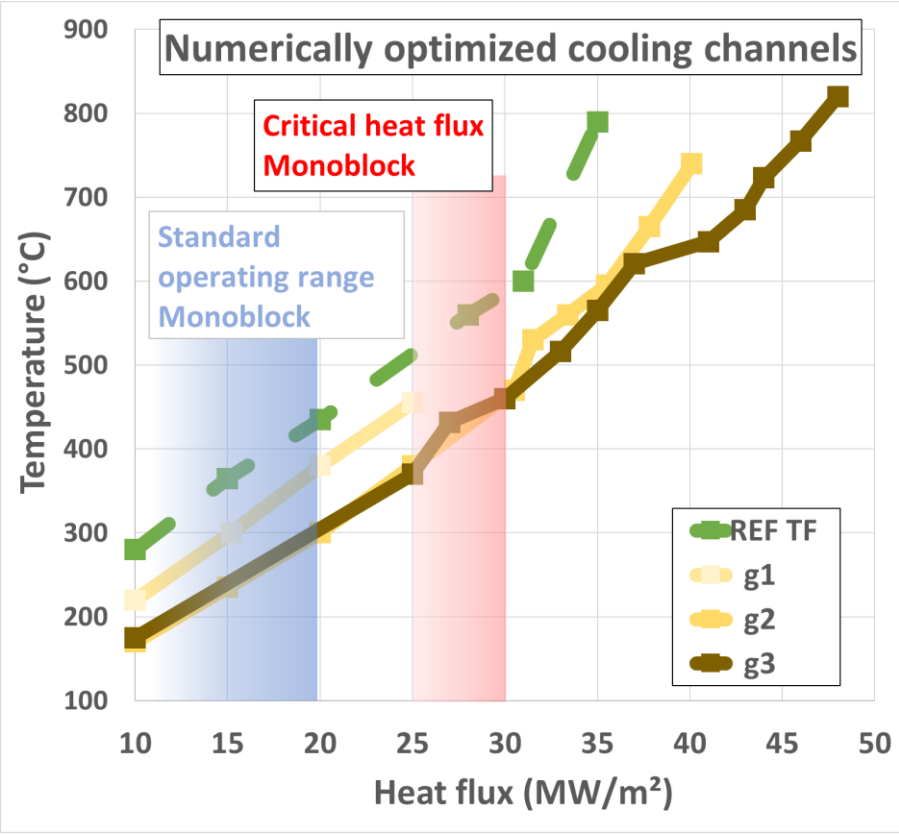
Reference with transvers fins more efficient than monoblock (tube with twisted tape): max steady state > monoblock critical heat flux

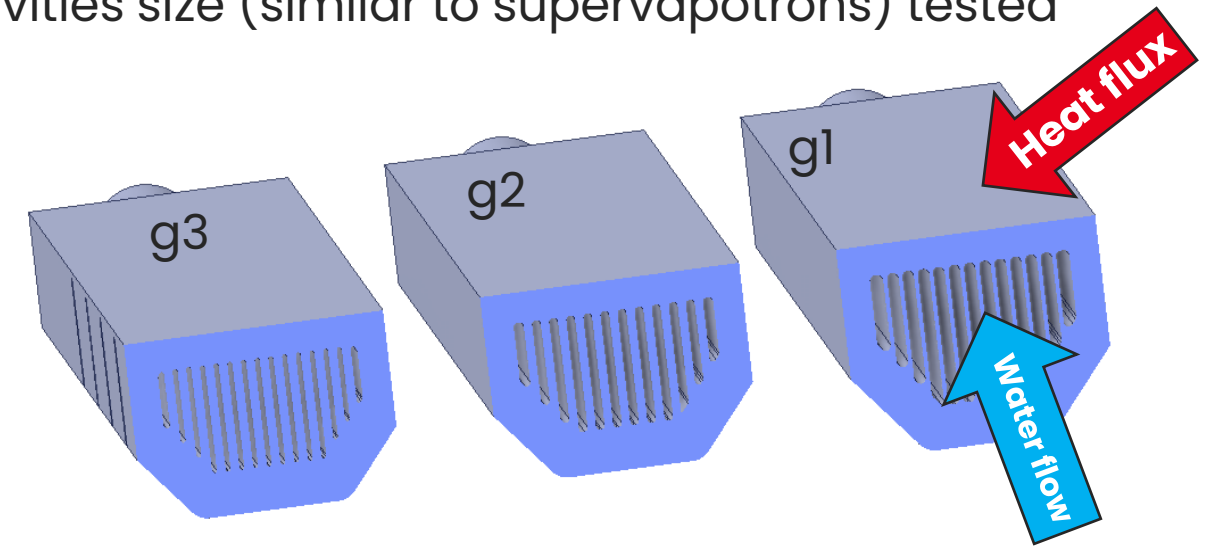


Beyond hypervapotron performances: validation of numerical optimization

Numerical optimization combining algorithmic design and single phase fluid simulation (i.e. boiling not taken into account)

3 cooling channel designs with different cavities size (similar to supervapotrons) tested





All designs have a better thermal behaviour than the hypervapotrons (with higher pressure drops)

Demonstration that the loop [modelling / optimization / manufacturing / testing] is efficient

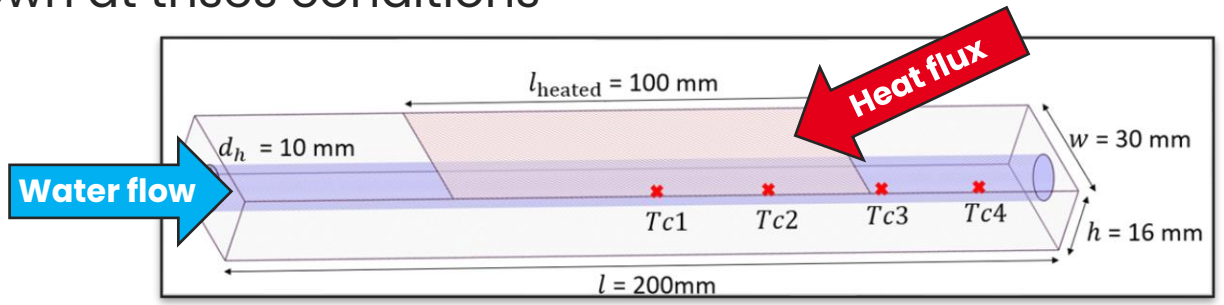
Fluid simulation
Boiling issues in fusion conditions

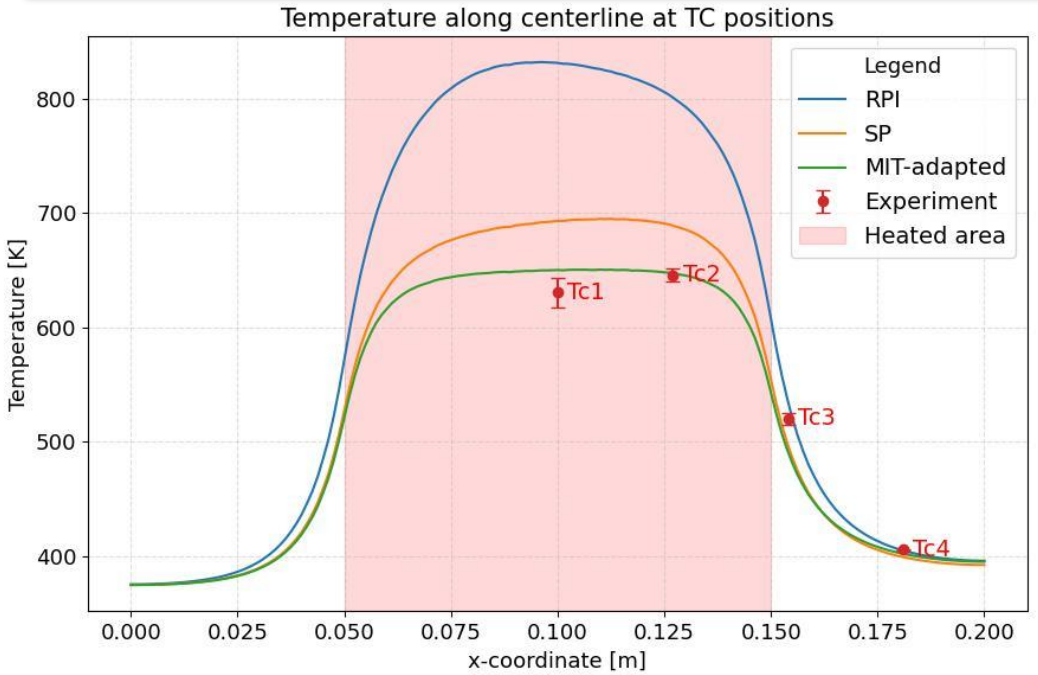
Jožef Stefan Institute
Ljubljana, Slovenia

Fusion conditions (10-20MW/m², 10m/s, subcooling 100K) exceed classical models (**RPI**) validation range : boiling parameters are unknown at thses conditions

More suitable model : MIT-adapted [1]:

- Developed on simple geometries (tube in rectangular shape)
- Single phase model unphysical
- RPI unable to follow the trend
- MIT-adapted closely follows the experimental measurements





Fluid simulation with boiling in fusion conditions is progressing, along with proper measurement (bubbles, velocities, temperature…)

[1] Končar et al., 2026 Journal of Heat and Mass Transfer

Towards a new era in fusion divertor design: cooling channels customed for specific plasma load

Widespread adoption of monoblock designs over **flat-tile hypervapotrons** in the early 2000s was a **compromise**, largely driven by the **design and manufacturing challenges** associated with hypervapotron technology

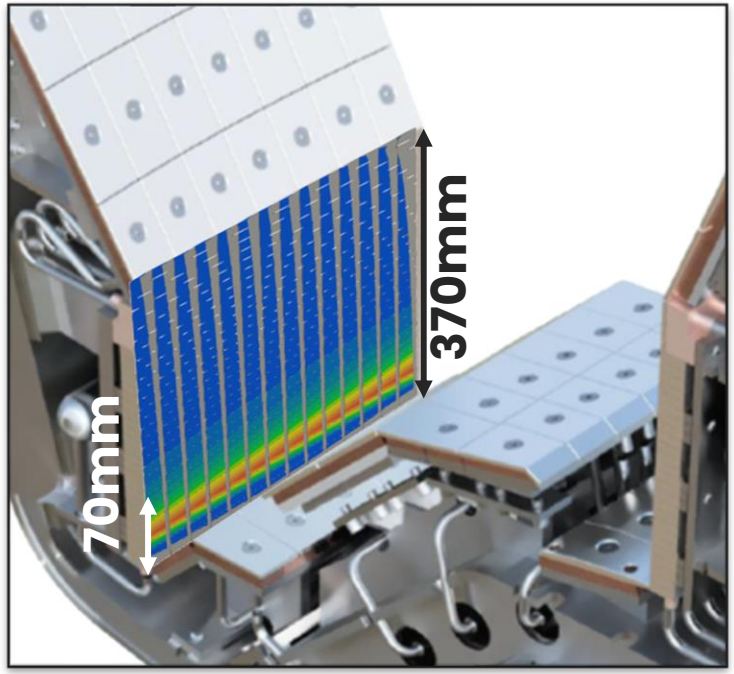
Additive manufacturing, especially **coupled with computational design** represents a **breakthrough in PFC technology**:

- Higher thermal performance (enhanced heat removal)
- Controlled pressure drop (optimized coolant flow)

Hypervapotron still to be evaluated in relevant conditions (W armour), to **validate the integrity of the armour / heat sink joint in plasma environment**

Additive manufacturing further unlocks the potential for **spatially optimized cooling structures**, defined by localized plasma loads

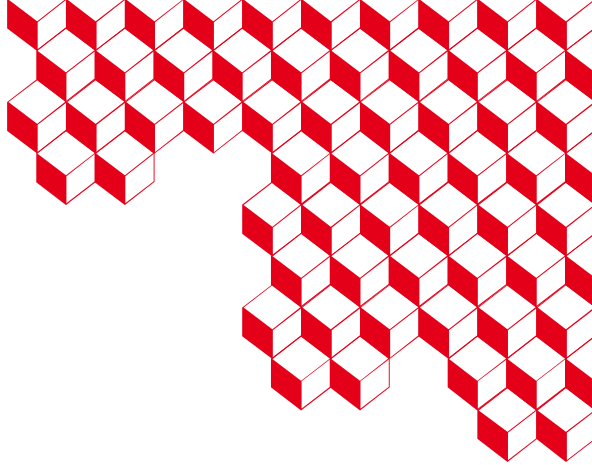
- High-efficiency heat removal at hot spots
- Low pressure drop designs elsewhere



JT-60SA divertor
Heat flux on outer target

Endless design possibilities can be explored via numerical optimization loops, enabling custom-tailored solutions for specific peak heat loads





Spare slides

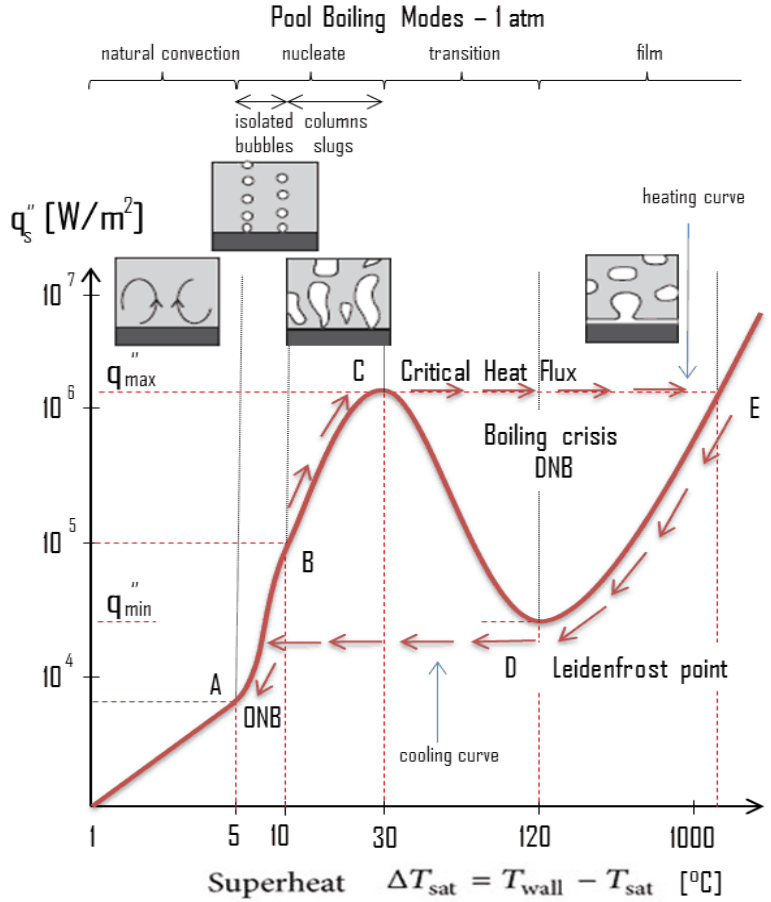
HTC increase – boiling and Nukiyama CHF in monoblocks

Main parameters (single phase)
- **System pressure**: Slightly improves transfer by increasing density and boiling point
- **Subcooling**: Delays boiling but has limited impact on single-phase heat transfer
- **Mass flow rate**: **Key** for effective heat transfer (dominant effect)
- **Fin geometry**: **Critical** for optimizing vortices and local heat transfer

In two-phases flow, Nukiyama graph explains bubble nucleation up to the vapour film in successive phases

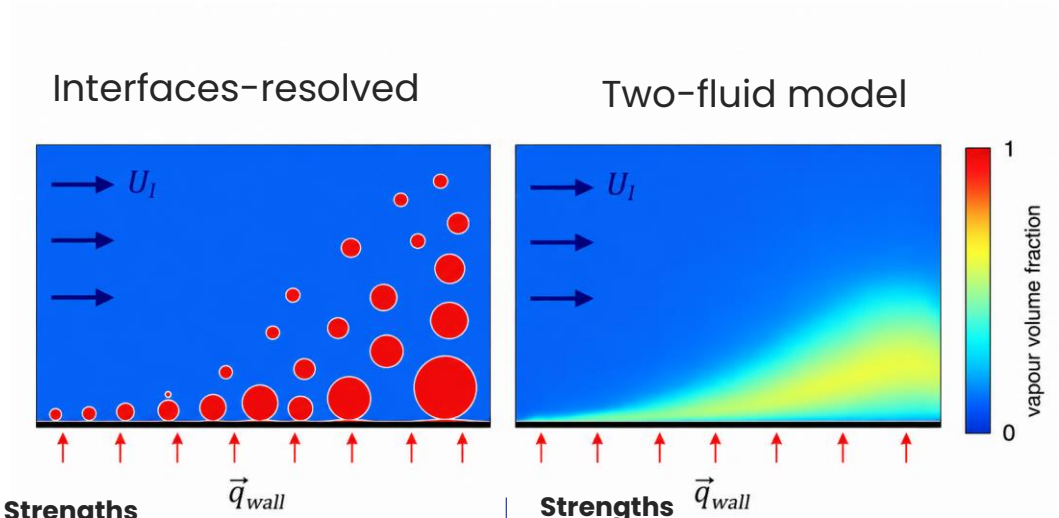
Tong 75 : ~55MW/m² - security factor 1,4 + peaking factor 1,6 → 25MW/m² for ITER conditions
Same values for JT 60SA hydraulic conditions → possible to compare CHF ITER

By experiment (Escourbiac et al., 2019) : ~30MW/m² CHF in monoblocks



Boiling modelling in two-fluid framework

Resolve interfaces or model them?



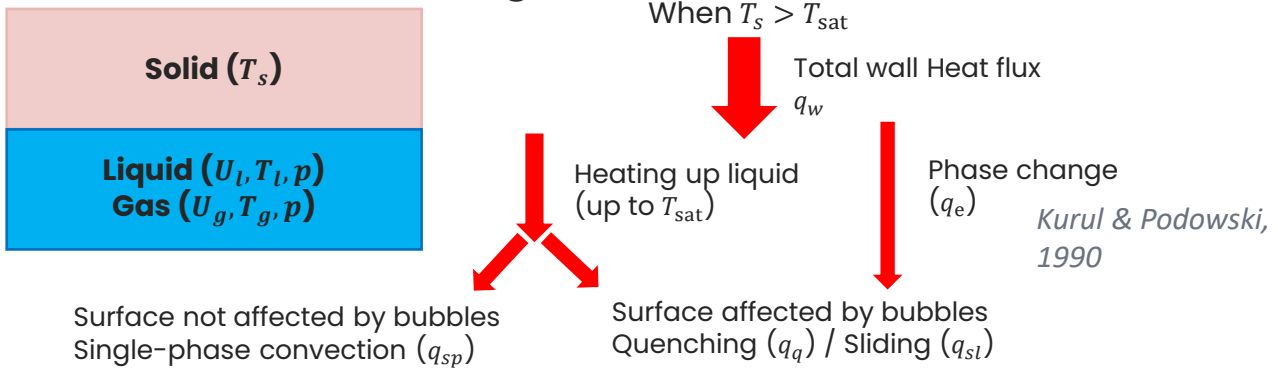
Strengths
- Individual bubbles and liquid–vapour interfaces are explicitly resolved.
- Provides detailed local information on bubble shape, motion and interaction.
- Useful for fundamental studies and developing closure models.

Limitations
- Requires a mesh and time step much smaller than the bubble scale.
- **Computationally expensive and generally limited to small domains.**
- Nucleation and other sub-bubble-scale phenomena still require modelling.

Strengths
- Treats liquid and vapour as interpenetrating continua - individual bubbles are not tracked.
- Makes component-scale simulations computationally feasible.
- Useful for engineering quantities such as void fraction, phase velocity and temperature.

Limitations
- Unresolved boiling and interfacial physics require closure models.
- Many closures rely on experimental correlations and empirical assumptions.
- Accuracy must be validated for the operating conditions being studied.

How to model boiling in the Two-fluid framework?



Kurul & Podowski, 1990

- The wall boiling model is used to describe the complex wall-fluid heat transfer physics
- It separetes distinct pysical heat transfer mechanisms (Example evaporation heat flux)

$$q_e = \underbrace{\frac{\pi}{6} d_w^3}_{\substack{\text{bubble volume} \\ \text{m}^3}} \quad \overbrace{\rho_v h_{lv}}^{\substack{\text{latent energy per unit volume} \\ \text{J m}^{-3}}} \quad \underbrace{f N_w}_{\substack{\text{departures per area and time} \\ \text{m}^{-2}\,\text{s}^{-1}}}$$

$$[q_e] = \left(\text{m}^3\right)\left(\text{J m}^{-3}\right)\left(\text{m}^{-2}\,\text{s}^{-1}\right) = \text{J m}^{-2}\,\text{s}^{-1} = \text{W m}^{-2}$$

- Uses measurable boiling parameters (Bubble size, freqency of departure, nucleation site density)



FEDORA
Single-site imaging informs d_w and f; field imaging provides N_w.
Gajšek et al., 2025