He-Cooled Divertor Concepts

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Contributions

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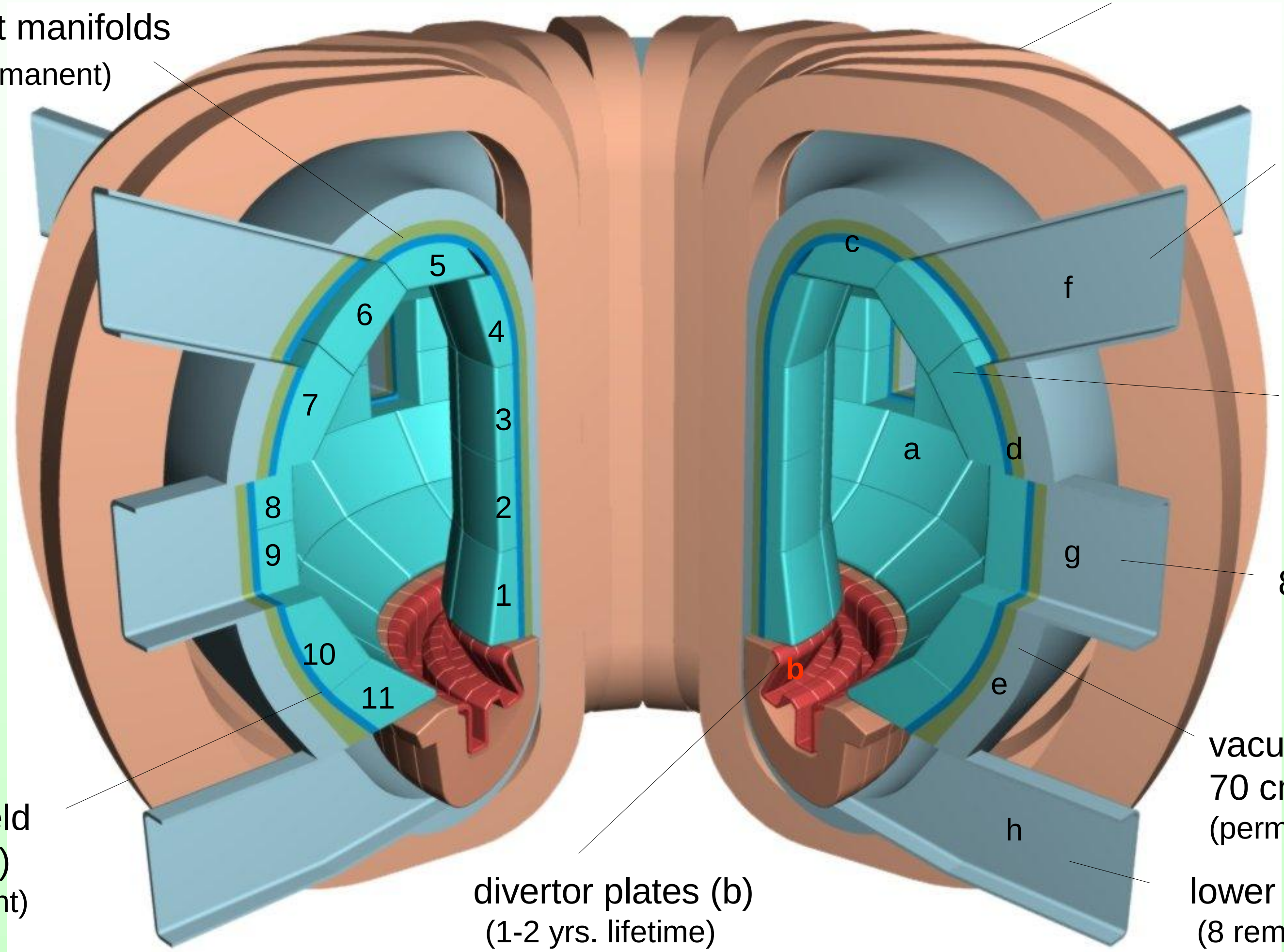
Outline

1. Introduction
2. Rationale of the He-cooled divertor concepts
3. Design of the proposed concepts of He-divertors
4. Related R&D
5. Conclusion and future work

Introduction: Fusion Power Plant (model C)



Fusion Power Plant Models investigated in the EU PPCS

	Model A	Model B	Model C	Model D	Model AB
Development rating	near term	near term	advanced	very advanced	near term
Blanket type	WCLL	HCPB	Dual Coolant	Self Cooled	HCLL
Divertor type	water cooled	He cooled	He cooled	Liq. metal cool.	He Cooled
Breeder / Multiplier	Pb-17Li / none	Li-ceramic / Be	Pb-17Li / none	Pb-17Li / none	Pb-17Li / none
Coolant	water	Helium	Helium and Pb-17Li	Pb-17Li	Helium
T-extraction	Pb-17Li circulation	He purging flow (1 bar)	Pb-17Li circulation	Pb-17Li circulation	Pb-17Li circulation
Structural Material	RAFM	RAFM	RAFM (FW ODS plated)	SiC_f/SiC	RAFM

Boundary conditions for the in-vessel components

In Blanket	Model A	Model B (AB)	Model C	Model D
Surface heating	**0.6**	**0.5 MW/m²**	**0.6 MW/m²**	**0.5 MW/m²**
Neutron wall load (av/peak)	**2.2 / 3.0 MW/m²**	**2.0 / 2.4 MW/m²**	**2.23 / 3.1 MW/m²**	**2.6 / 3.4 MW/m²**

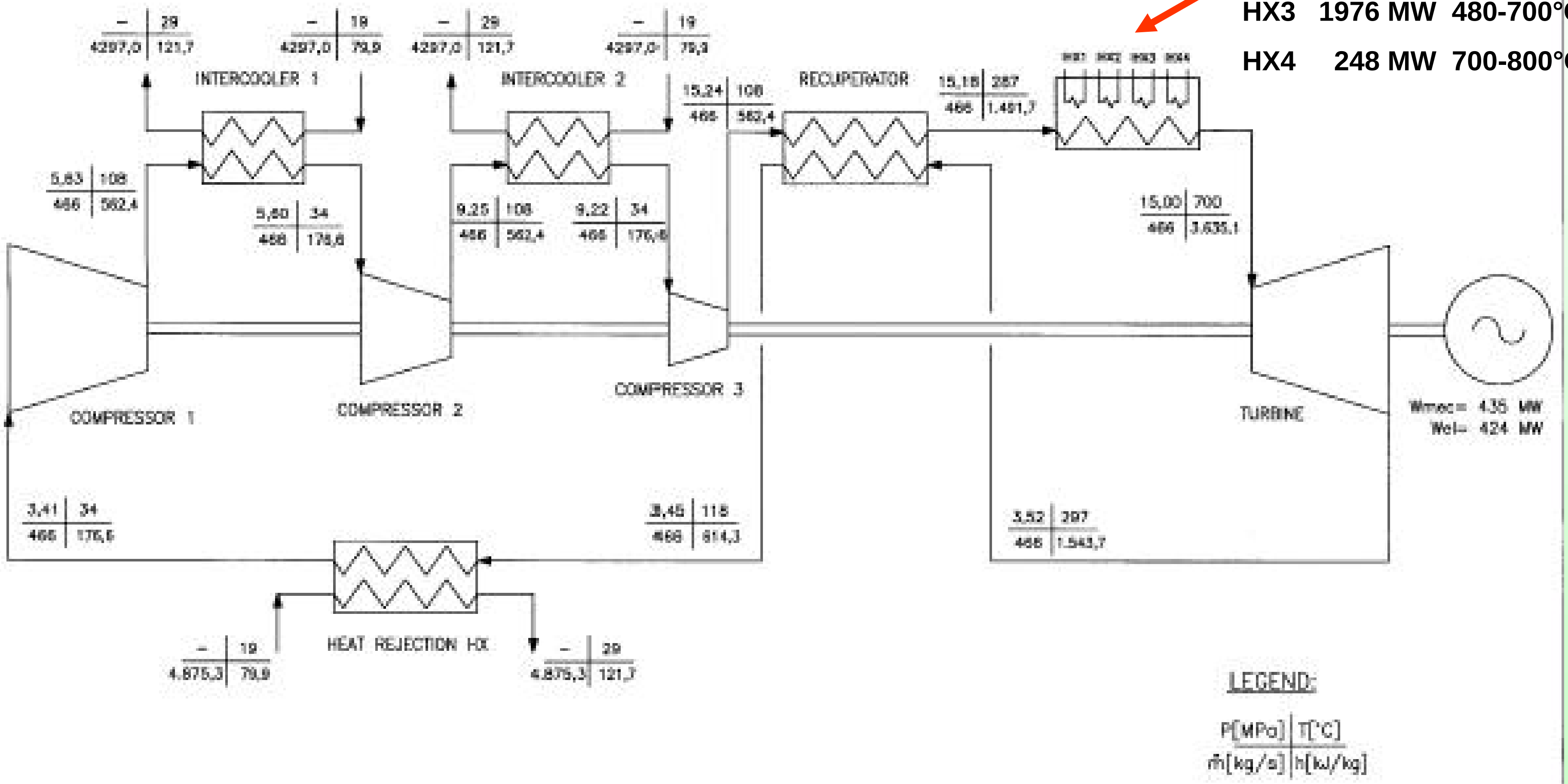
In Divertor				
Surface heating (av / peak)	**5 / 15 MW/m²**	**5 / 10 MW/m²**	**5 / 10 MW/m²**	**/ 5 MW/m²**
Neutron wall load (average)	**2.0 MW/m²**	**1.6 MW/m²**	**1.7 MW/m²**	**1.8 MW/m²**

He cooled divertors have being proposed …

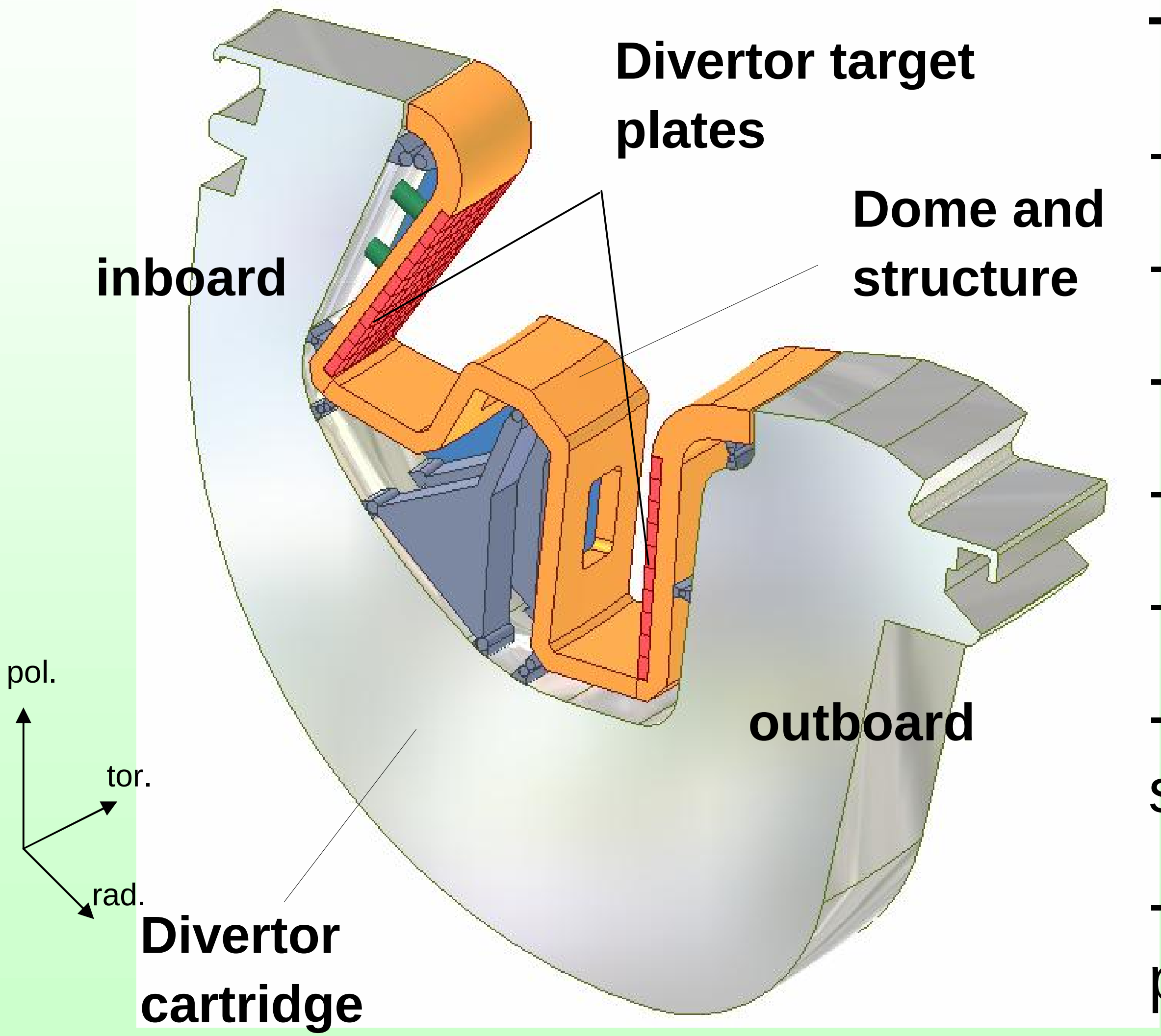
- To use the same coolant flowing in the blanket systems: at the present three reactor concepts (HCPB [model B], Dual Coolant [C], HCLL[AB]) that are under investigation the EU Programme envisage He cooled divertors.
- To integrate the divertor loop in the power generation system increasing the overall efficiency of the reactor (He allows a design with temperatures comparable or higher than in the blanket system)
- To avoid safety concerns for incompatibility of water with breeding/multiplier materials (especially in the case of Be based concepts, Model B, to avoid the Be-steam exothermal reaction with H production)

Integration in the power generation system

HX1	1432 MW	300-480°C	FW
HX2	335 MW	480-615°C	Divertor
HX3	1976 MW	480-700°C	PbLi
HX4	248 MW	700-800°C	Divertor



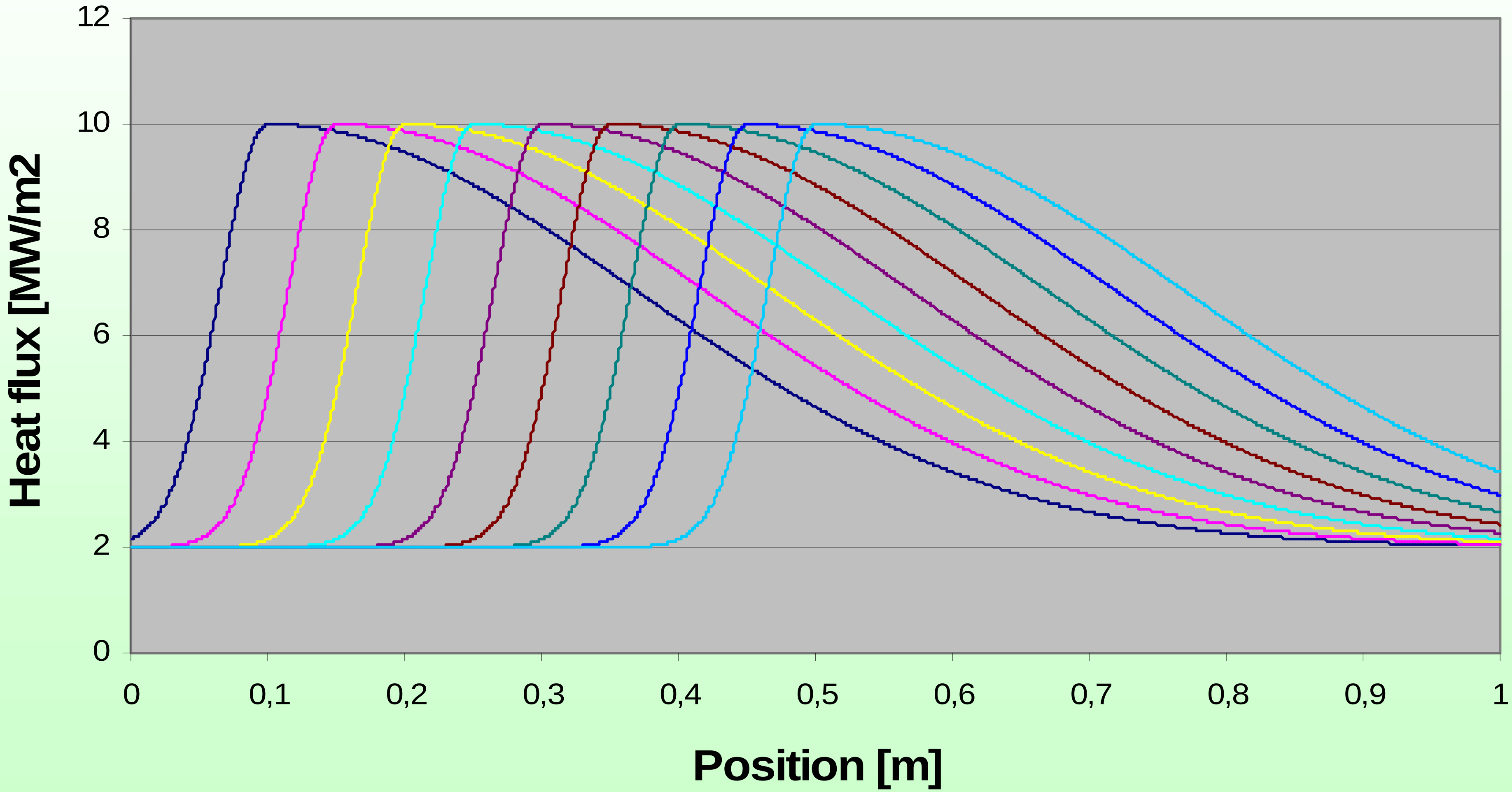
Divertor cassette for Model C and Target Plate Requirements



Target Plate (outboard):

- length 1m
- heat peak: 10 MW/m^2
- average heat: 5 MW/m^2
- moving strike point: 40 cm
- protection layer: 5mm (W)
- allowable temperatures and stresses in the materials
-Pumping power / Thermal power < 0.1

Design loading conditions



Issues for the successful development of a He-cooled divertor

The critical part of the design is the OB target plate in which incident heat fluxes not lower than 10 MW/m^2 are expected. These very demanding requirements can be fulfilled if these two issues can be successfully addressed:

1. The identification of a heat transfer mechanism between Helium and plasma side structure able to reach heat transfer coefficient greater than 30 $kW/m^2\,K$.
2. The selection/development of materials with very good thermal properties and a large operational temperature window that can be used as structural material (high pressure helium containment) for the high flux region at the plasma side.

Materials and anticipated operational temperature windows required for a high temperature divertor

Component	Material	Min Temp.	Max Temp.
Tiles	W	tbd (600°C) DBTT	2500°C Melting temperature 3410°C
High heat flux structure (high pressure He containment)	W-alloy	600°C DBTT	1300°C re-crystallisation
Structure and manifolds	W-alloy ODS …	600°C DBTT 400°C DBTT	1300°C re-crystallisation 700-750°C strenght limits

High flux He-cooled divertor concept development

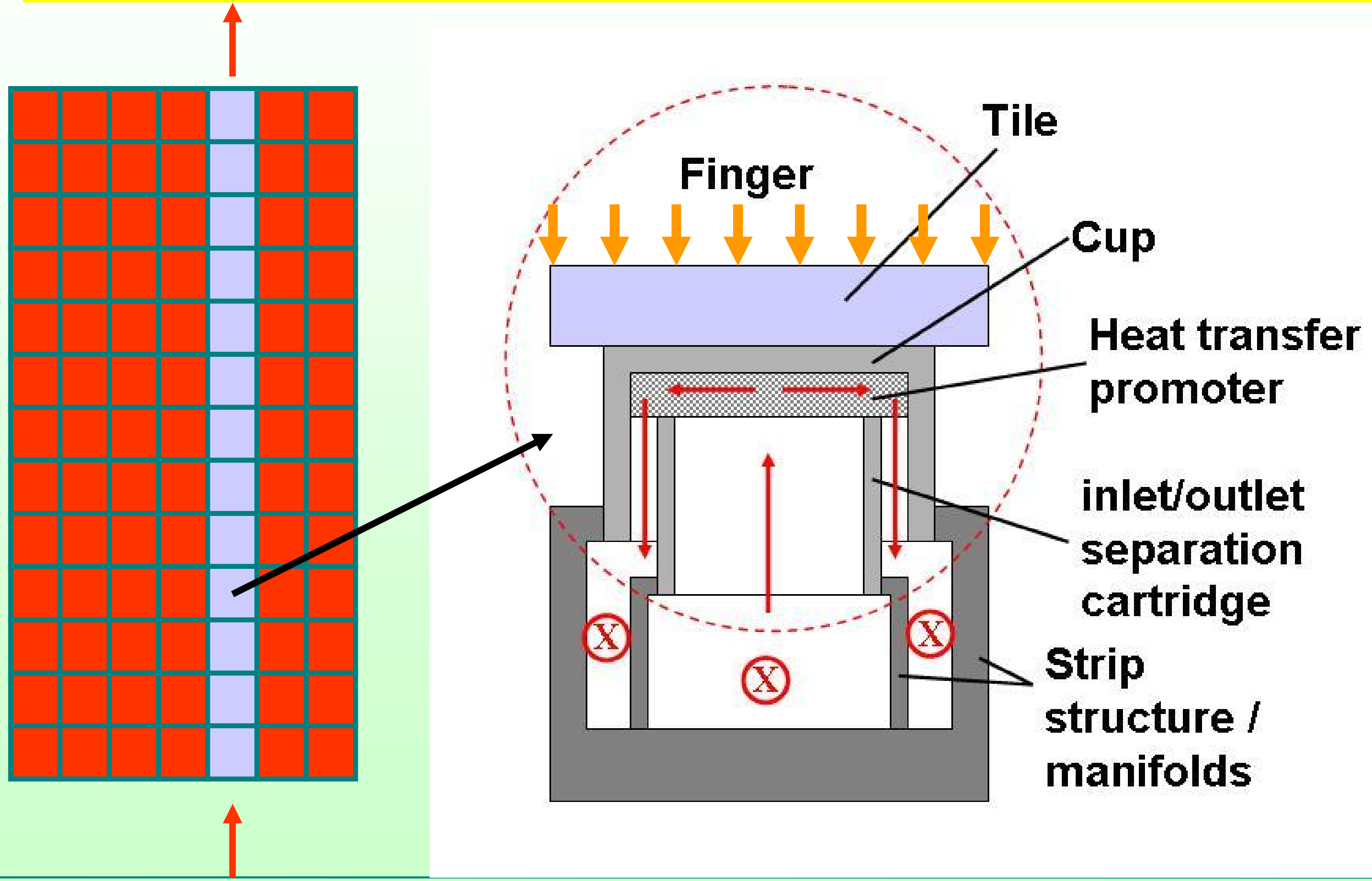
A) Plate design (enhancement of the heat transfer coeficient -> radial cooling):

- PPA-99: Unconventional design (FZK), qmax ~ 5 MW/m²
- PPCS/II (2000-2001): Simple slot (FZK), qmax ~ 6 MW/m²
- PPCS/III (2001): Modified slot (FZK), qmax ~ 10 MW/m² **(in Model B)**

B) Modular design (thermal stress reduction):

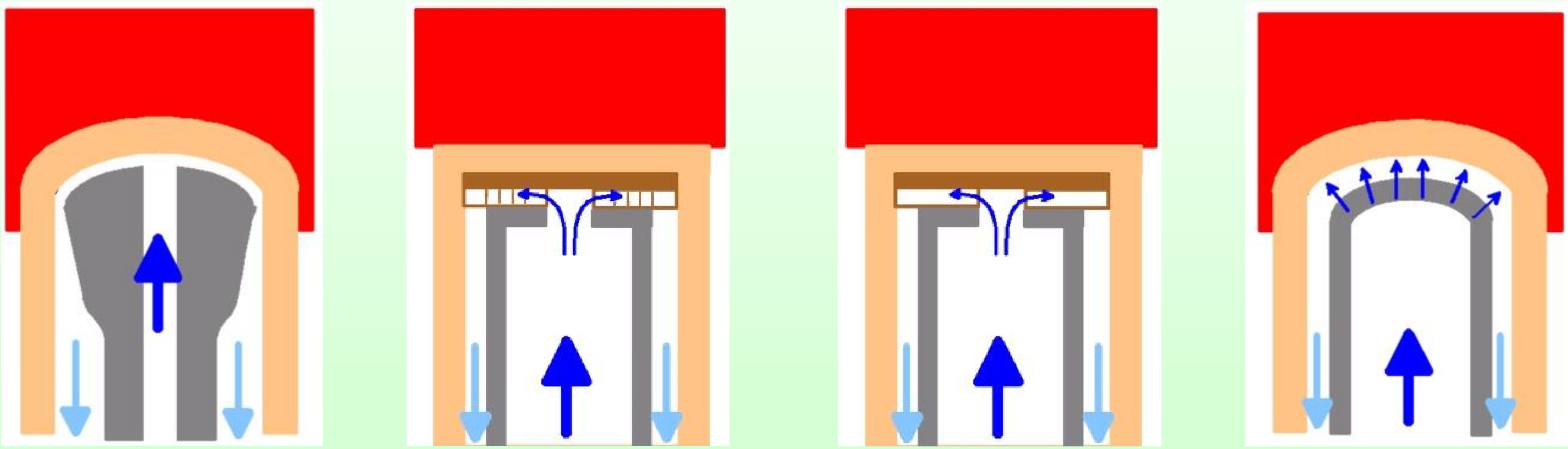
- Ø PPCS/III (2002): Modified **HETS** (ENEA), qmax ~ 10 MW/m²
- Ø PPCS/III (2002) - **Model C**: Pin-array **HEMP** (FZK), qmax ~ 10 MW/m²
- Ø TRP-001 (2003-2004) – Investigation on design concepts based on **HETS, HEMP, HEMS and HEMJ**

Principle of the modular design and the radial cooling



Cooling Technology: Heat transfer promoters

$$\dot{q} = htc \cdot \frac{A_c}{A_{Armor}} \cdot (T_w - T_c)$$



HETS
single-jet

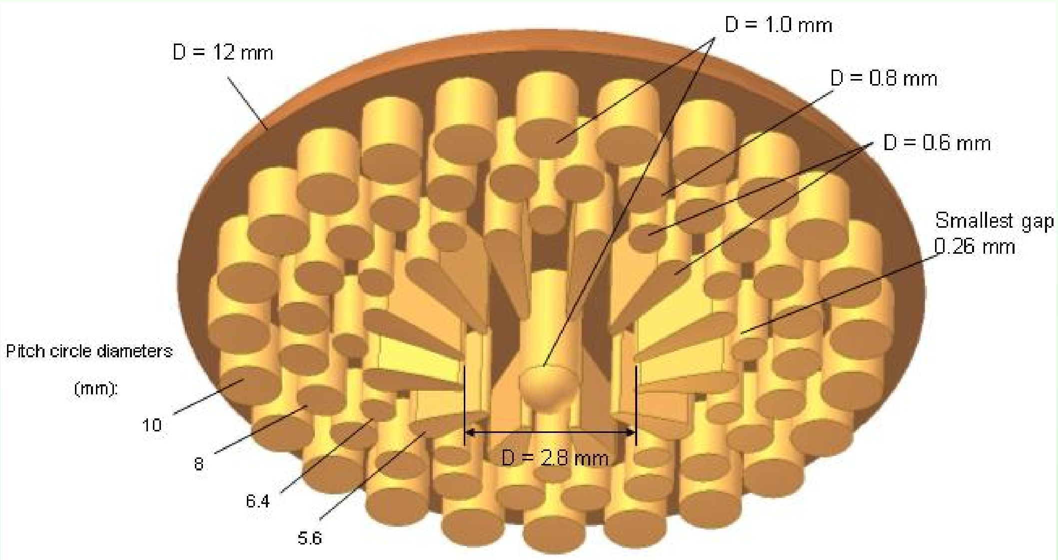
HEMP
pin array

HEMS
slot array

HEMJ
multi-jet

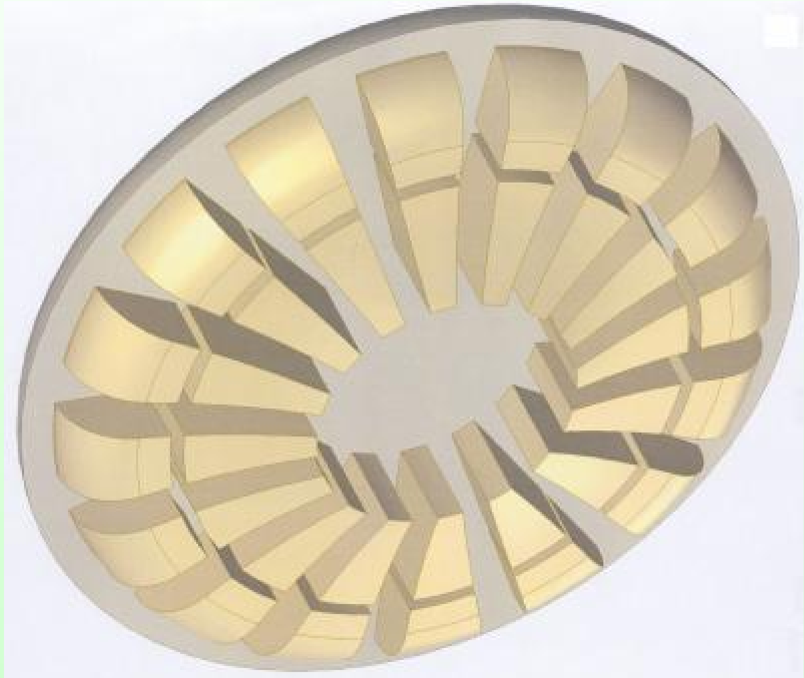
Cooling Technology: pin and slot array

Pin array



HEMP

Slot array



HEMS

Cooling Technology: : Jet Impingement

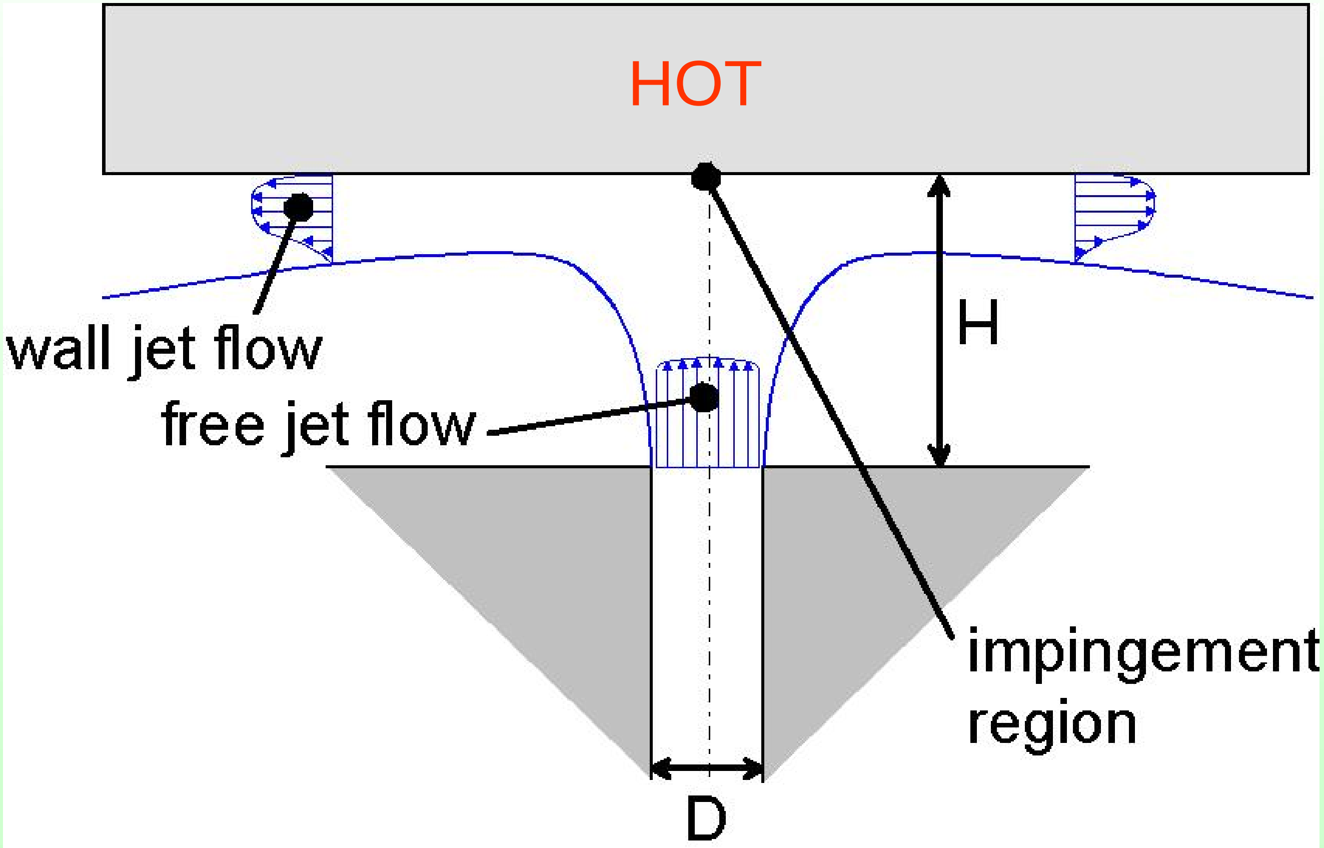
Cooling technology applied in the fields of:

- **Aircraft Engines**
- **Gas Turbines**
- **Burners**

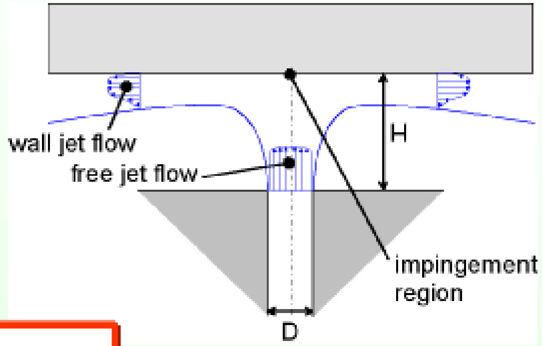
…

à DEMO Divertor

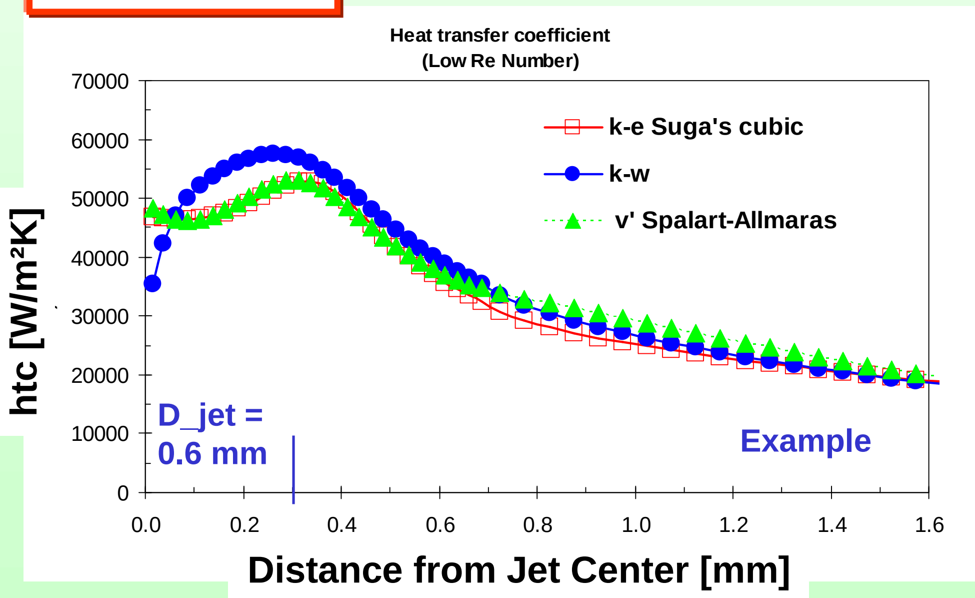
Jet Impingement

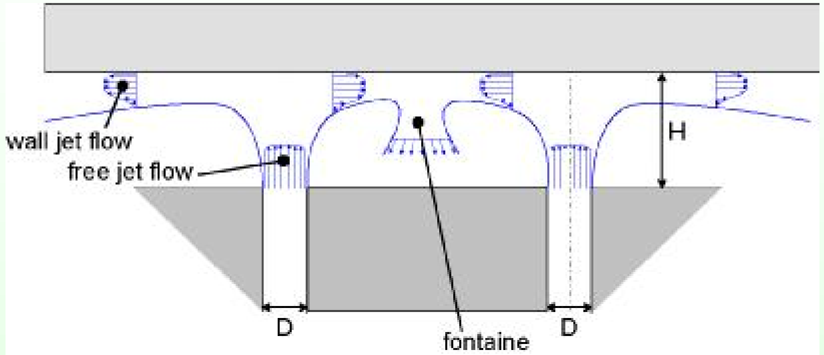


COOLING TECHNOLOGY: Jet Impingement in HEMJ

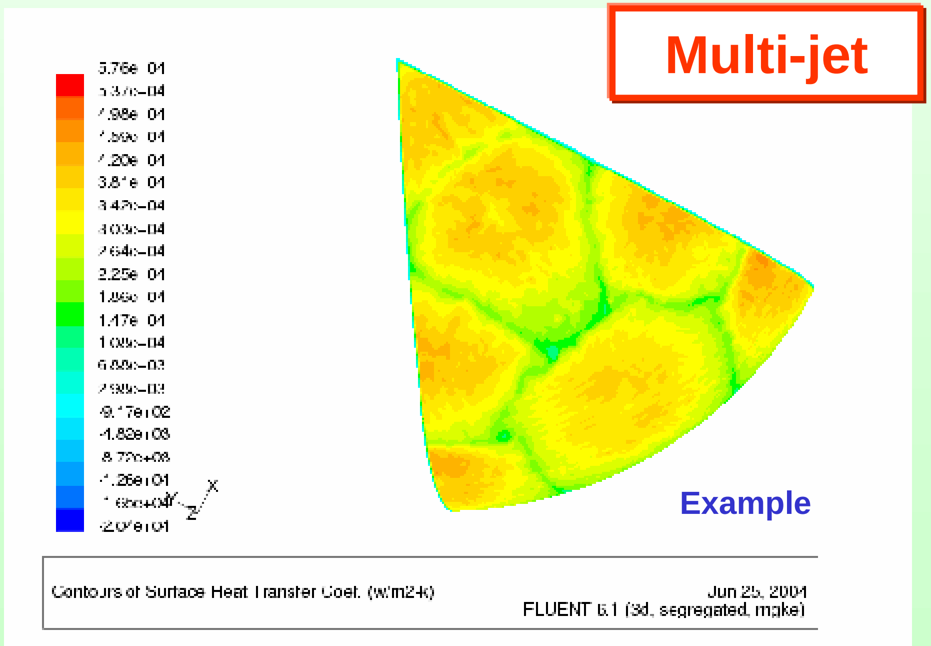


Single-jet

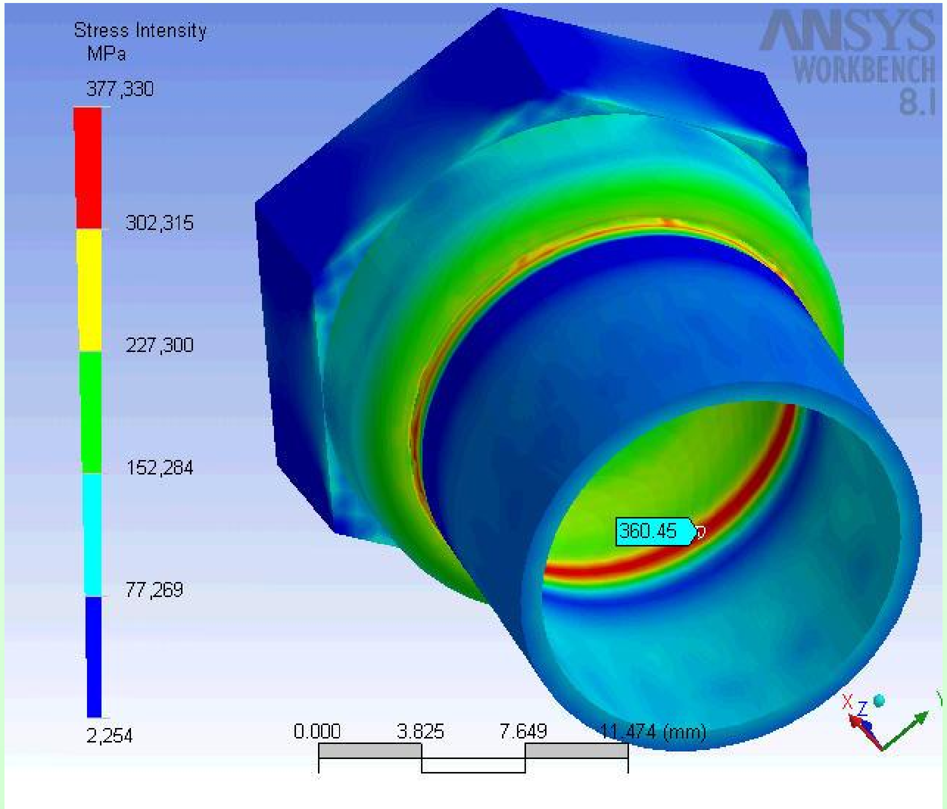


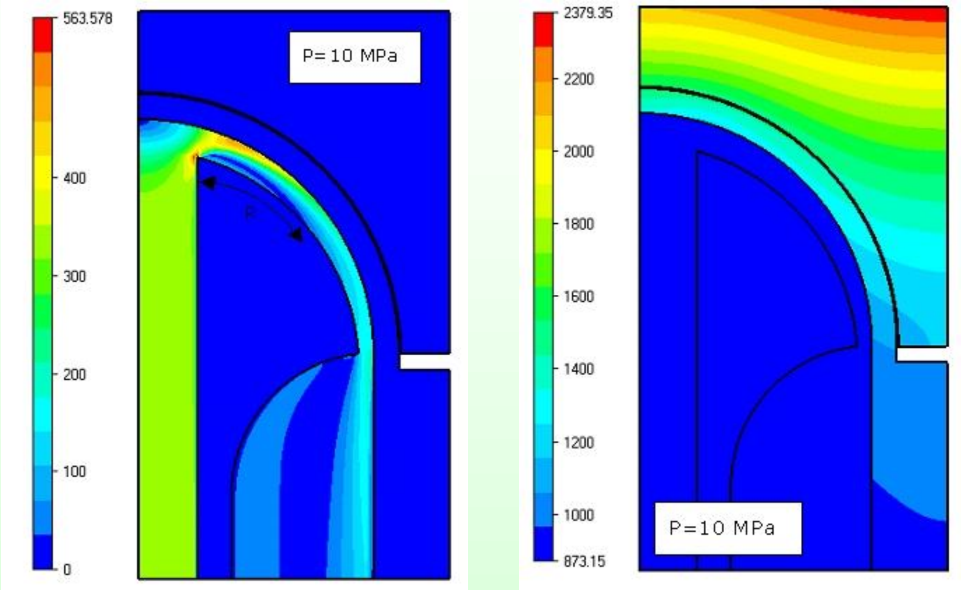


Multi-jet



Comparison of Cooling Systems (1/2)





Velocity and temperature field in HETS (UKAEA)

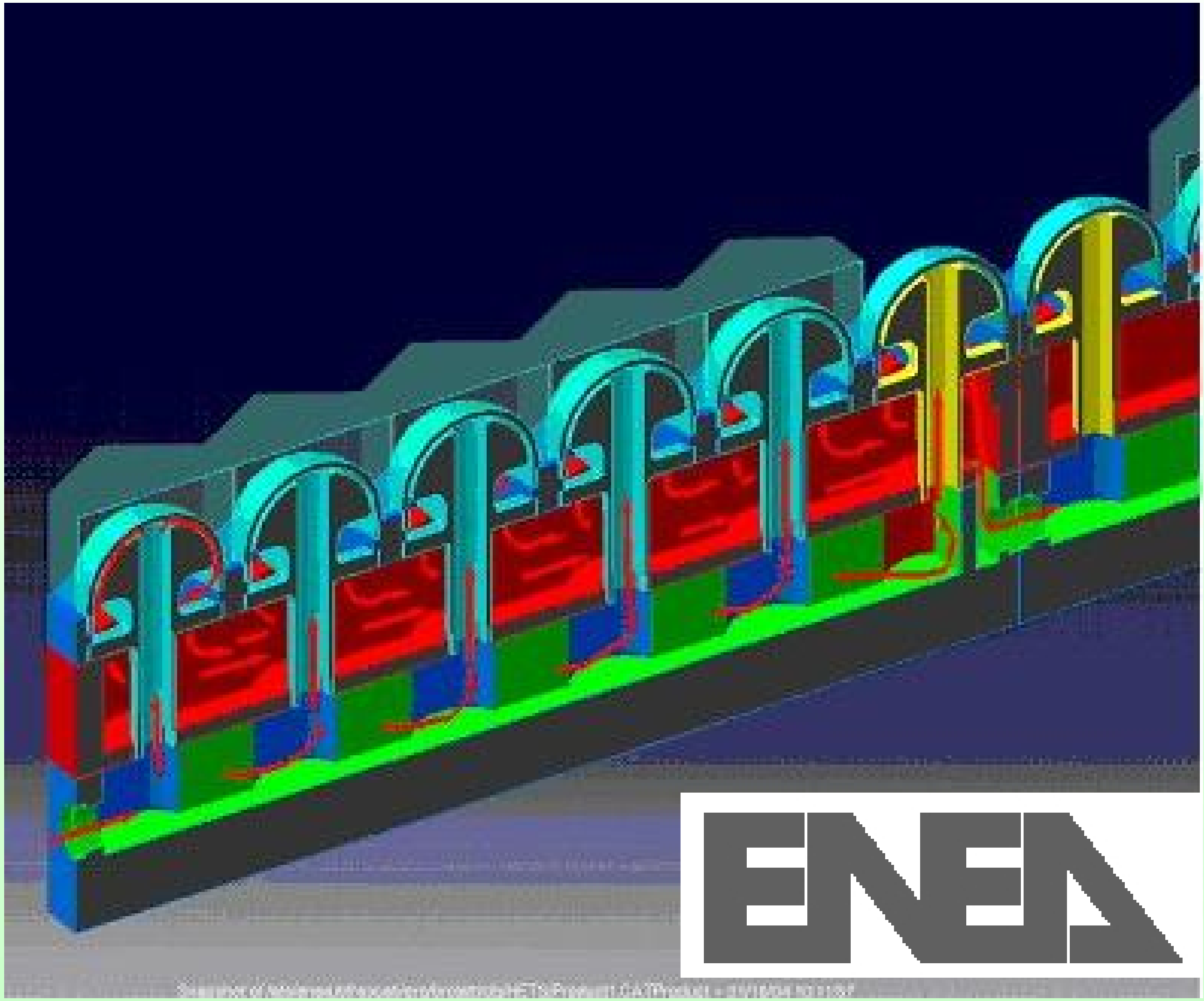
Stress analysis for the HEMJ concept (EFREMOV)

Comparison of Cooling Systems (2/2)

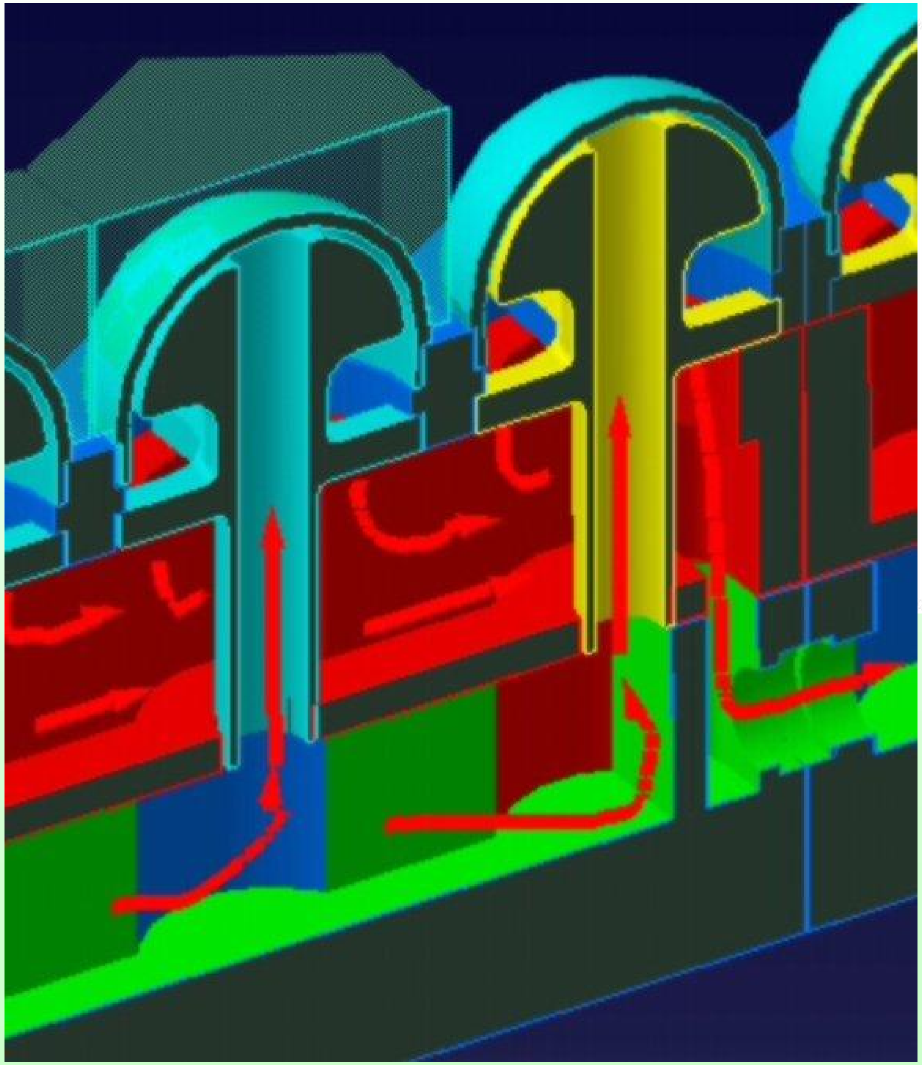
- **Cooling performances** (according to the requirements on heat flux density, allowable tempertares and stresses, pumping power limitation, etc.)
- **Fabrication** (available technique, mass production, cost-efficiency, etc.)
- **Reliability** (sensibility to blockage and tollerances, mass balancing, etc.)

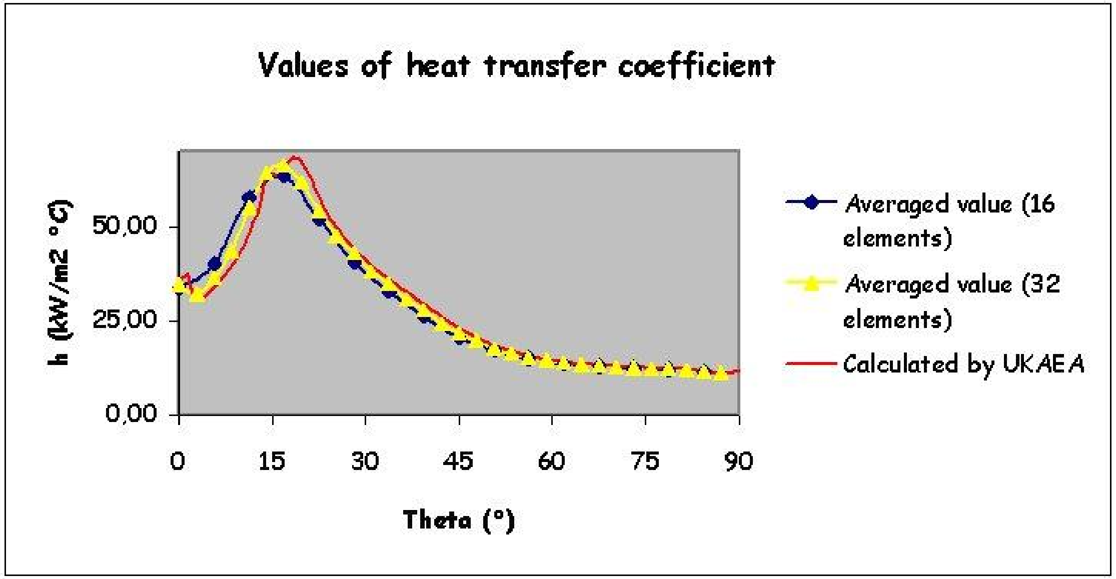
At present the design groups of ENEA and FZK have selected as reference option (for the starting of the mock-up tests) jet cooling concepts, namely the HETS and the HEMJ, respectively.

HETS Design



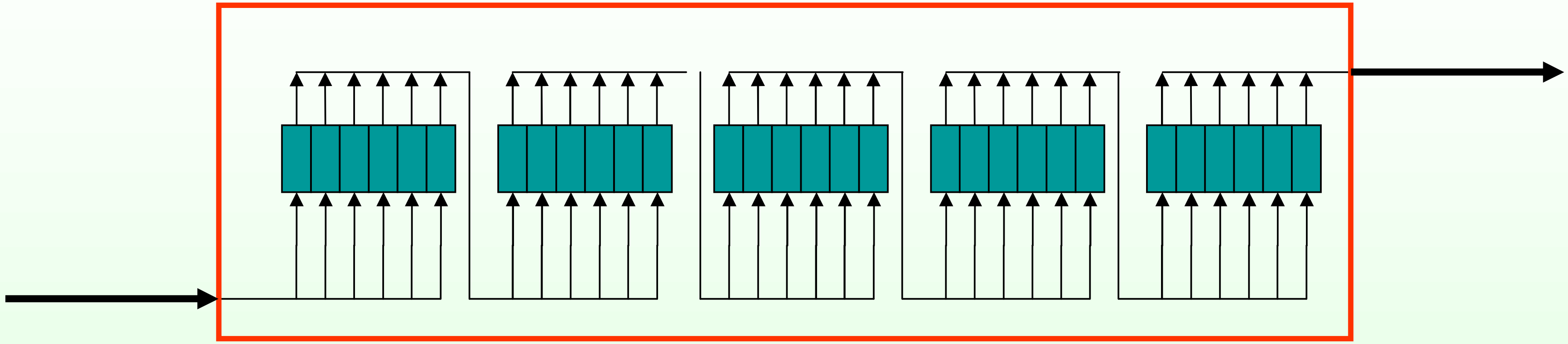
HETS: Detail of the flow mechanism





Calculated heat transfer coefficient in HETS (θ is the angle from the dome top)

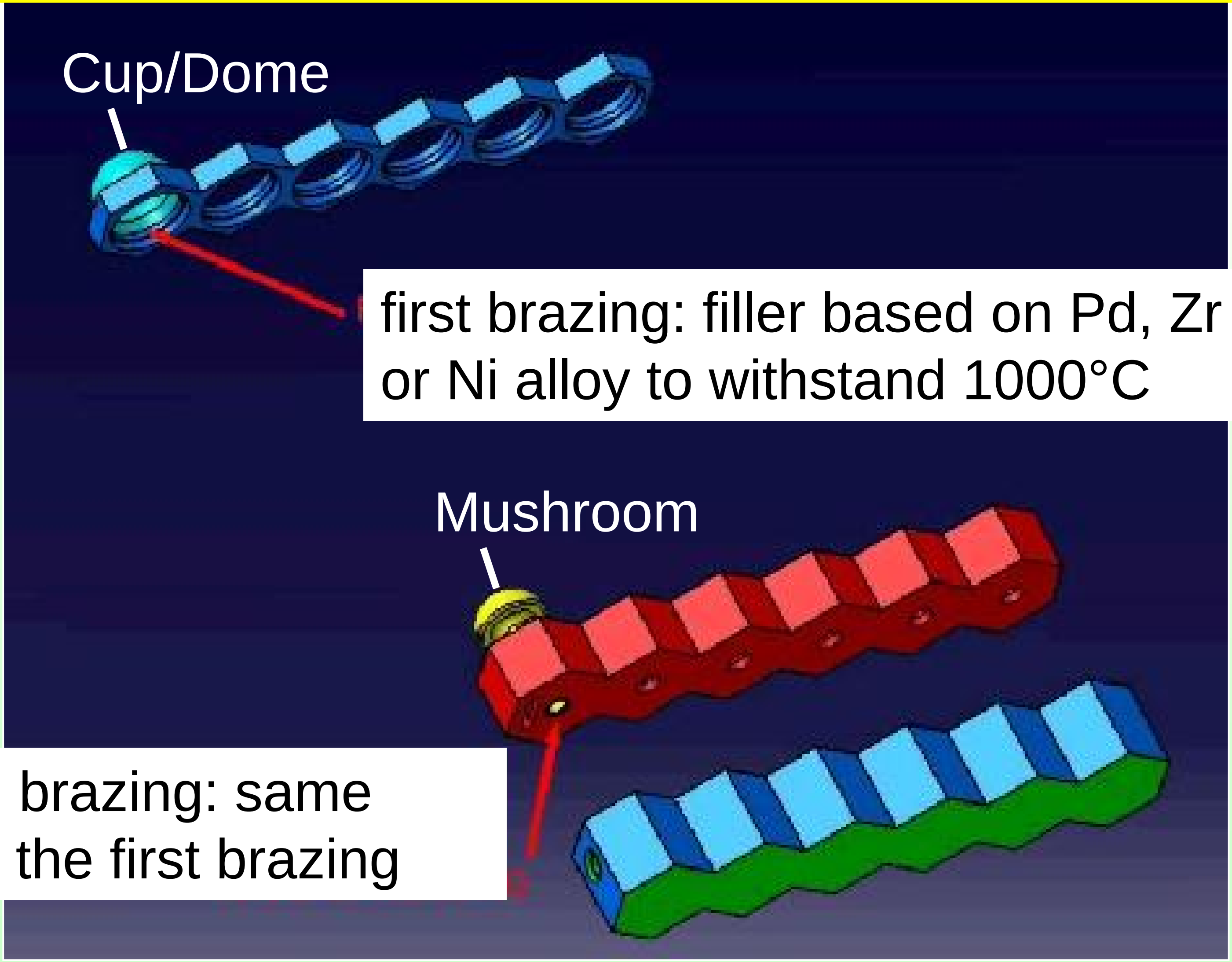
HETS: Hydraulic lay-out



Finger type and dimens.	He in/out	Coolant pressure	Mass flow	Average Heat Transfer Coeff.	Pressure drops
HEX 35 mm	600-669°C	10 MPa	30 g/s	~ 30 kW/m^2 K	0.06 MPa

T inlet [°C]	Power in a strip [kW]	Pressure [MPa]	Mass flow in a strip [g/s]	ΔT [K]	Pressure Drops [MPa]	W_p/W_{th} [%]
600	182	10	180	195	>0.3	>6.3

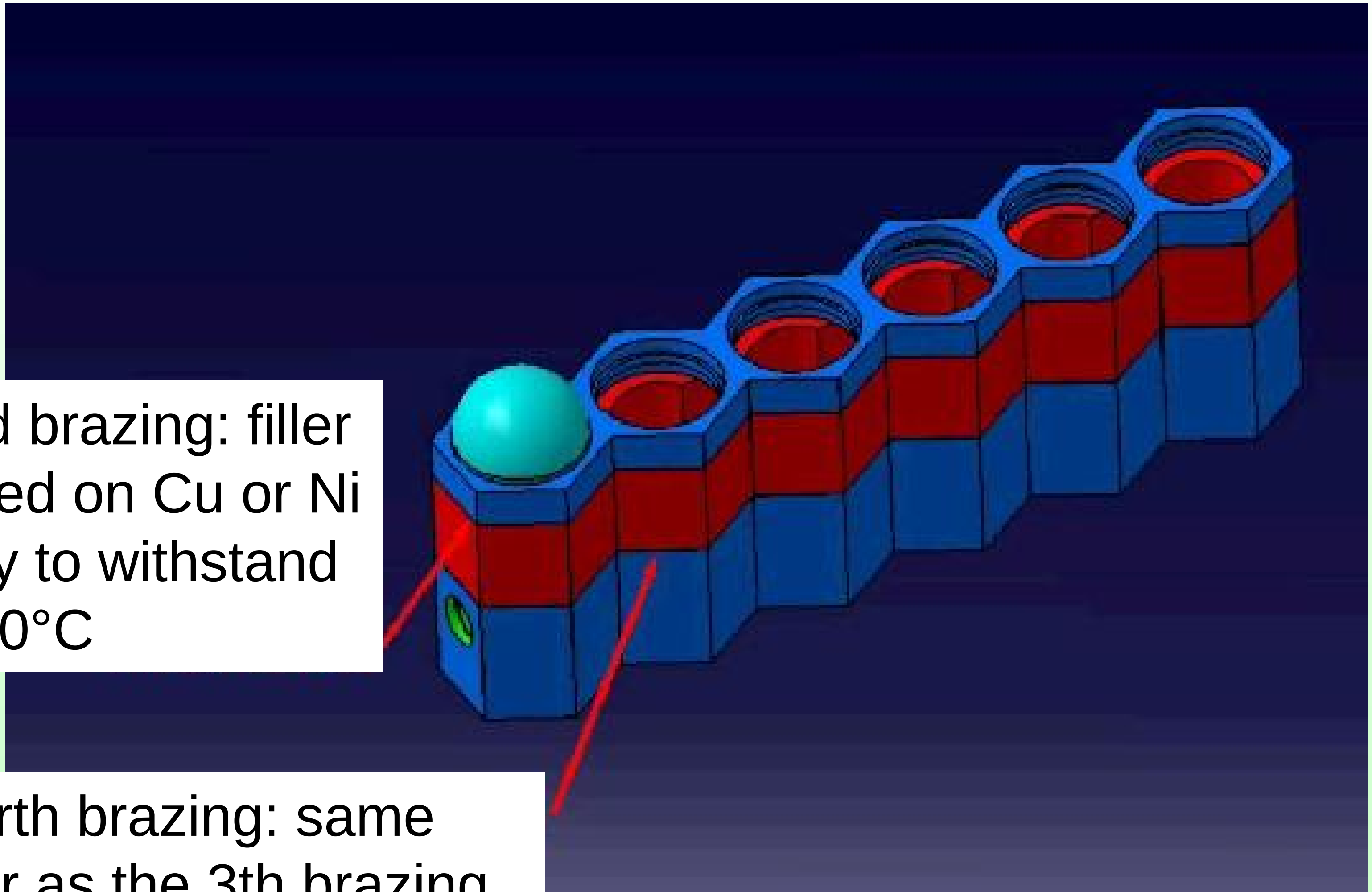
HETS Manufacturing sequences (preliminary) 1/2



first brazing: filler based on Pd, Zr or Ni alloy to withstand 1000°C

second brazing: same filler as the first brazing

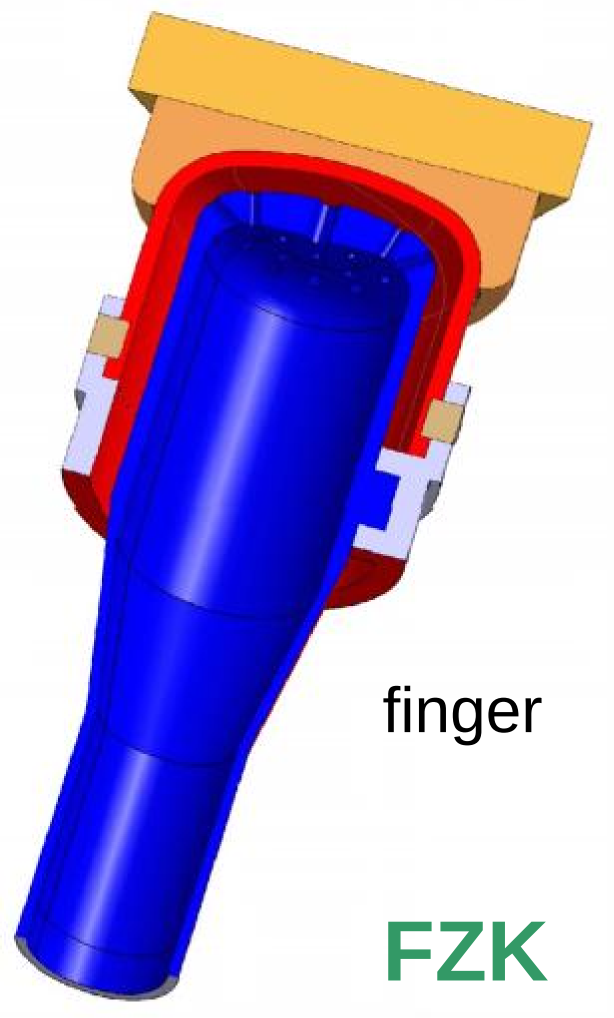
HETS Manufacturing sequences (preliminary) 2/2

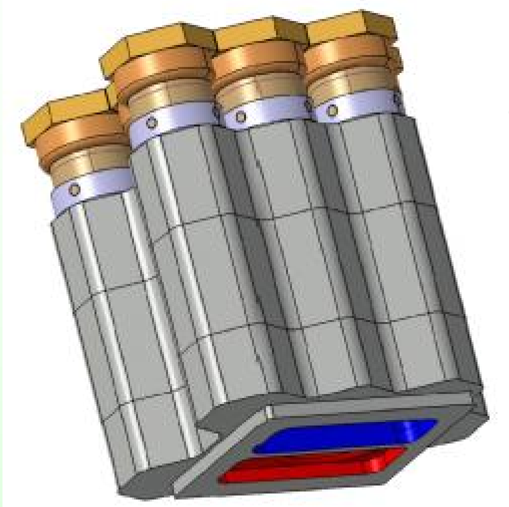


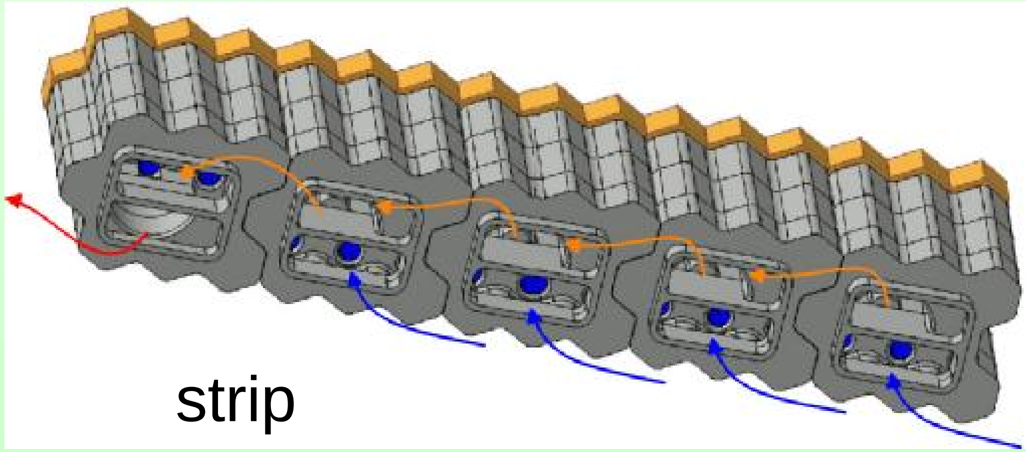
third brazing: filler based on Cu or Ni alloy to withstand ~800°C

fourth brazing: same filler as the 3th brazing

HEMJ Design

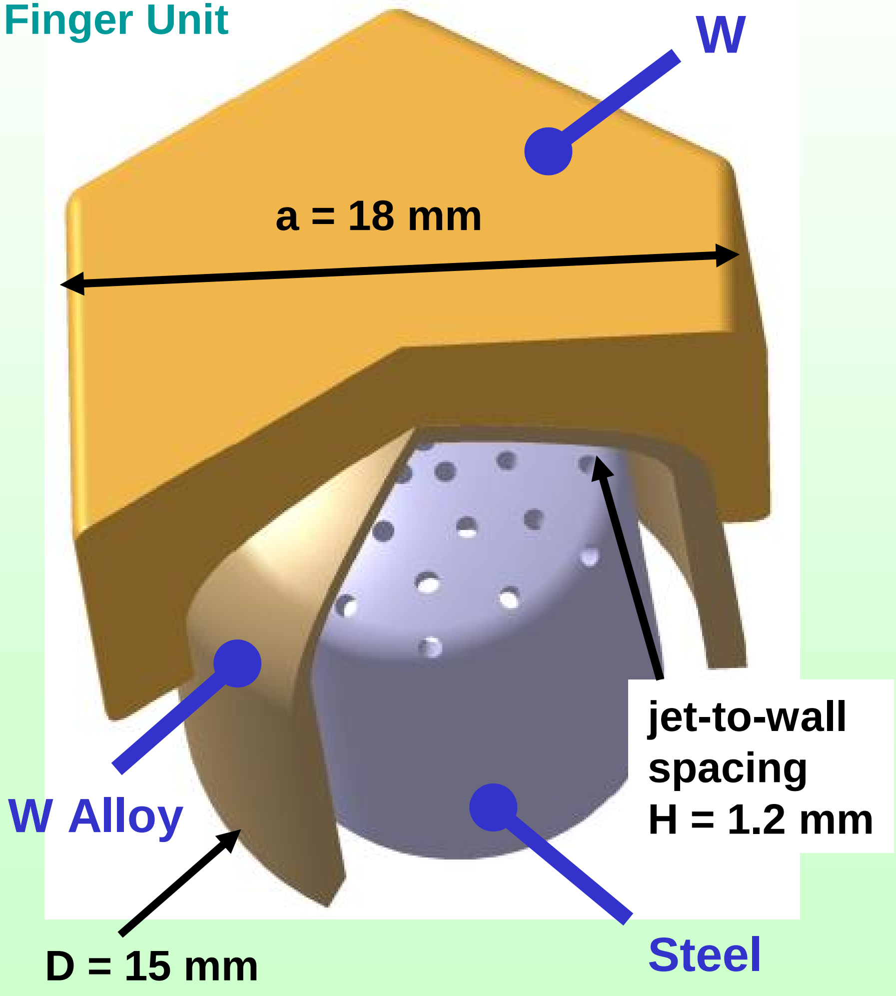




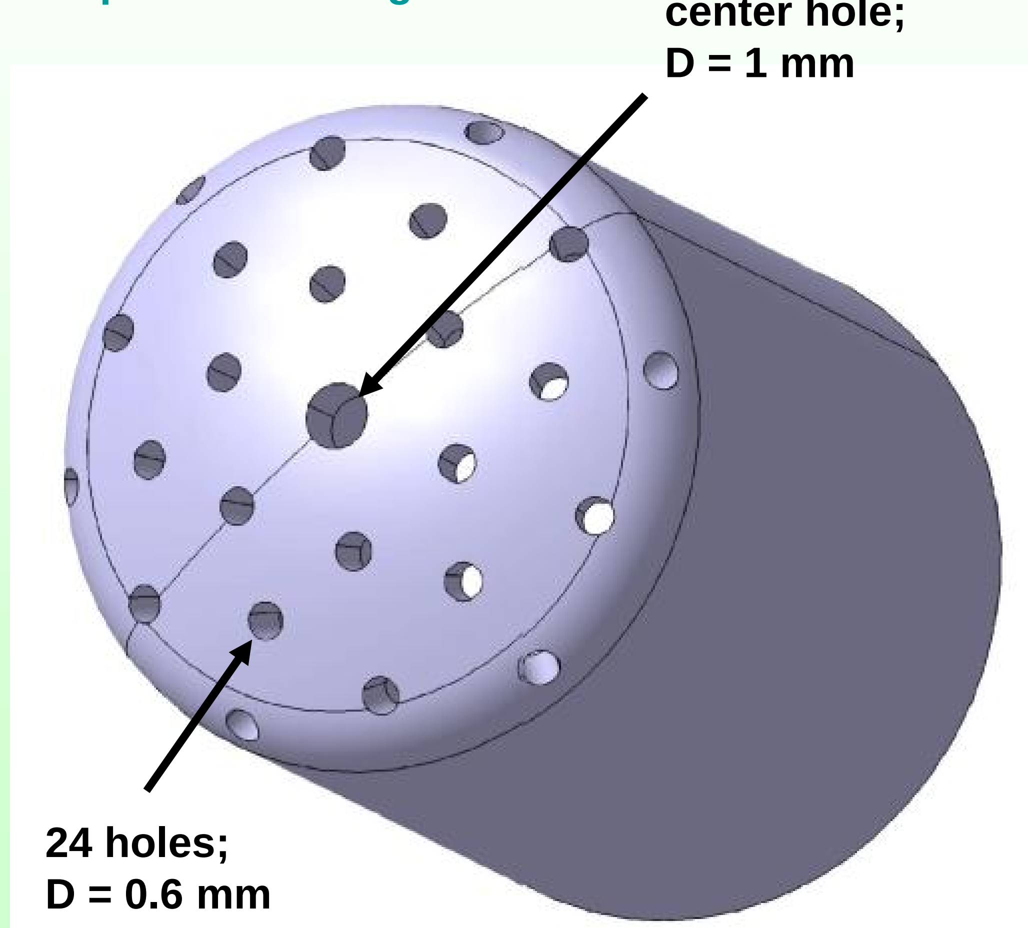


Layout example for Multiple-He-Jet-Cooled Divertor

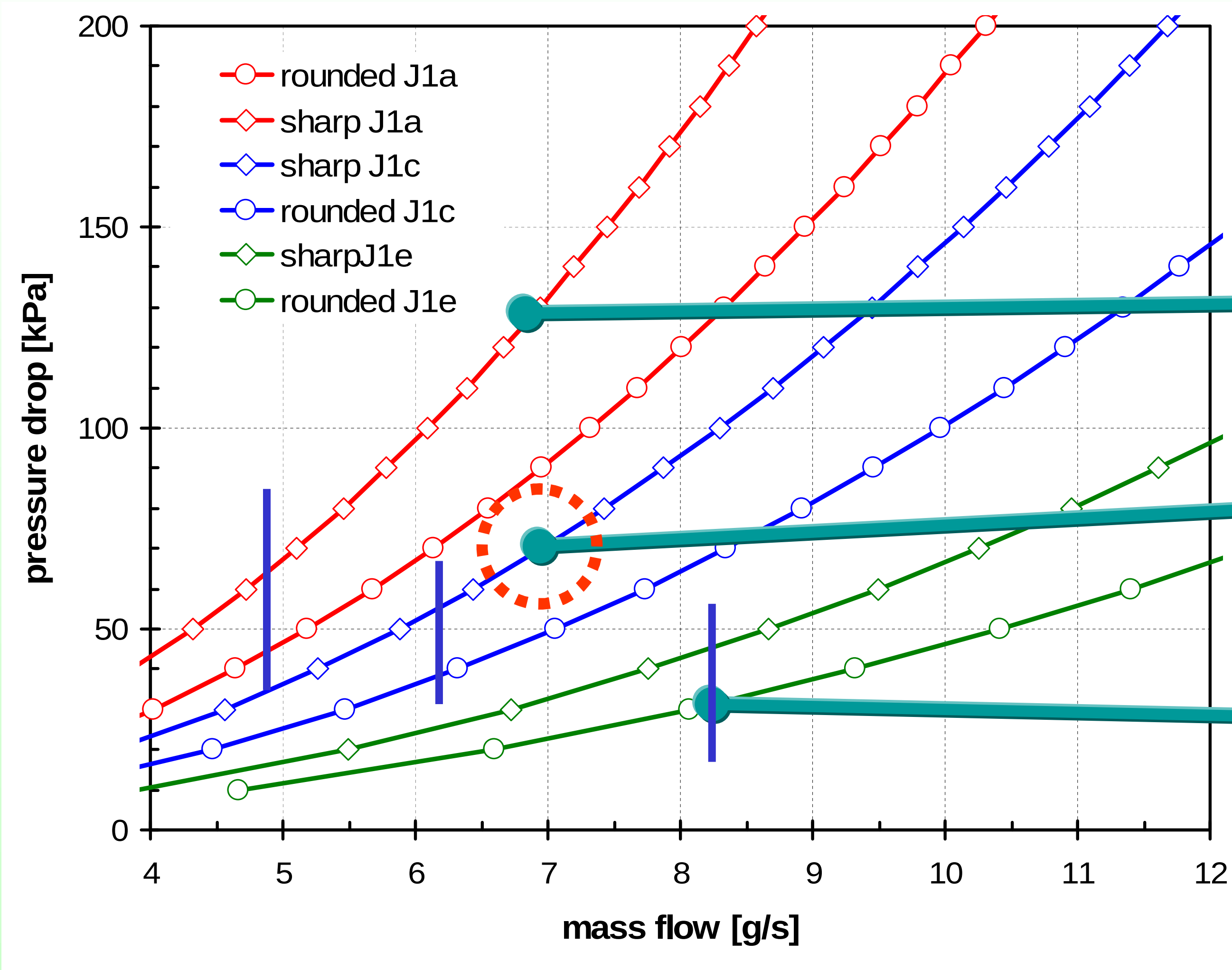
Finger Unit



Multiple Jet Cartridge



LAYOUT EXAMPLES



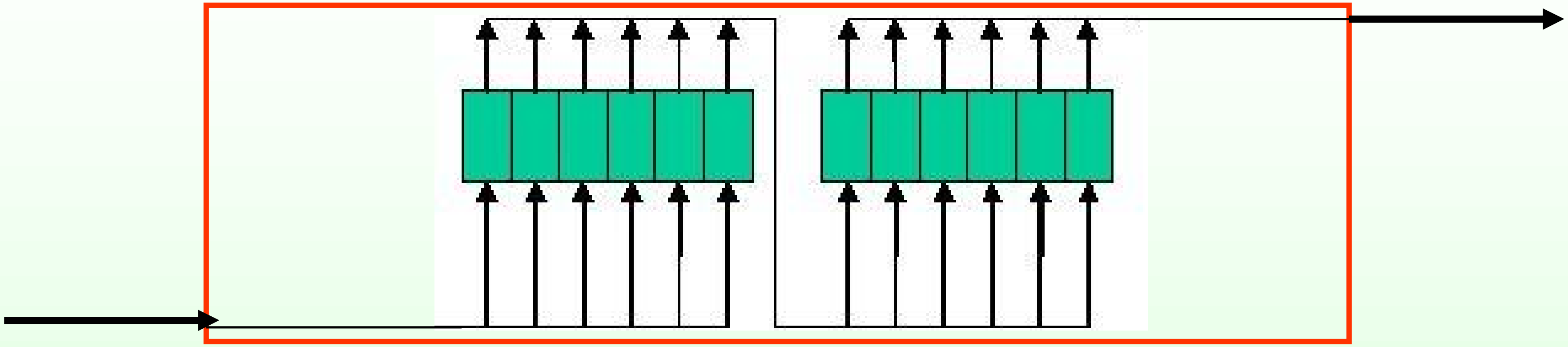
limit for heat flux 10 MW/m²:

rel. compressor power: 10 %

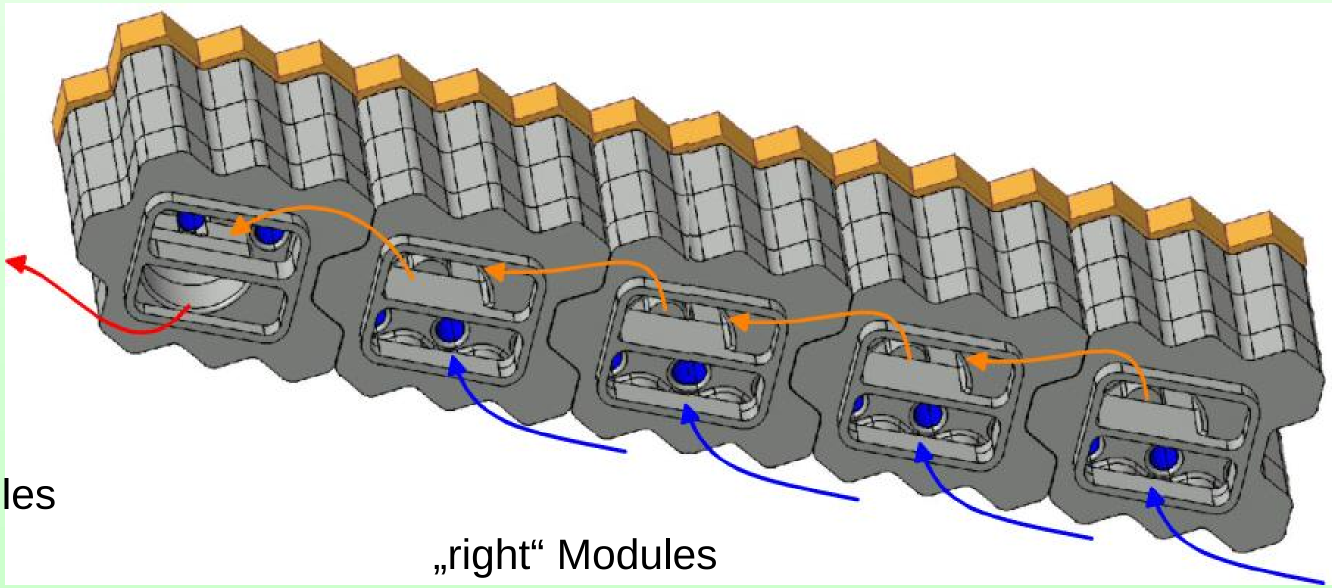
rel. compressor power: 7.1 %

rel. compressor power: 6.3 %

Hydraulic lay-out of the target plate (schematic)



HEMP / HEMS: 3x30 fingers in parallel, in 2 sections in series

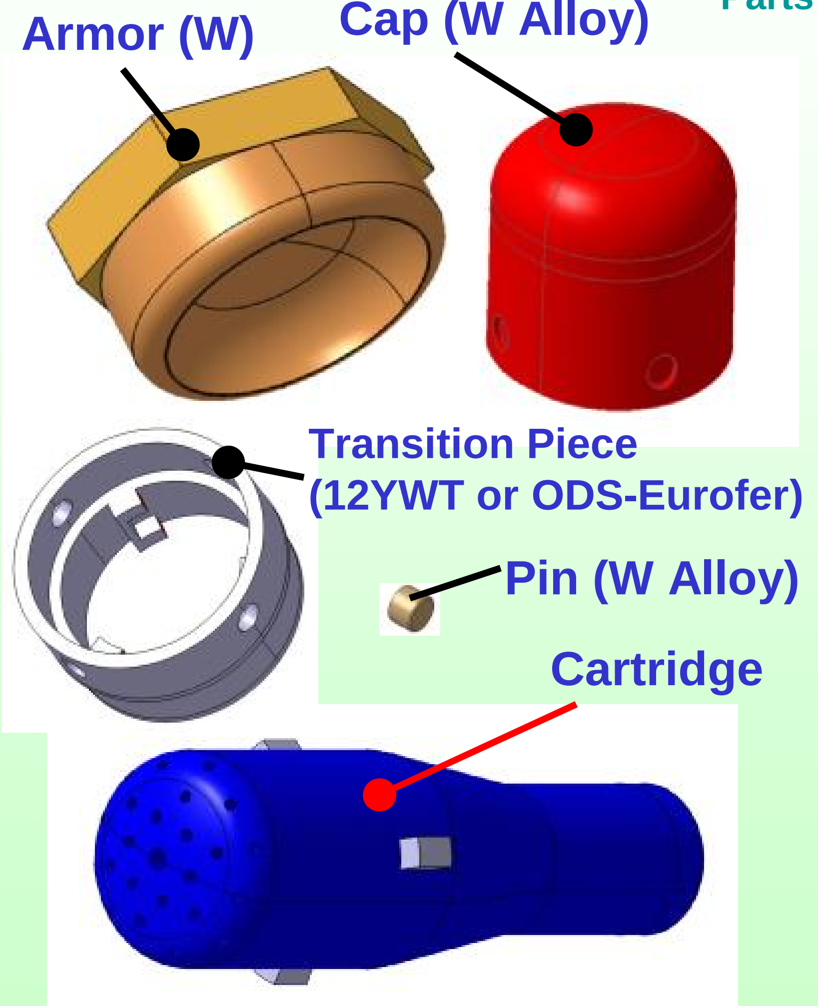


„left“ Modules

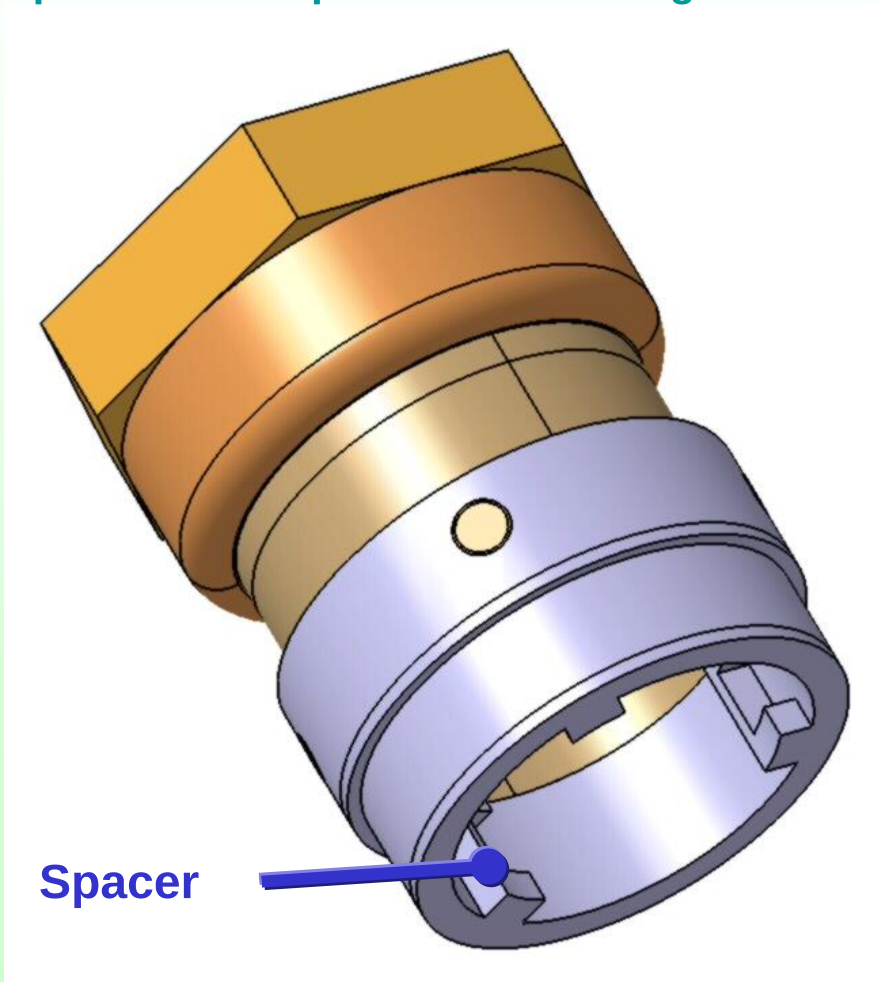
„right“ Modules

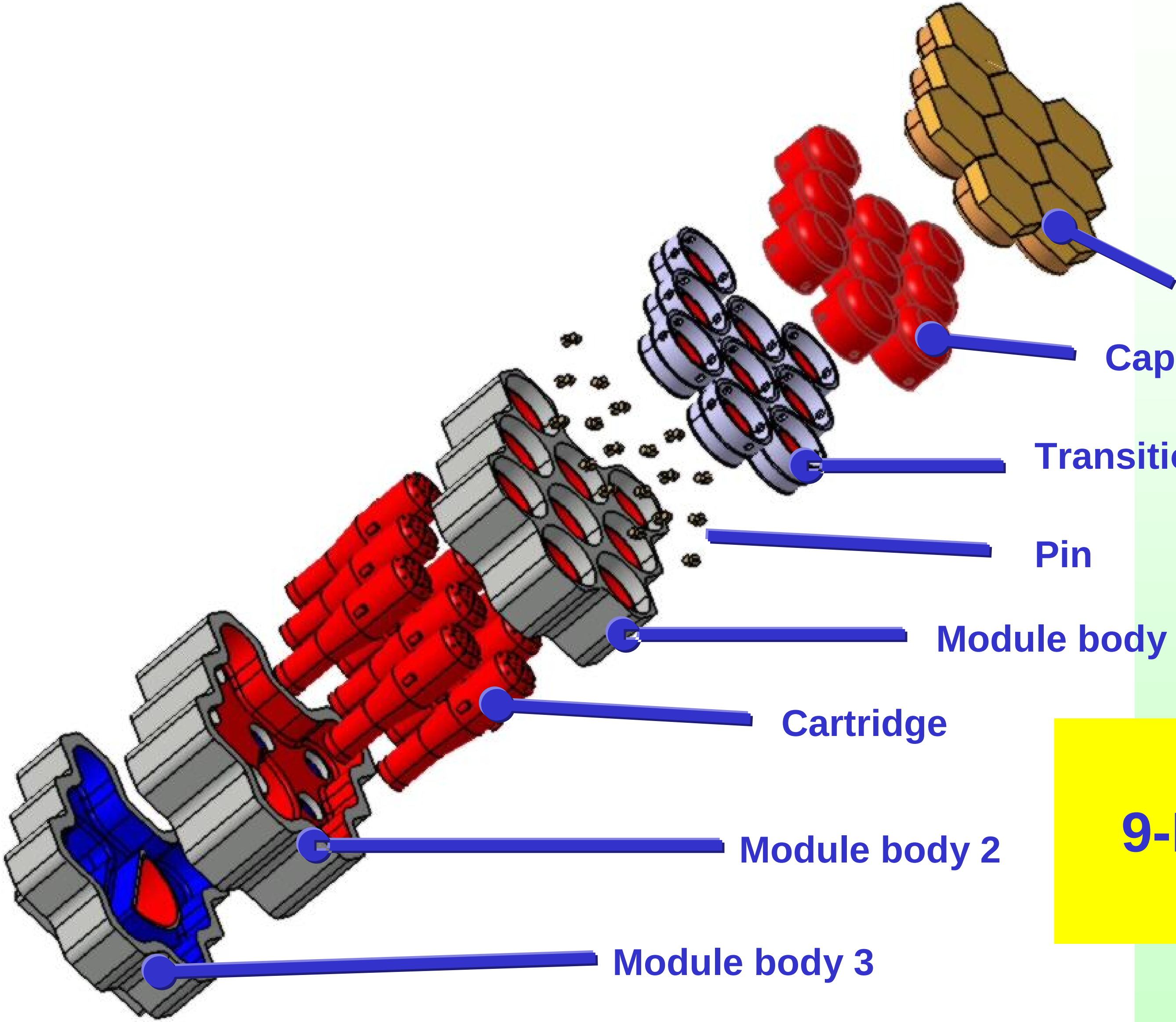
HEMJ Finger

Parts

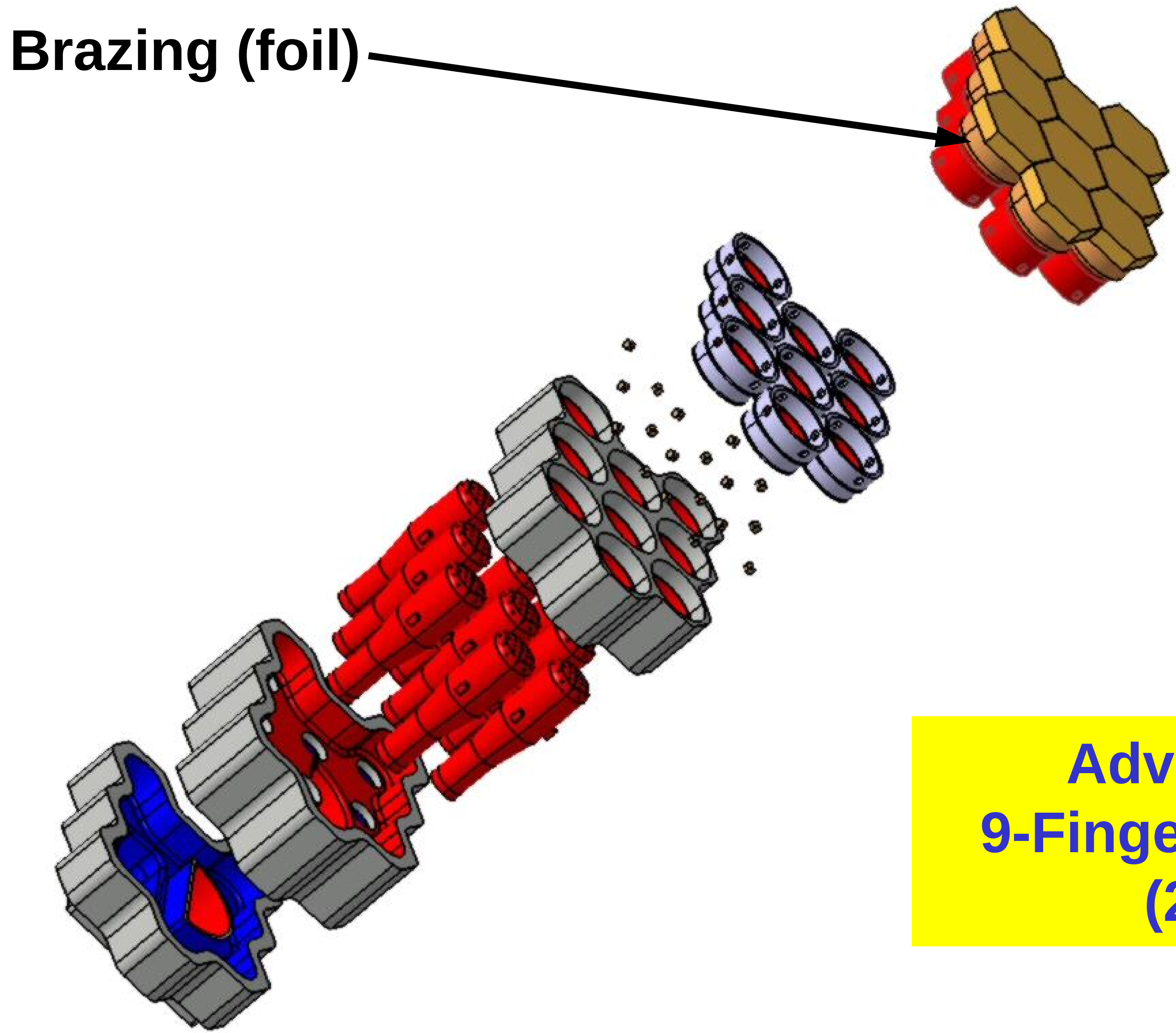


Cap/Tube with Spacers for Cartridge



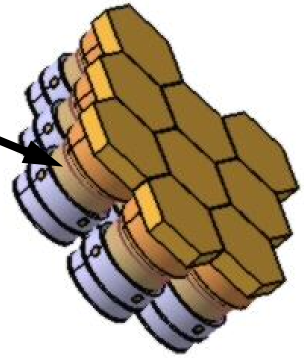


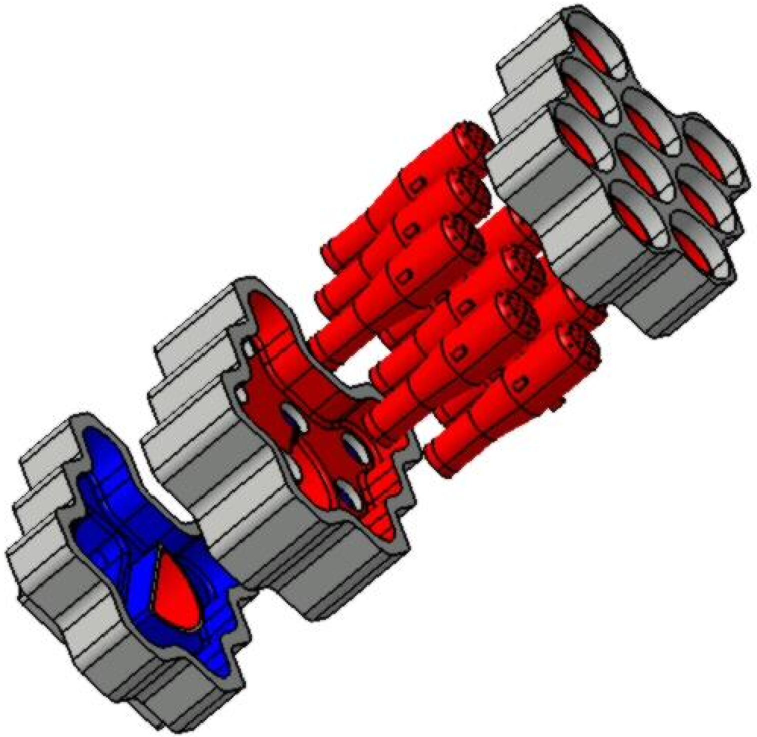
Advanced 9-Finger module (1/7)



Advanced 9-Finger module (2/7)

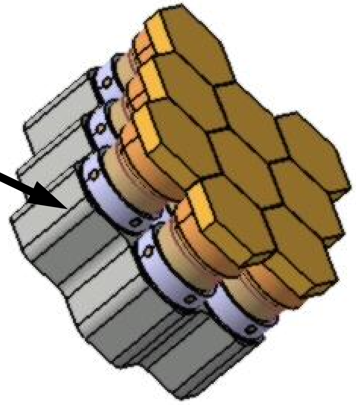
Brazing with cast copper

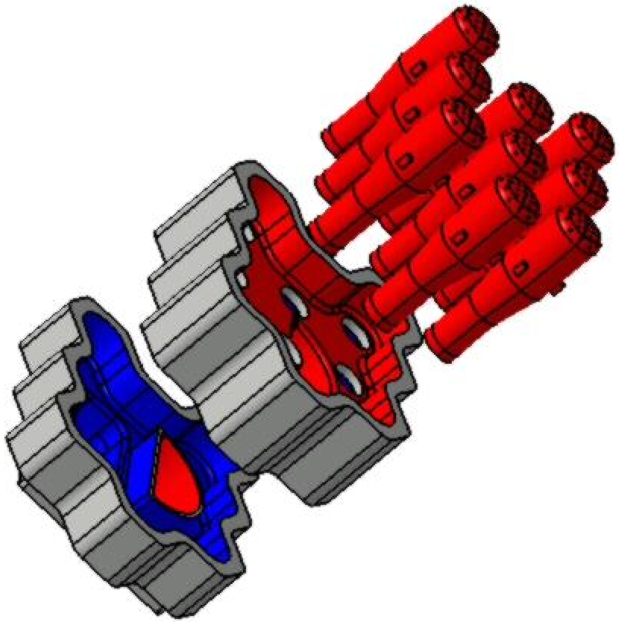




Advanced 9-Finger module (3/7)

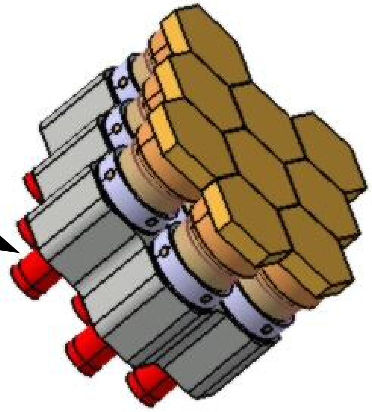
Welding (from below)

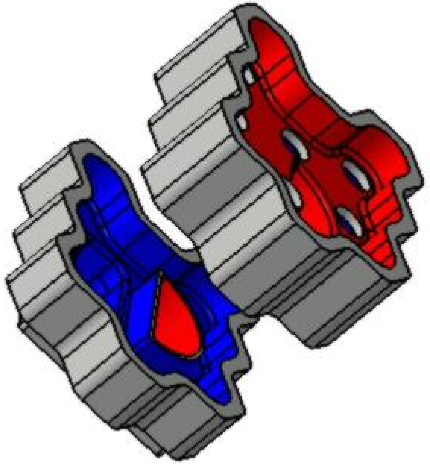




Advanced
9-Finger module
(4/7)

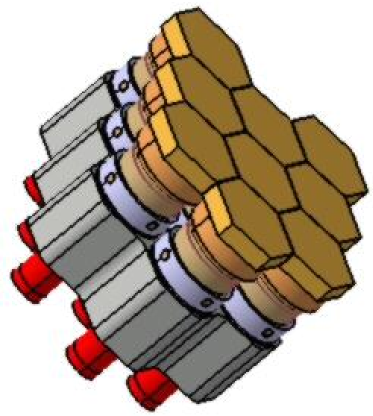
Insert (welding)

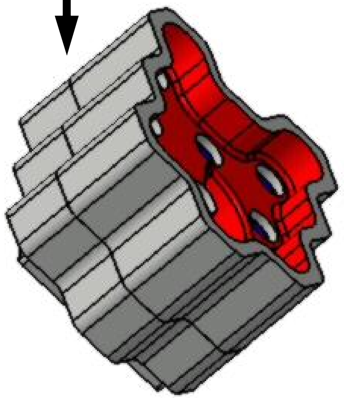




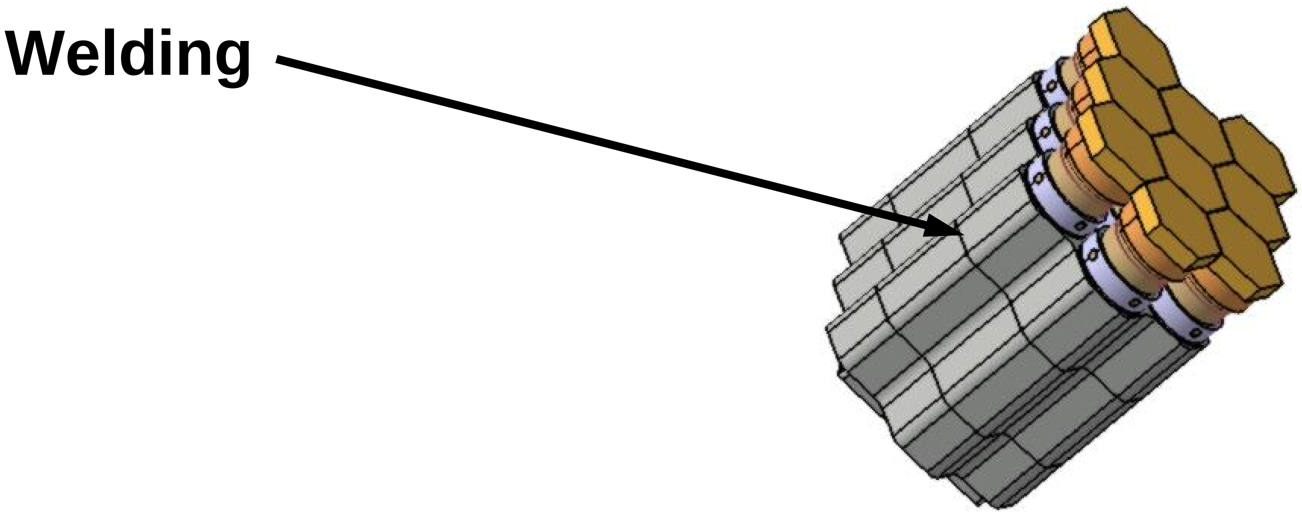
Advanced
9-Finger module
(5/7)

Welding





Advanced 9-Finger module (6/7)

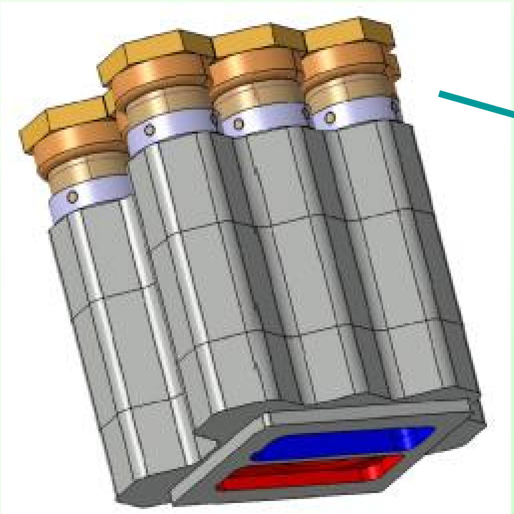
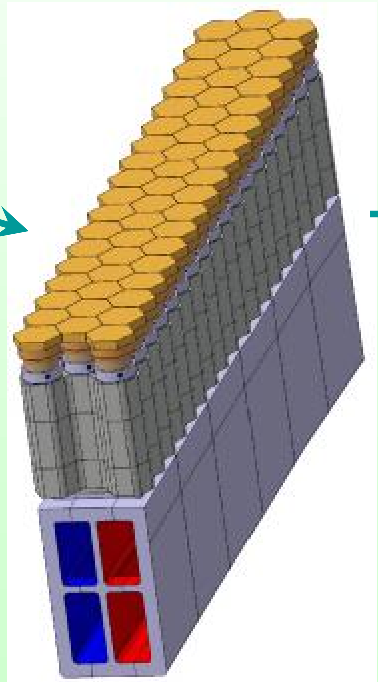
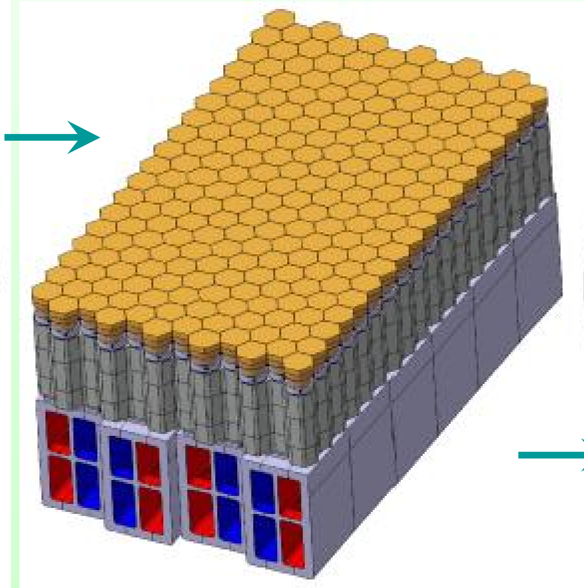
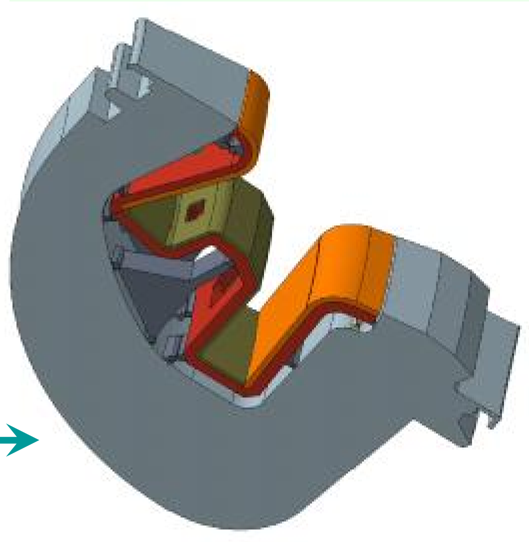


Advanced 9-Finger module (7/7)

High reliability, low waste during fabrication

Construction Kit Principle:
Small Units advantageous for R&D progress
Small Units can be tested before assembling

9-Finger Unit	Stripe-Unit	Target Plate	Divertor Cassette

Test, Assembly → Test, Assembly → Test, Assembly → ...

Measurement of pressure drops for HETS with air

Measurement device (left) and detail of the test section (right) for pressure drop experiments.

HEBLO (FZK) – Test facility for CFD-Validation

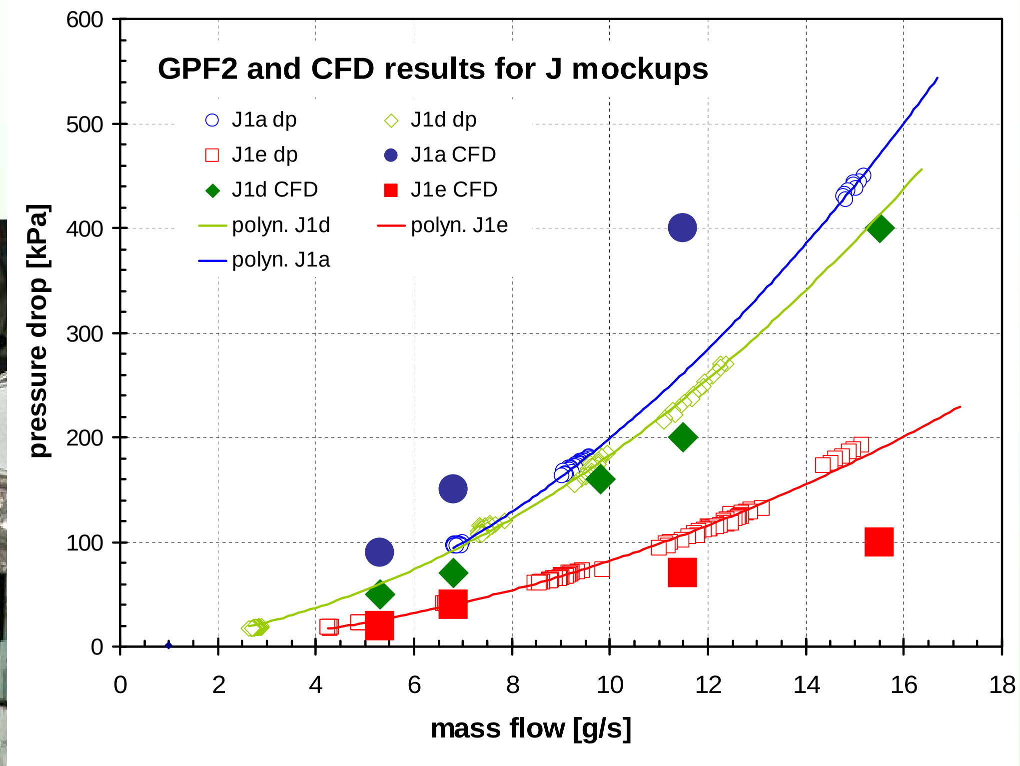
Temperature Cycle

operation pressure	8 MPa
helium flow rate	120 g/s
Helium temp. (max.)	430 °C
He-heating power	60 kW
Surface heating	3 kW

Testprogram for 2004 / 2005:
10:1 Mock-up for HEMJ
10:1 Mock-up for HEMS
10:1 Mock-up for HEMP

Pressure drops and HTC measurements for HEMJ with Helium

EFREMOV under FZK contract



Pressure drop measurements with the Gas Puffing Facility 2

HEMJ cartridges for GPF2 experiments

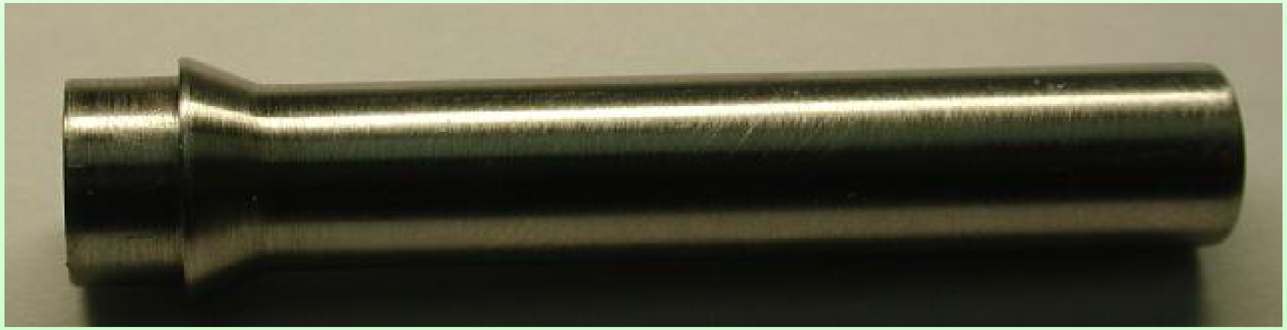
HEMJ J1a

HEMJ J1-b

HEMJ J1-c

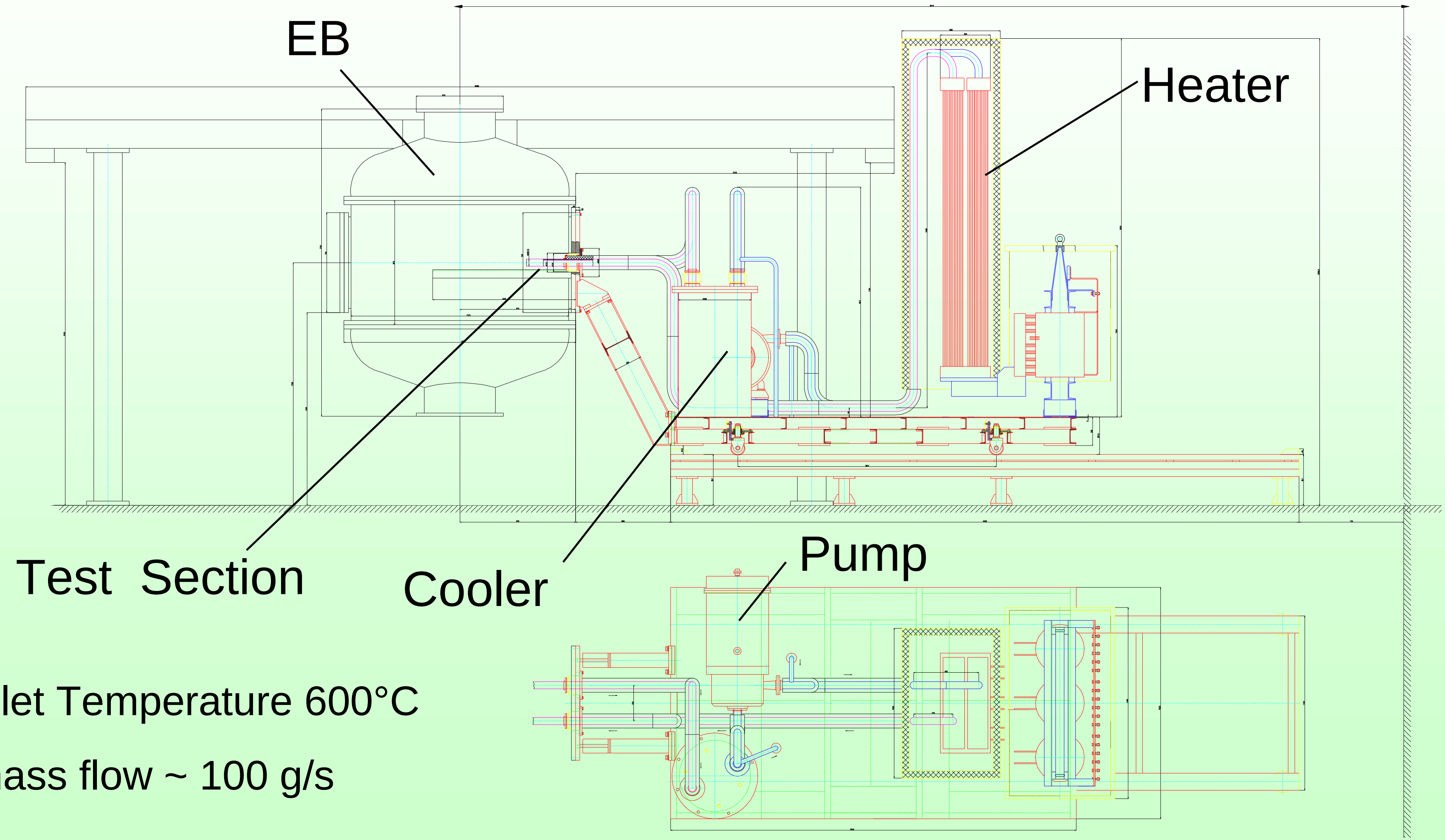
HEMJ J1-d

HEMJ J1-e



Tube for mockup

Helium facility + EB at EFREMOV (in construction)



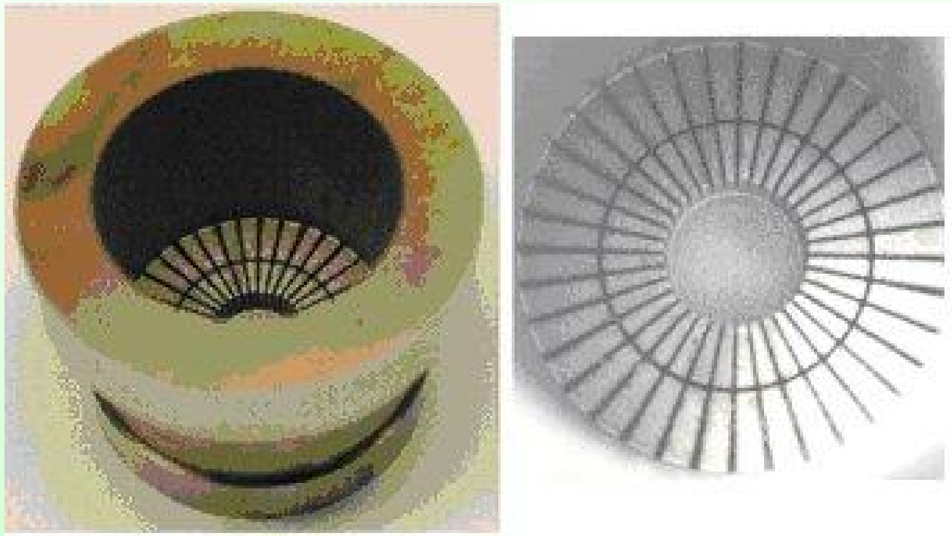
inlet Temperature 600°C

mass flow ~ 100 g/s

Proposed fabrication and joint technologies

	HETS [ENEA]	HEMJ (HEMP/HEMS) [FZK]
Tiles	Plasma spray/ powder technology	Cutting from rods and grinding
Cup (dome)	Machining	Deep drawing from cross rolled WL10 + finishing
Promoter	-	(EDM, ECM, PIM, Laser)
Structure	Brazing of different parts (900) Pd or Zr	Standard ODS alloy machining; tube: extrusion
Joint: Tiles – Cup	Plasma spray/ brazing	Brazing or bonding (T=1300°C) by commercial alloys, Zr, V, Stemet alloys, NiCu, NiTi
Joint: Cup – Structure	W-W Brazing, Cu or Ni based	Transition joint (Mechanical interlock + Cu sealing)
Joint: Promoter – Cup	-	(Brazing or bonding (T=1300°C) by commer. alloys, Zr, V, Stemet alloys, NiCu, NiTi)

Examples of W mock-up fabrication for cap and slot array



t.

Mock-up of W-thimble with integrated slot array fabricated by EDM process.

Laser: duo YAG+Nd, 100W, 50Hz, 0.1 ms

Parameter	Value
Pass length, mm	860
Pattern length, mm	196
Removed volume, mm^3	55
Working velocity, mm/s	1.67
Pass number	3
Machining duration, s	1900
Applied energy, kJ	160
Sublimation energy, J/mm^3	84
Removing efficiency, %	3.5

W-slot array prepared by Laser process

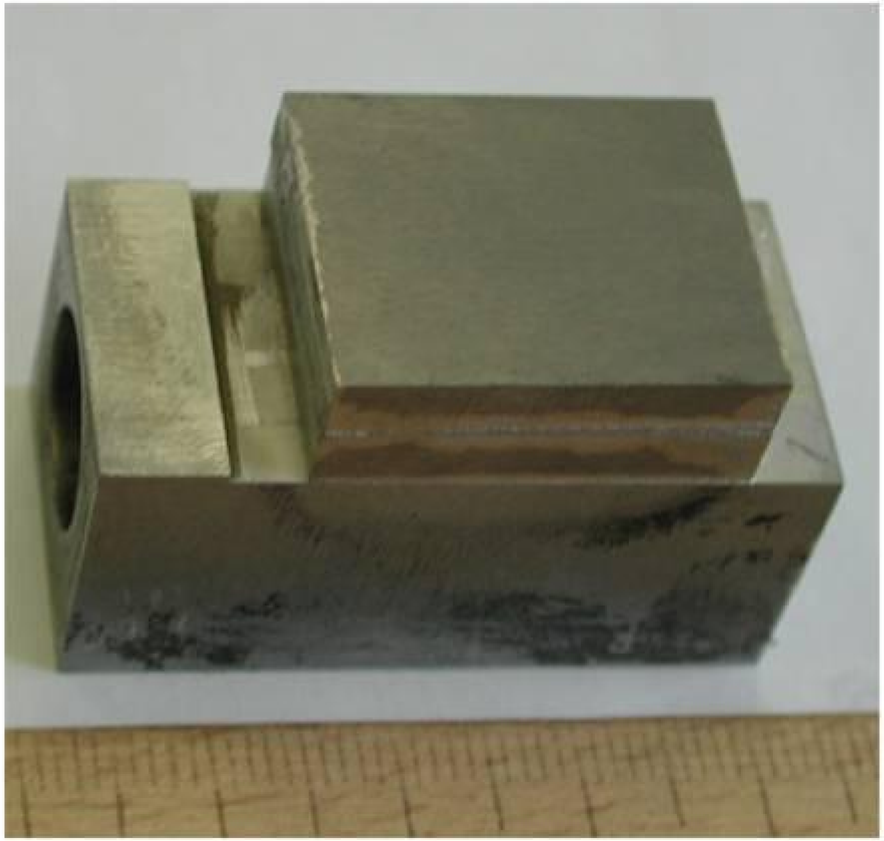
EFREMOV under FZK contract

R&D on fabrication technologies: cup manufacturing

EFREMOV under FZK contract

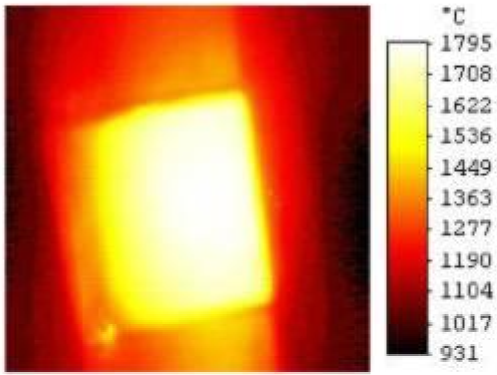
WL-10 showed satisfactory machining ability in comparison with conventional tungsten

R&D on fabrication technologies: high temperature W-joint



Screening test :

10 MW/m^2	100 cycles	OK
12 MW/m^2	100 cycles	OK
14 MW/m^2	100 cycles	OK
15 MW/m^2	100 cycles	OK
16 MW/m^2	100 cycles	OK



Mock-up brazed with STEMET 1311 filler metal undergone successfully HHF screening tests

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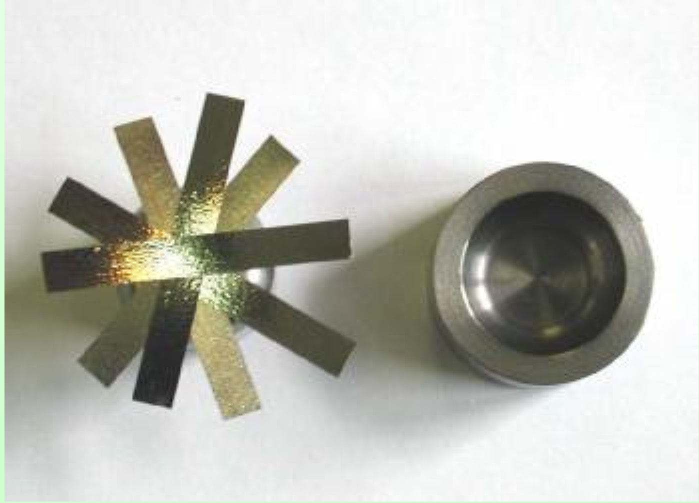
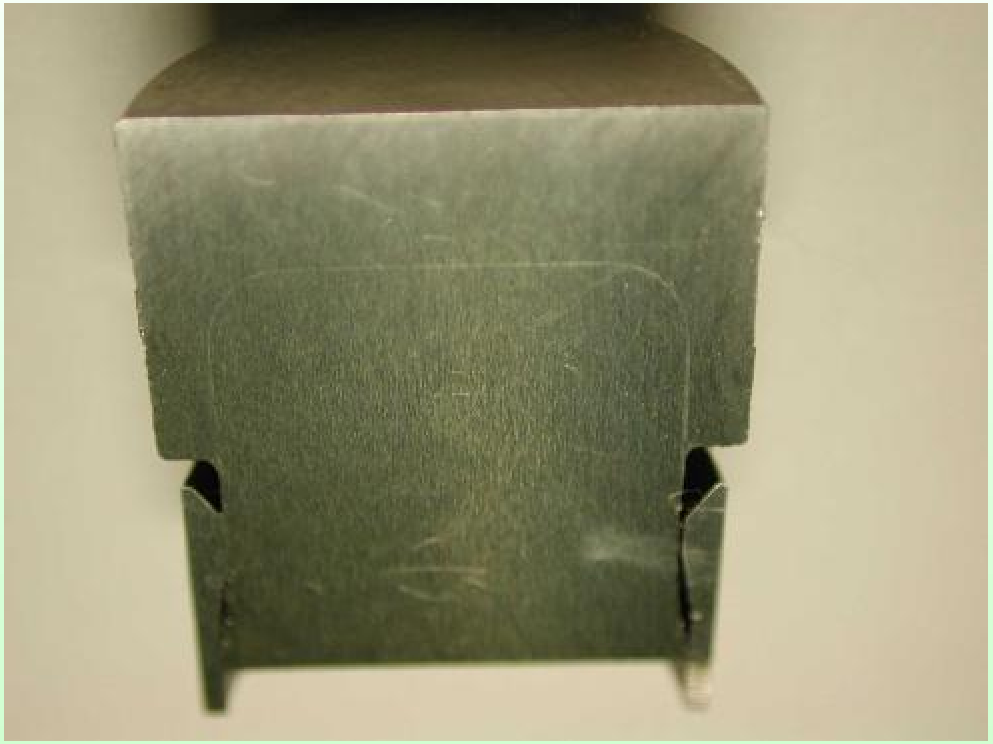
R&D on fabrication technologies: high temperature curved W-joint





Brazing successful

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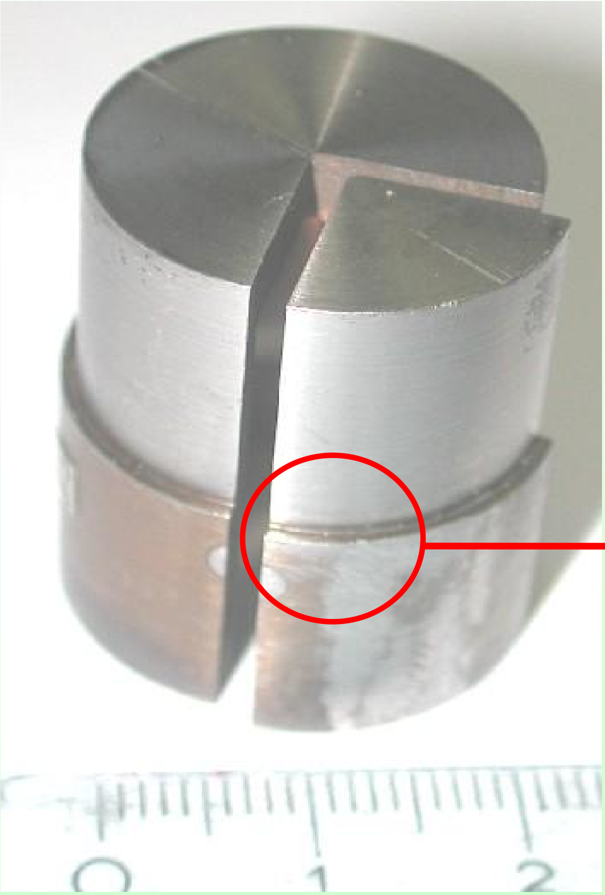
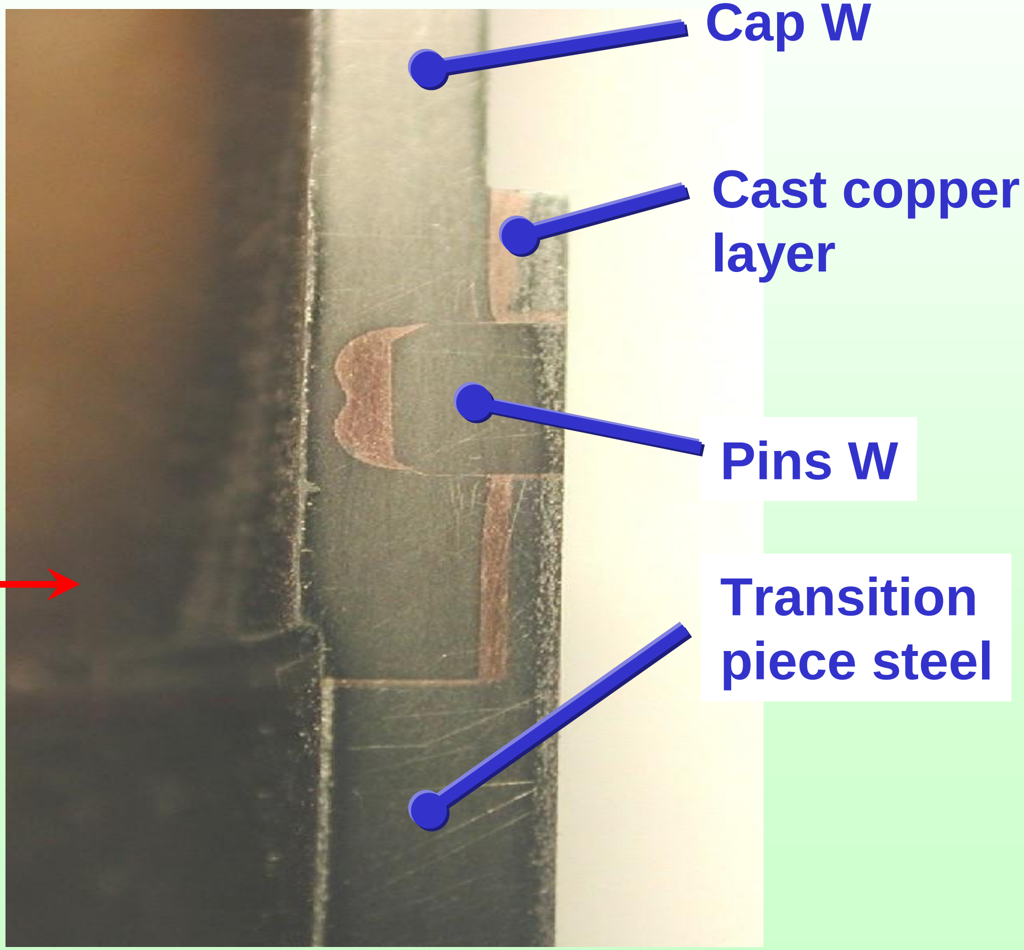
W-Cap – Steel Joint (Efremov Inst.)

W-Cap – Steel-Tube Joint MOCKUP



Cross-section of lock-area



R&D on fabrication technologies: W-steel joint

Main elements for W-Steel joint with new (conic) lock

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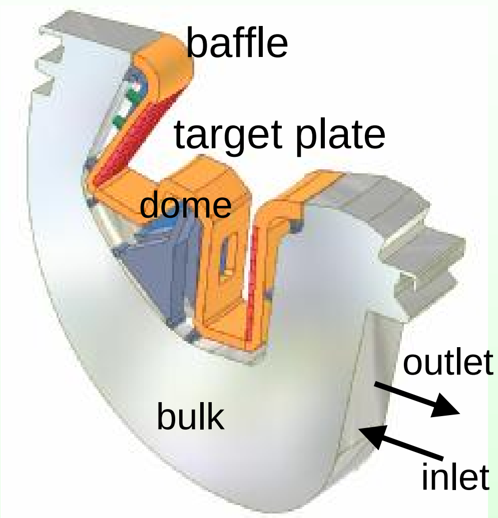
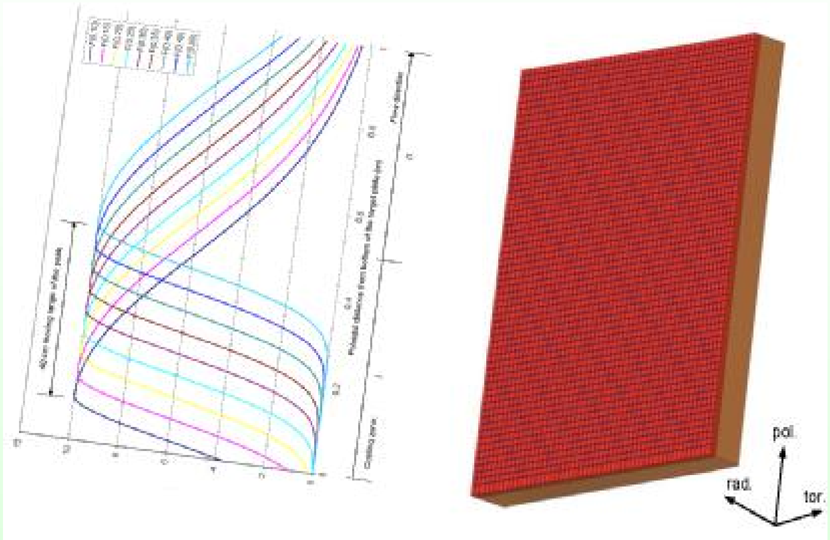
Finger mockup (without armour tile) after casting (left) and after post-testing examination (right).

HEMP Divertor: thermohydraulics design



$\Delta p_{total} \approx$ 0.44 MPa

$P_{pump} \approx$ 8.6 % of $Q_{divertor}$



OB target plate

Zone I, 50 cm → 634 °C → Zone II, 50 cm → 701 °C → Baffle + dome → **717 °C**

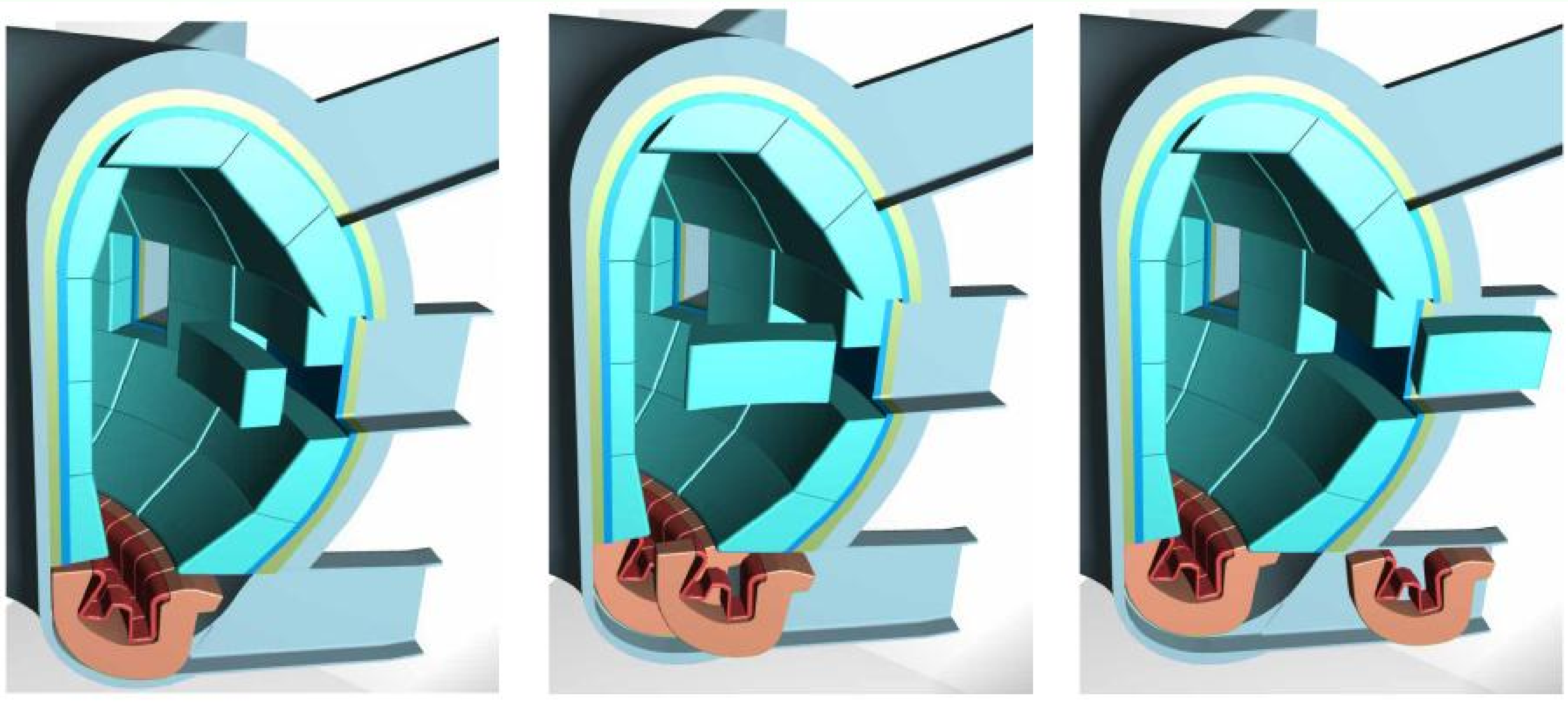
outlet

$\Delta p \approx$ 0.17 MPa

He 10 MPa, **540 °C**, 9.6 kg/s → bulk → 600 °C → Zone I, 50 cm

inlet

Replacement path of the divertor cassettes



Conclusions and future work

- Two divertor conceptual designs based on HETS (ENEA) and HEMJ (FZK) have been defined.
- Close link between the major fields: design, material/fabrication, performance analyses and experiments
- Results of analyses show that 10 MW/m^2 could be achieved with satisfactory performances (pressure drop, Helium temperatures, efficiency of power generation systems, etc)
- Pressure loss and heat transfer coefficient have been calculated. A verification with experiments is ongoing (programme started in 2004).
- Promising fabrication methods for divertor components have been defined, further R&D works required
- Technological experiments concerning W/W and W/steel joints successfully performed at Efremov, further R&D needed for improvement (FZK)
- Building of helium loop in EFREMOV started in 2004, first experiments can start presumably mid 2005

Objectives: He-cooled Divertor on the way to ITER & DEMO