ISFNT-11, Barcelona, September 2013

Status and Prospects of the EU Development of the He-cooled Divertor For DEMO Power Plant

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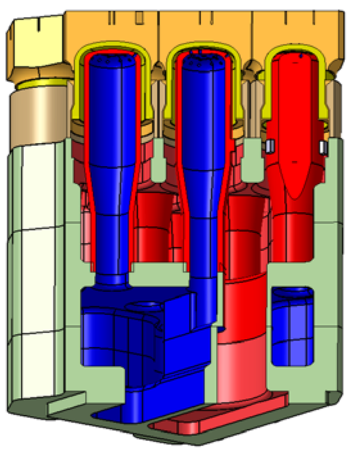
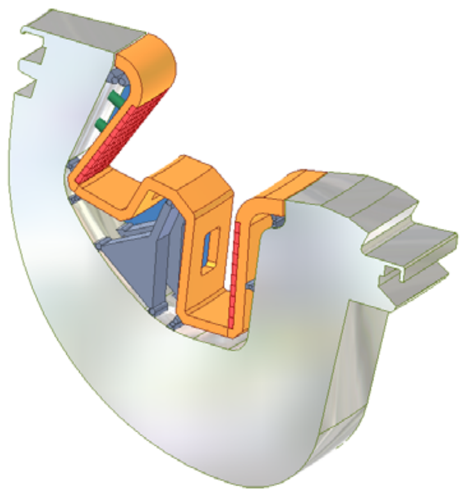
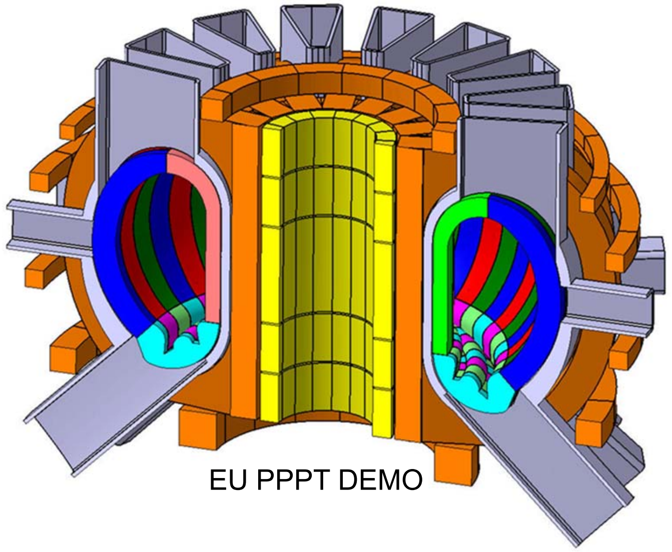
KARLSRUHE INSTITUTE OF TECHNOLOGY (KIT)



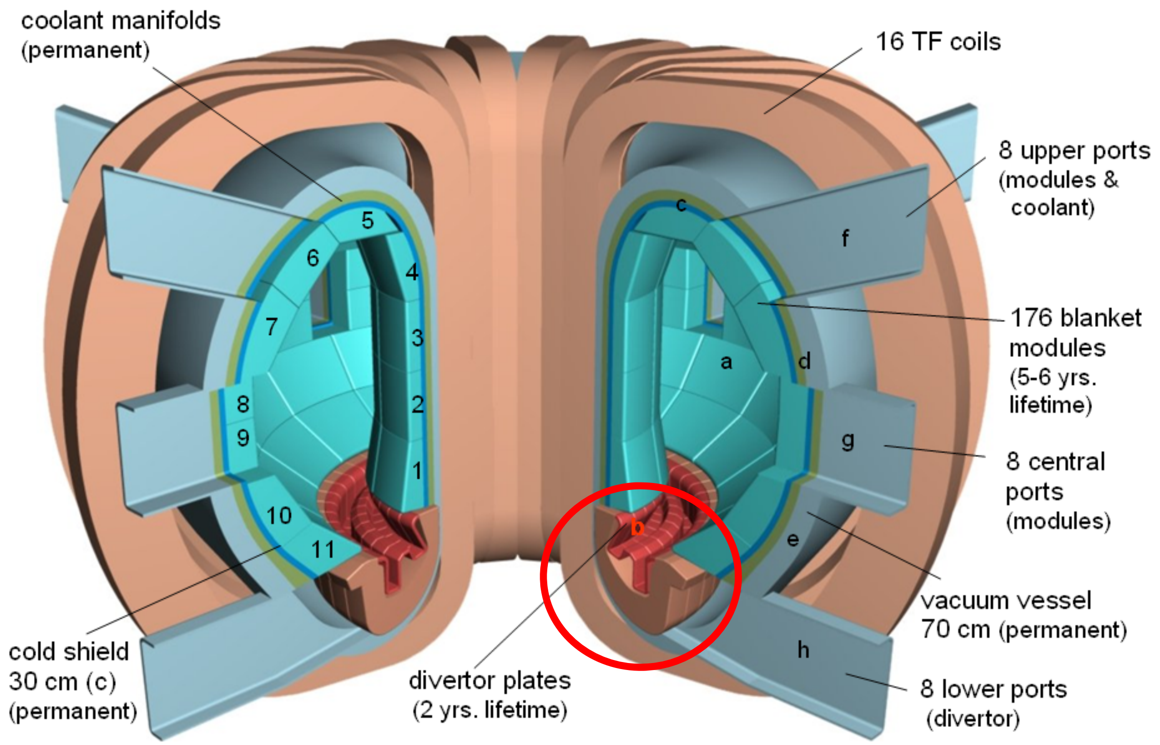


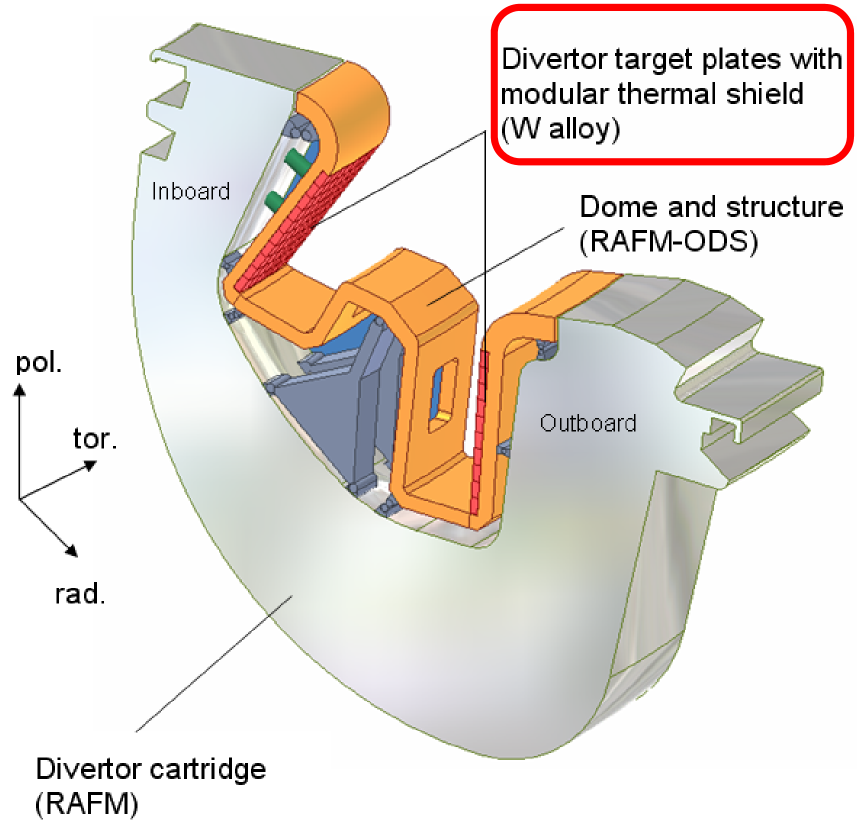


Content

EU PPCS Model C ⇨ Basis for HC Divertor Design

[P. Norajitra et al., Fusion Eng. Des., 69 (2003) 669-673]

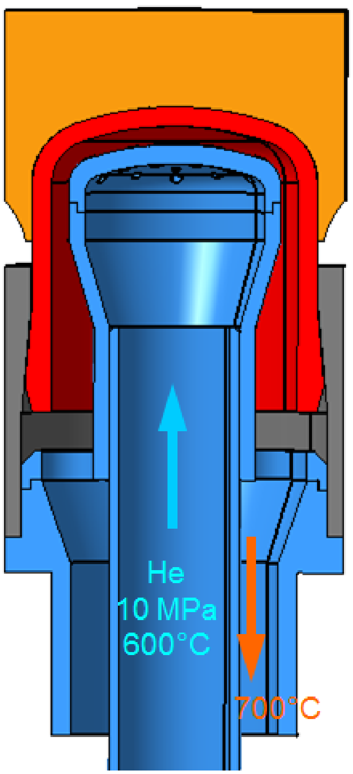


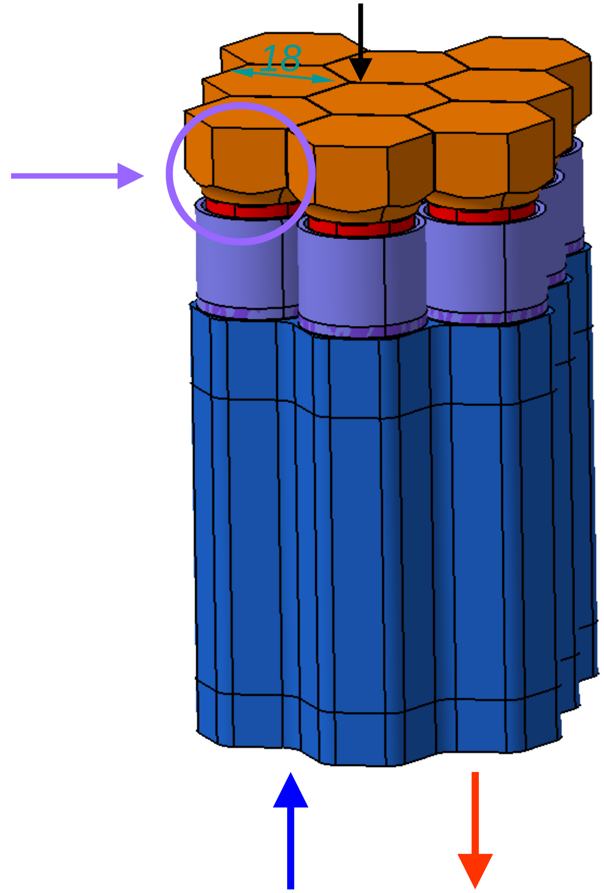


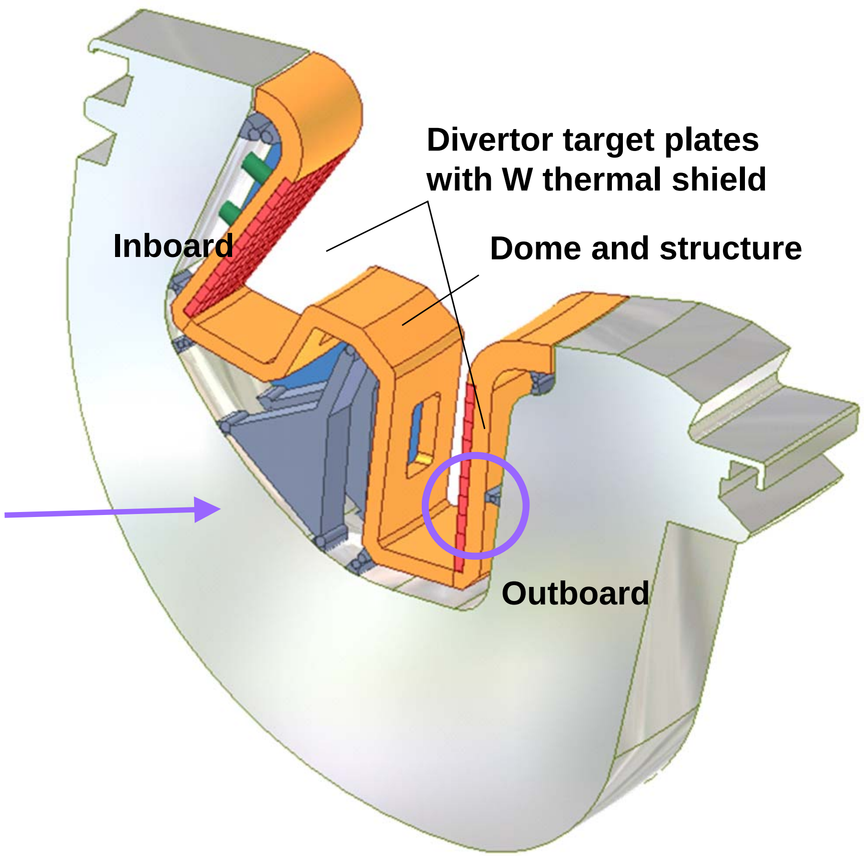
Content

He-cooled Modular Divertor with Jet Cooling (HEMJ)

[ISFNT-8] [P. Norajitra et al., Fusion Eng. Des. 83 (2008) 893–902]





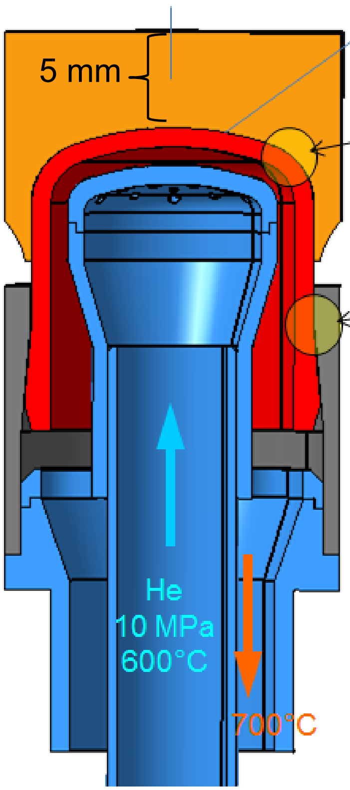


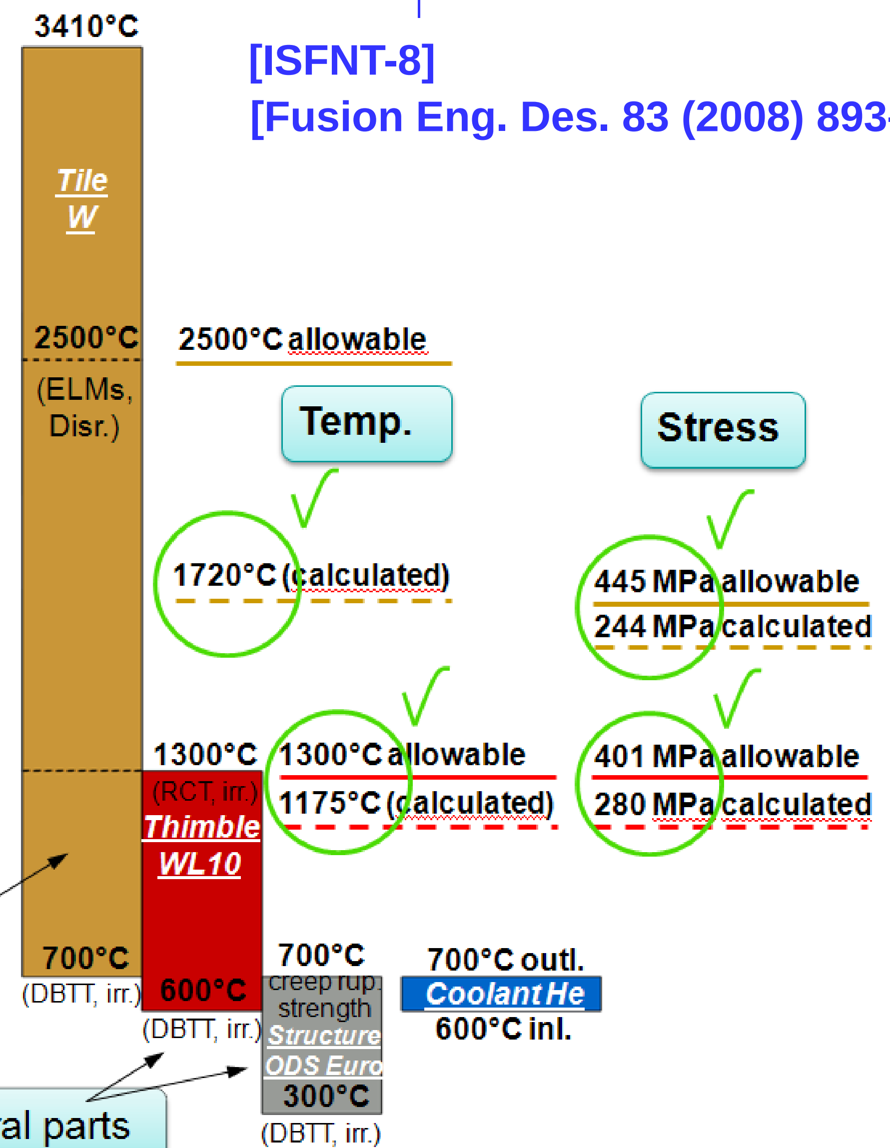
1-Finger module **9-Finger module** **Divertor cassette**

HEMJ: Materials, T- Windows, T and Stress Check

[P. Norajitra et al., J. Nucl. Mater. 367–370 (2007) 1416–1421]

[ISFNT-8]
[Fusion Eng. Des. 83 (2008) 893–902]

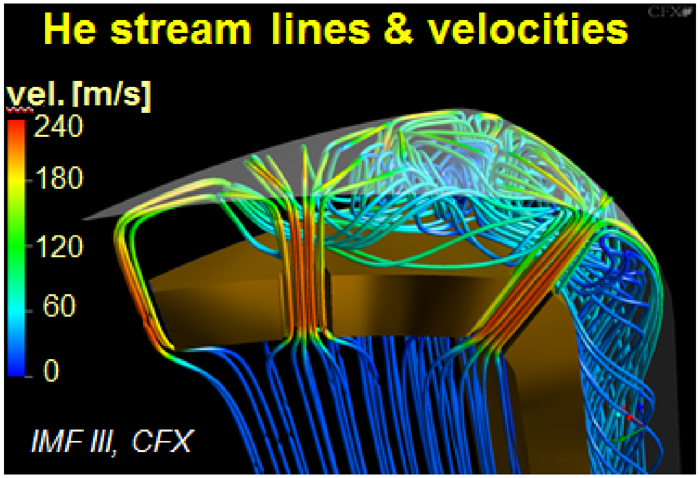




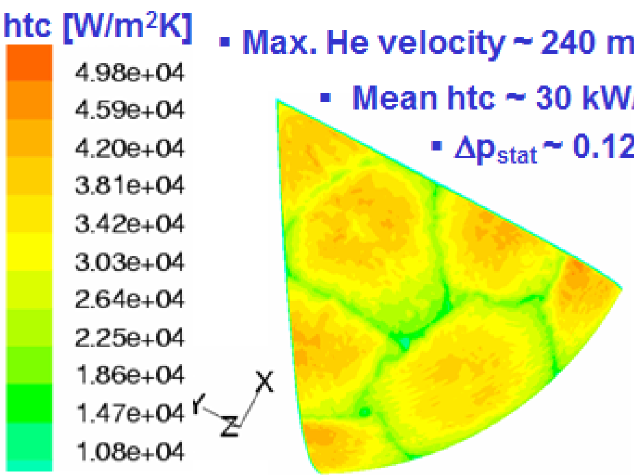
Layout reference case
10 MW/m^2
mfr 6.8 g/s per finger
pumping power ≤ 10%$Q_{removal}$

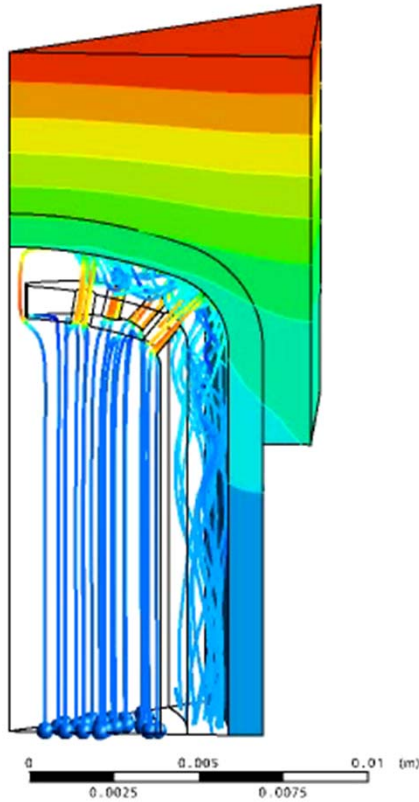
HEMJ: CFD Analysis (Fluent, ANSYS/CFX)

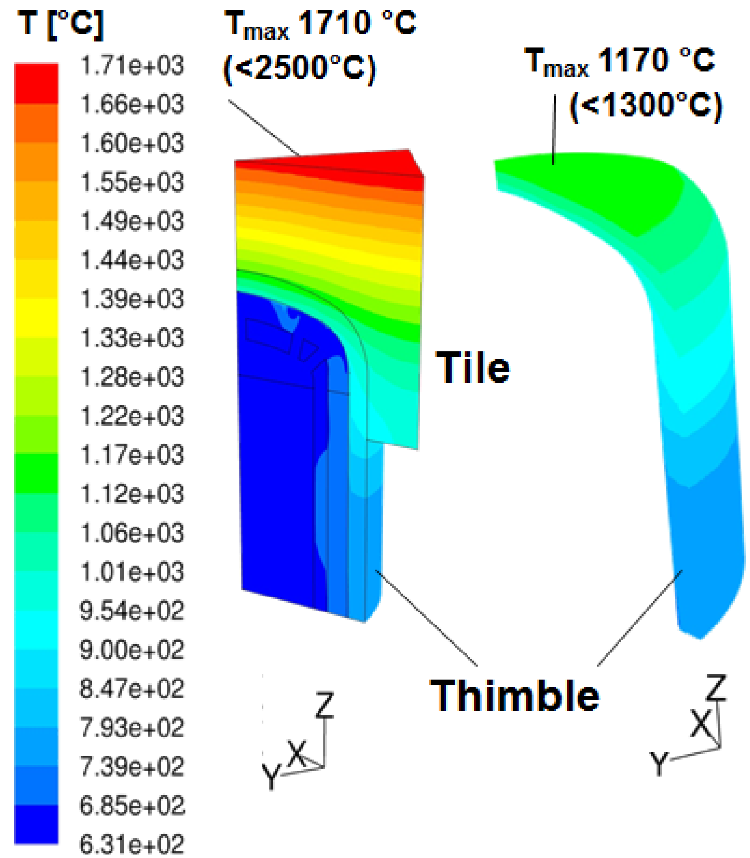
(Currently also co-operation with IJS within the framework of EFDA PPPT)



- Max. He velocity ~ 240 m/s
- Mean htc ~ 30 kW/m²K
- Δp_{stat} ~ 0.12 MPa





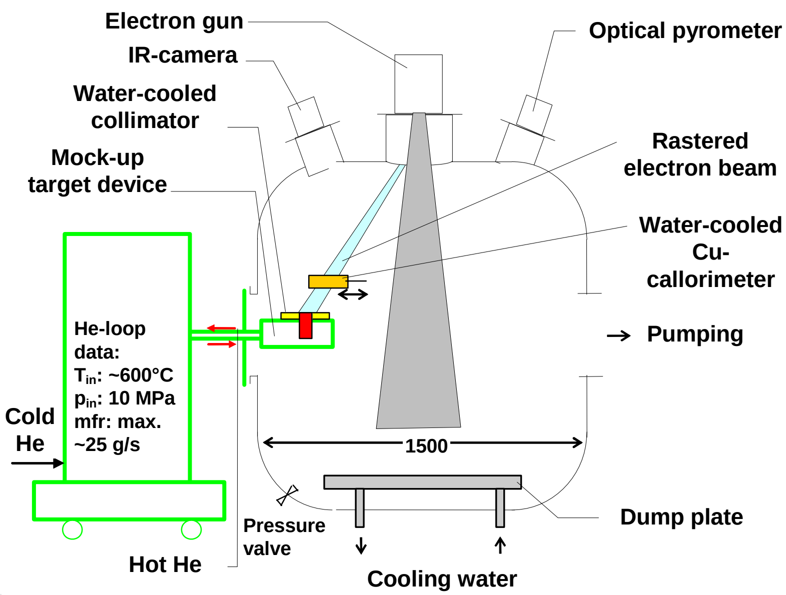


[R. Kruessmann, V. Widak]

Content

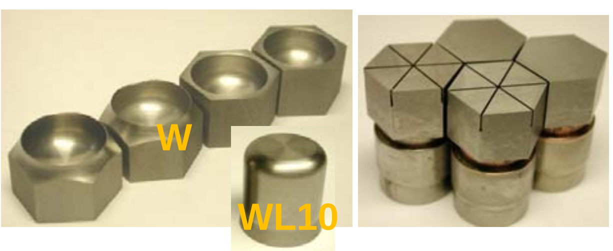
Design verification and validation by HHF tests at Efremov

[P. Norajitra et al., Fus. Eng. Des., 85 (2010) 2251–2256]



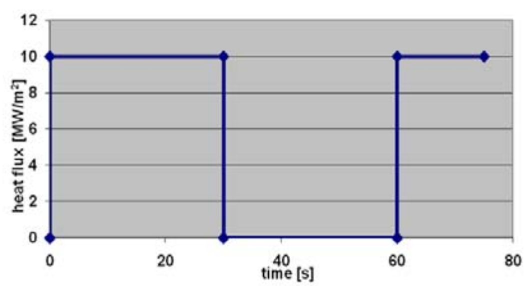
EB (EH 200V, 200 kW, 40 kV)

He loop* & E-beam combined test facility [I. Ovchinnikov, V. Kuznetsov] (*financed by KIT)

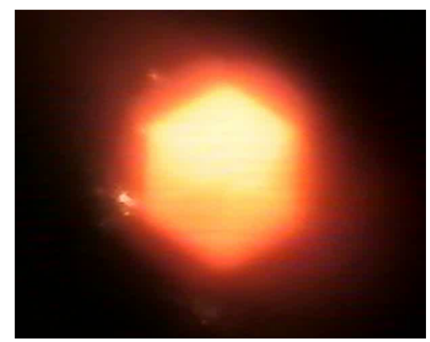


1st mock-ups (Efremov) using STEMET 1311 & Cu/Co fillers [R. Giniyatulin]

Mock-up placed in holder



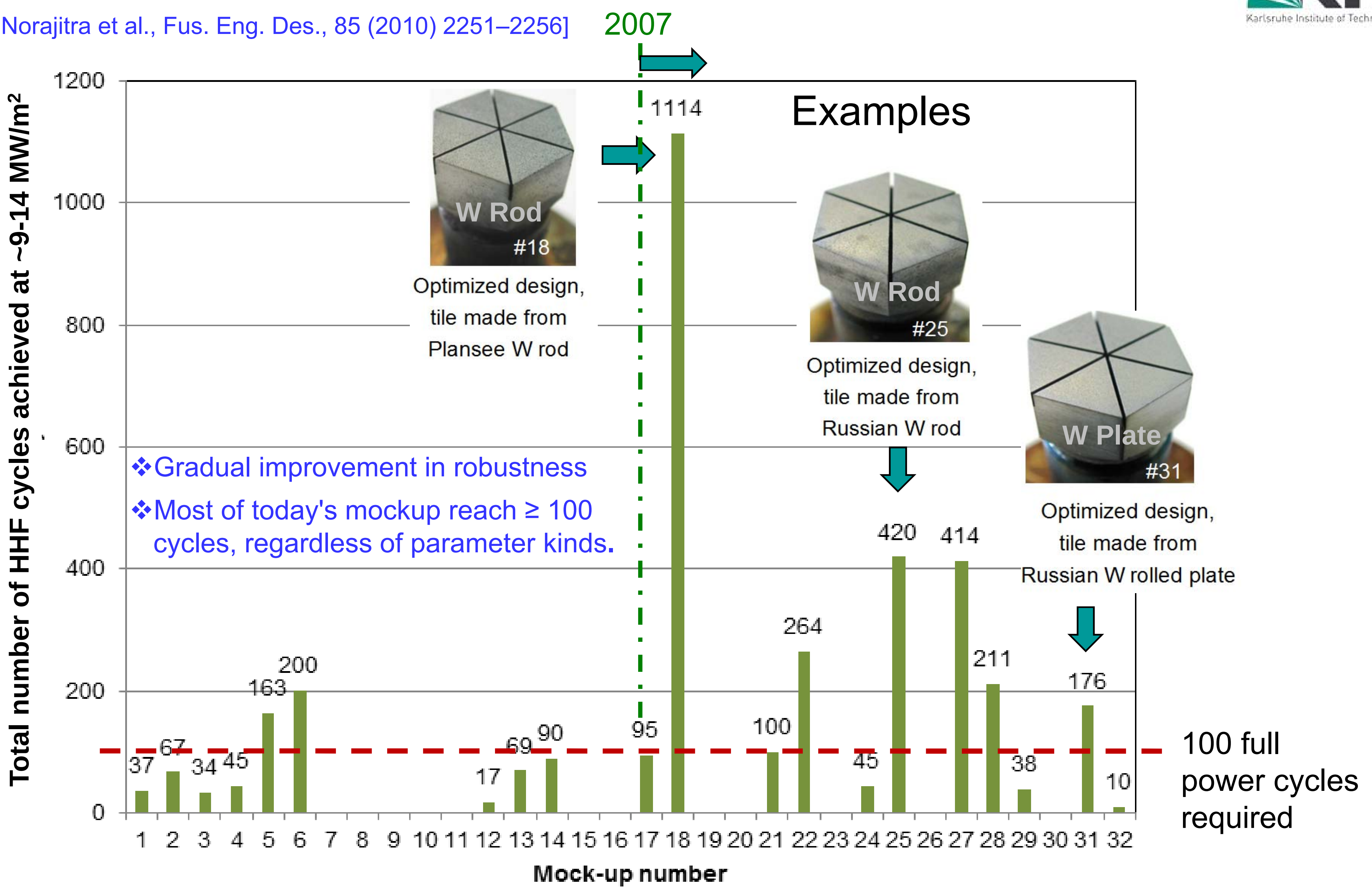
Heat load cycle (30s-30s) “Hot-stand-by”



IR image at 10 MW/m^2

HHF tests at Efremov: Results summary

[P. Norajitra et al., Fus. Eng. Des., 85 (2010) 2251–2256]



HHF tests at Efremov: Results summary

[P. Norajitra et al., Fus. Eng. Des., 85 (2010) 2251–2256]

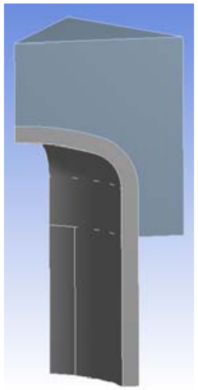
Type of failure	Mockup #
Non-uniform tile surface temperature distribution due to <u>initial cracks in tile material</u>	21
<u>Tile detachment</u> and <u>overheating</u>	4, 14, 17, 24, 28, 32
<u>Cracks</u>	
- at the top of the tile	12, 13, 14, 22, 25
- at the sides of the tile	4, 27
- at the top and the sides of the tile	1, 7, 10
- in thimble	19
- in tile and thimble	2, 3, 5, 8, 9
<u>Gas leakage</u>	
- through tile and thimble	3, 5, 7, 10, 12, 13, 18, 31
- through thimble near the WL10-steel joint	1, 2, 15, 20, 19, 29

Countermeasure

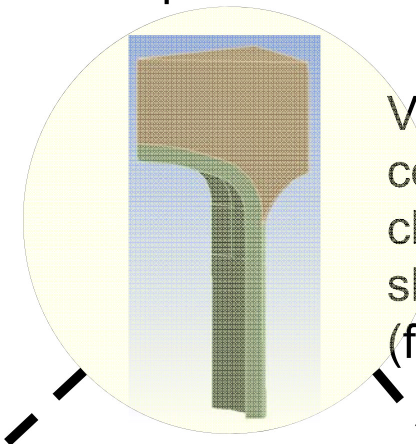
- NDT development (coop. CEA)
- Design improvement (reducing stresses)
- Microcrack-free machining
- High temperature brazing (appropriate filler material)

Optimization of Design for Stress Reduction

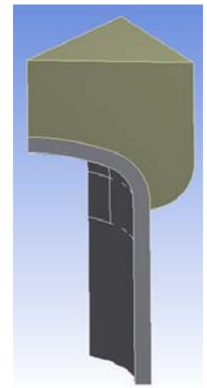
Example versions



Initial
basic
version

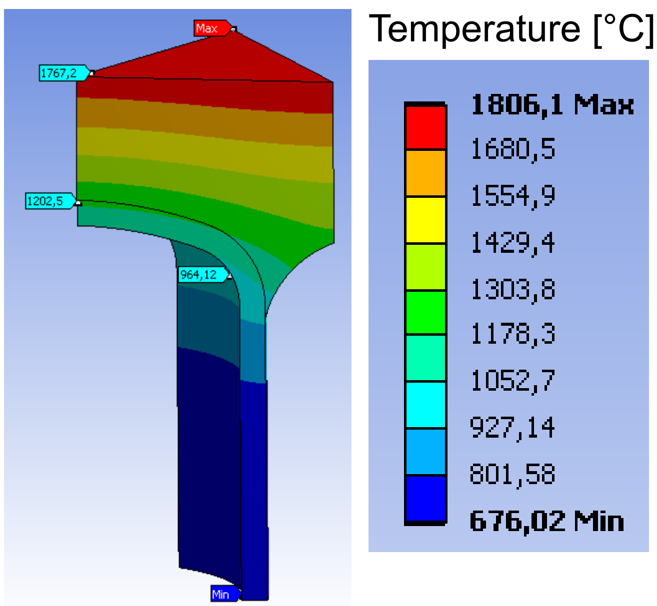


Version with
concave
chamfered tile
shoulder
(favorite)



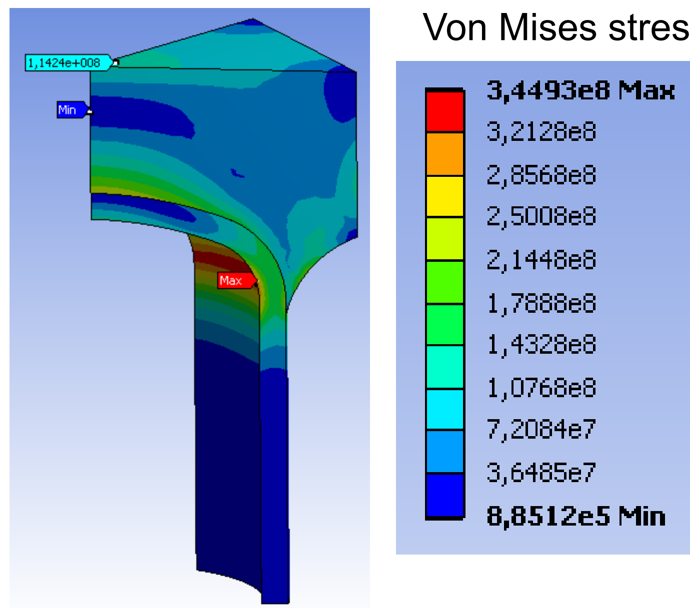
Version with
convex
chamfered
tile shoulder

Temperature [°C]



Max.:
~1806°C (tile)
< 2500°C allow.
~1202°C
(thimble) <
1300°C allow.

Von Mises stress [Pa]



Max.:
~244 MPa (tile)
< 445 MPa allow.
~345 MPa
(thimble) < 355
MPa allow.

Content

1. Introduction
2. The reference design HEMJ
3. Design verification and validation by HHF tests
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5. Other design-related assessments
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   - Non-destructive testing method for HEMJ (EU PPPT)
   - Deep-drawing W thimble (EU PPPT)
   - W-W joining using low-activation Ti interlayer
   - Induced EM load on divertor finger and impact tests
   - Alternative LT design using Ta alloy
6. Conclusion and outlook

Machining of parts made of W/W alloys with crack-free quality)

KIT Karlsruhe Institute of Technology

Turning

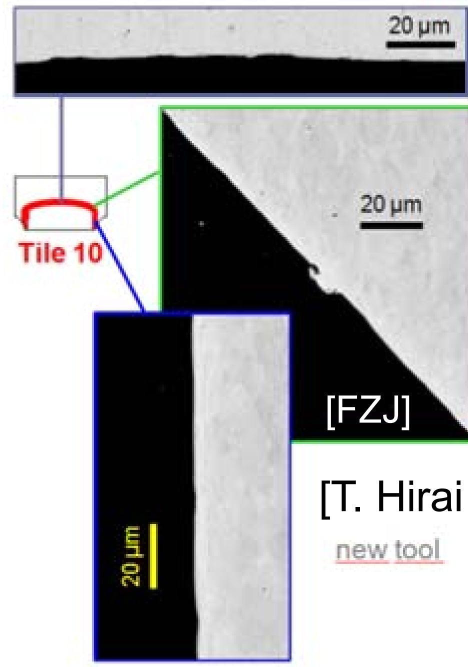
WL10 thimble

Steel conic sleeve

Milling

Milling

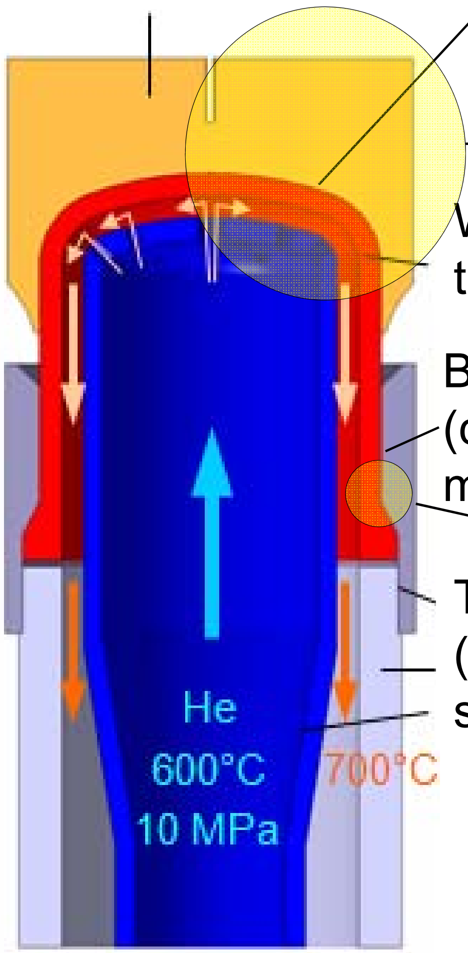
[J. Reiser]



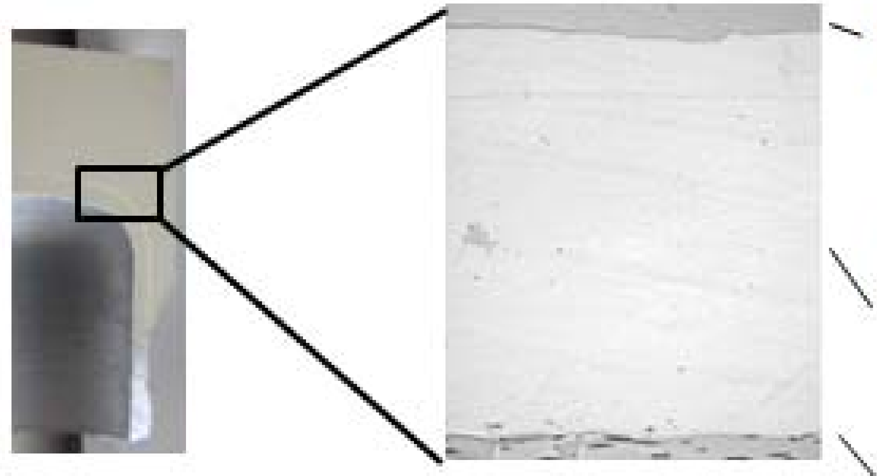
[T. Hirai et al.]

new tool

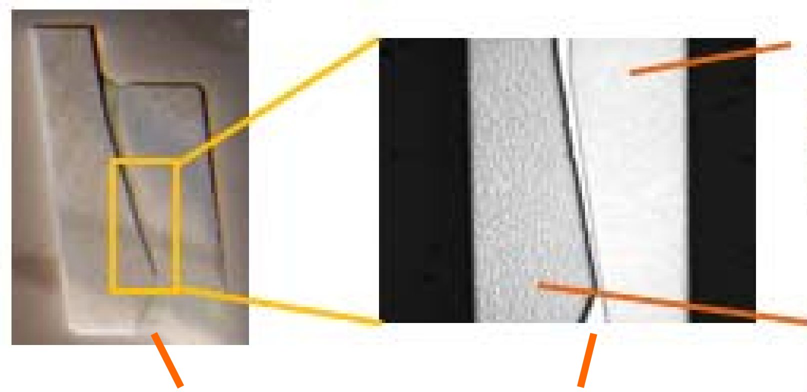
Brazing of divertor parts (W–WL10, WL10–steel)



[J. Aktaa et al., this conference]



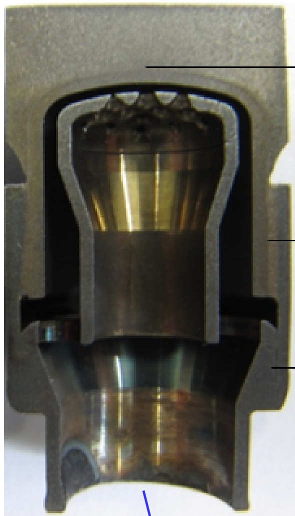
[J. Reiser, L. Spatafora, V. Widak]



PdCu filler: Tbr ~1120°C

HEMJ 9-finger module production

[P. Norajitra et al., FS&T VOL. 62, July/Aug. 2012]



W-WL10 joint brazed with PdNi

WL10-steel joint brazed with CuPd

TIG seal welding (steel-steel joint)

1-finger modules

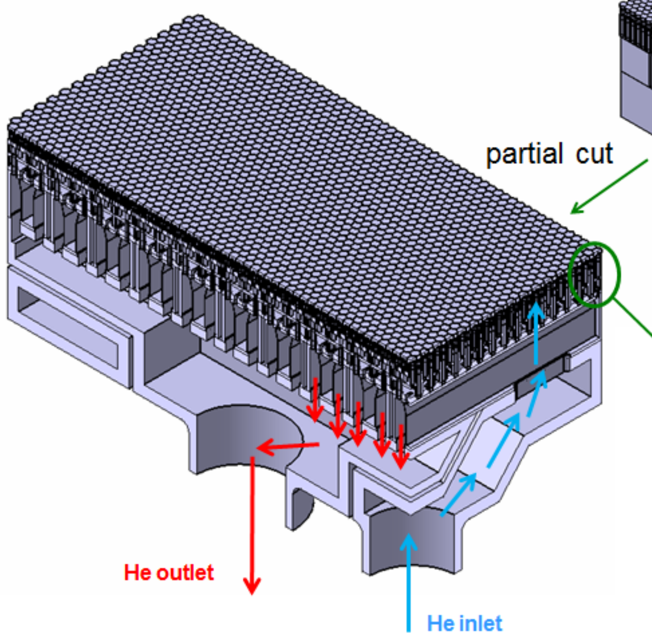
9-finger module (W) for HHF tests (Efremov, HELOKA)

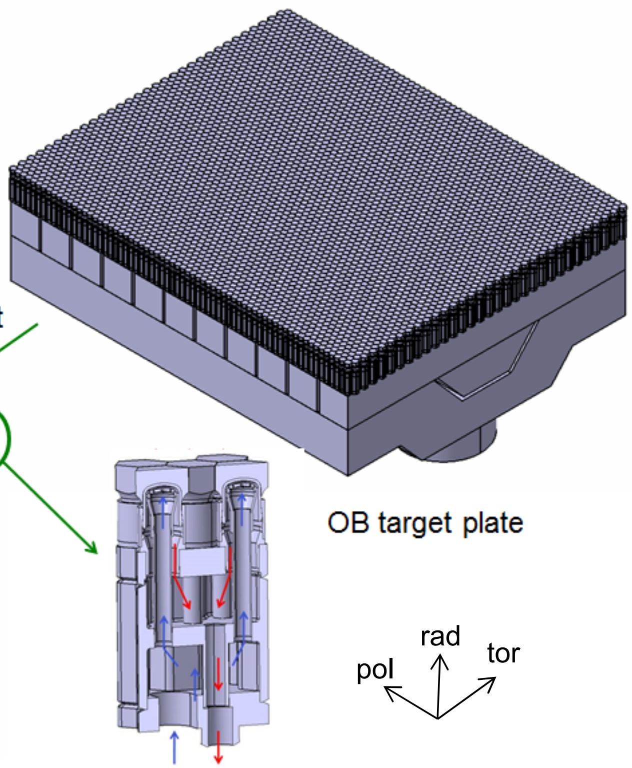
9-finger module (brass) for NDE (SATIR, CEA)

Content

Integration of 9-finger modules to an OB target plate

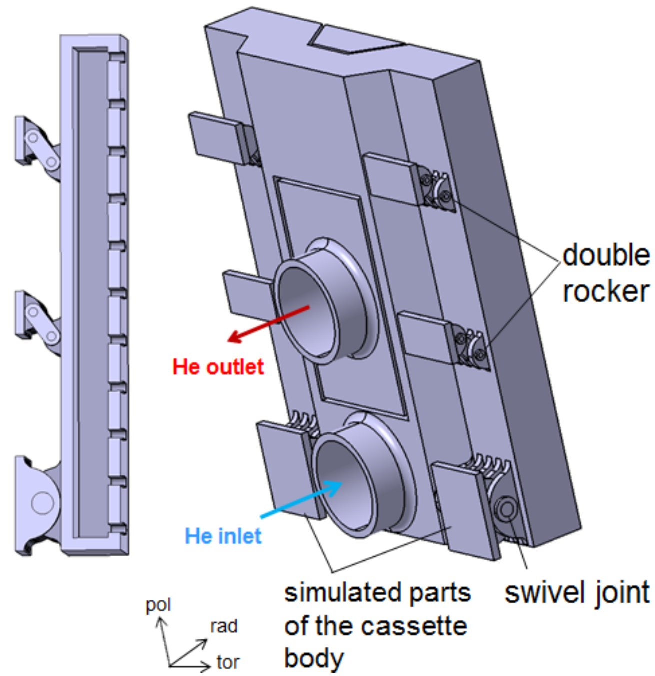
[P. Norajitra et al., Final Report WP12–DAS02–T05-D1, EFDA_D_2LDRJW, v.1.2, 2012]





Target plate ring duct cooling system with 3 header/manifold levels

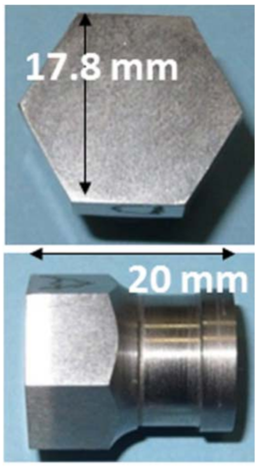
[L. Spatafora]



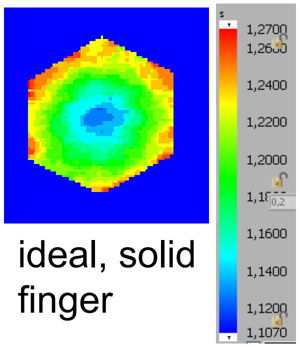
Target plate attachment design

Non-destructive examination of HEMJ finger modules at the SATIR facility, CEA

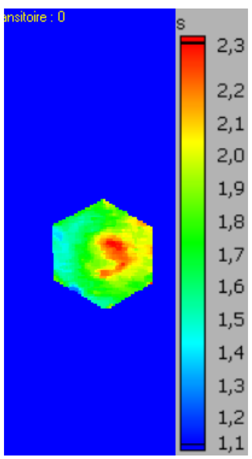
[M. Richou et al., Fus. Eng. Des. (2013), http://dx.doi.org/10.1016/j.fusengdes.2013.05.071]



W 1-finger

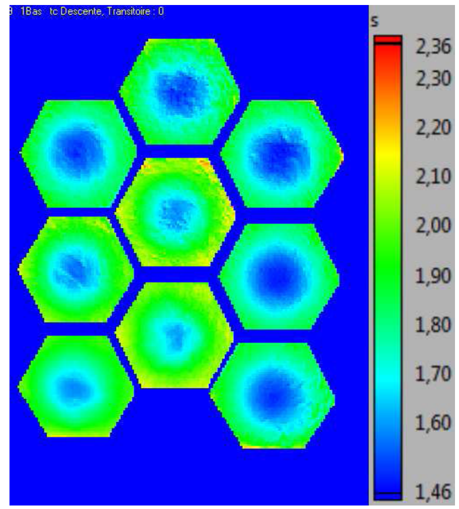


ideal, solid finger

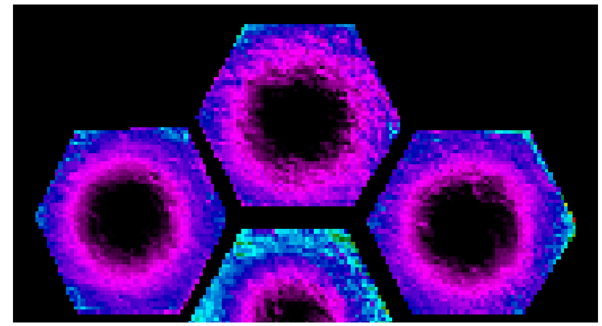


with defective braze joint

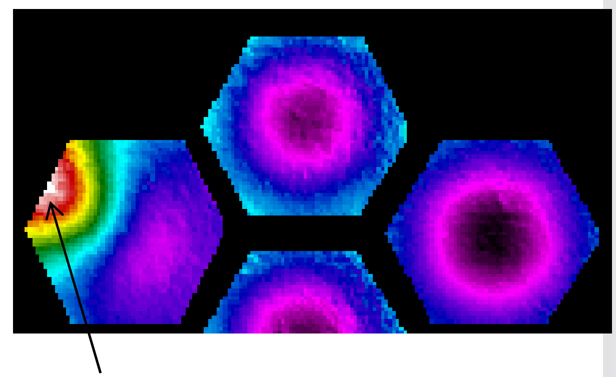
Brass 9-finger



Infrared thermography: Homogeneous thermal response



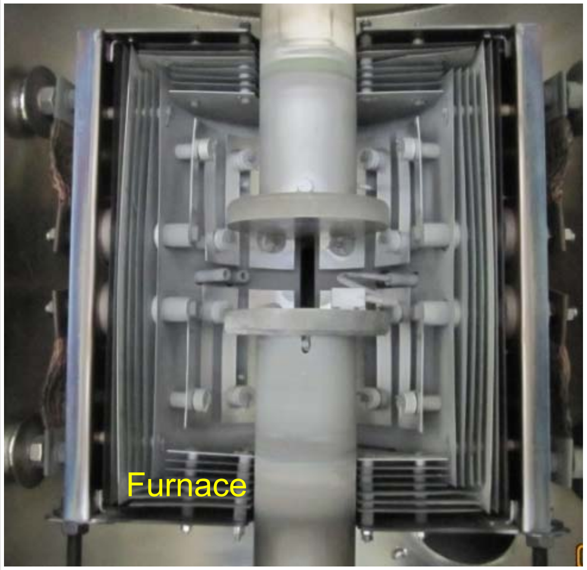
Interface joint w/o defect

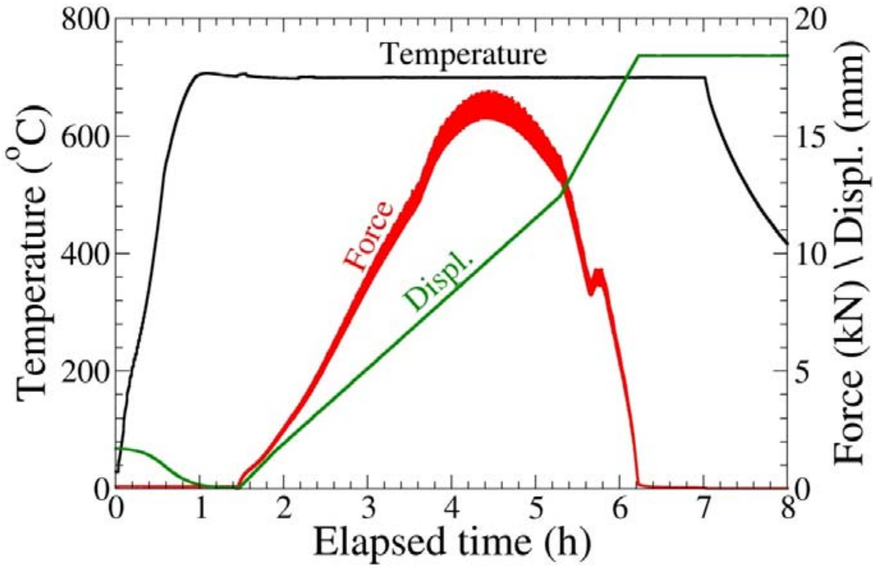


Simulation: 30% artificial defect in interface joint

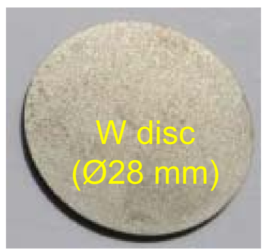
➡ Non-destructive methods for QA are identified and tested.

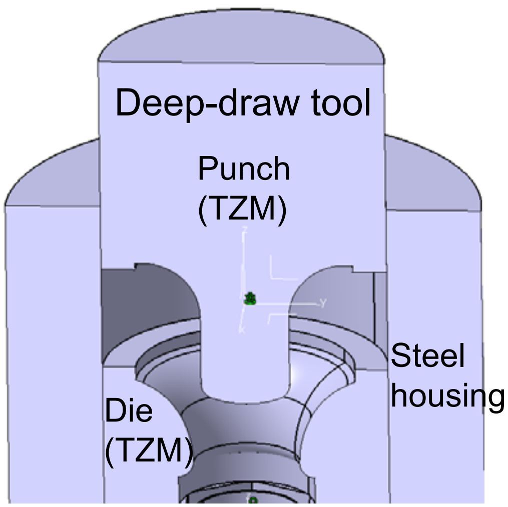
Path-controlled deep-drawing W thimble in vacuum furnace

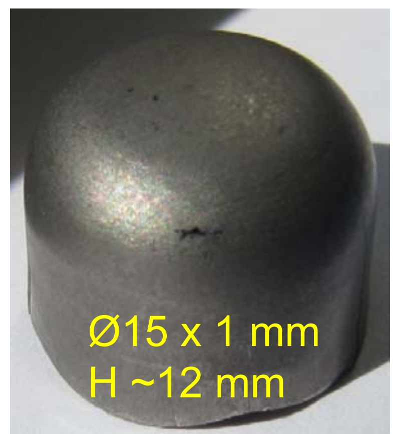




Parameter: T = 700°C, displ. rate = 1 µm/s







Good result

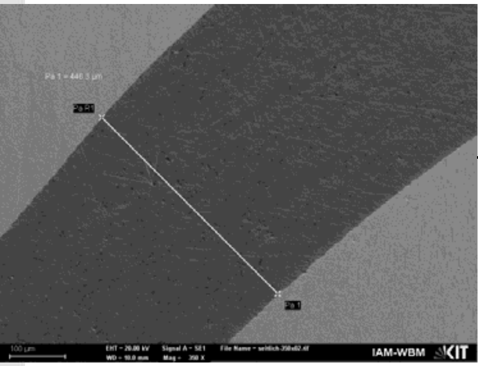
[W. Basuki, L. Spatafora]

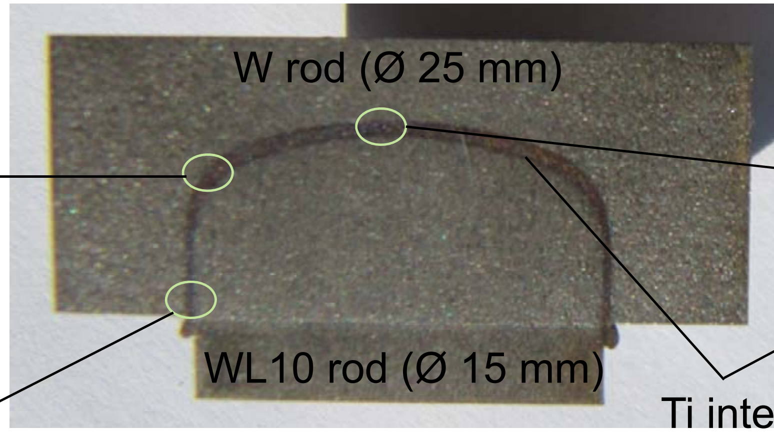
[MAT-HHFM Mon. MTG, Ljubljana (Slovenia), June 2012]

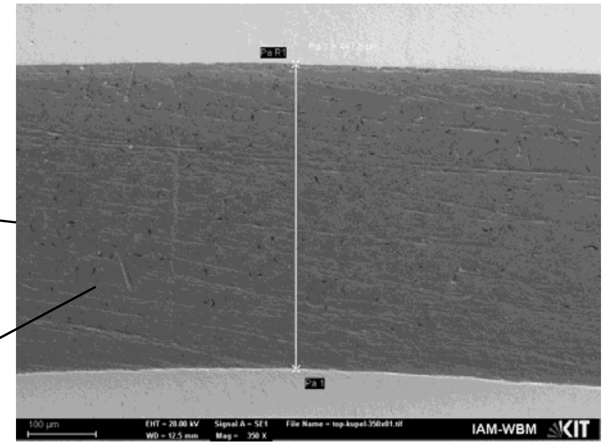
Advanced W-W joining using <u>low-activation</u>Ti interlayer

[P. Norajitra, W. Basuki, L. Spatafora, → ICFRM-16]

New technology: W–Ti–W joining by diffusion bonding





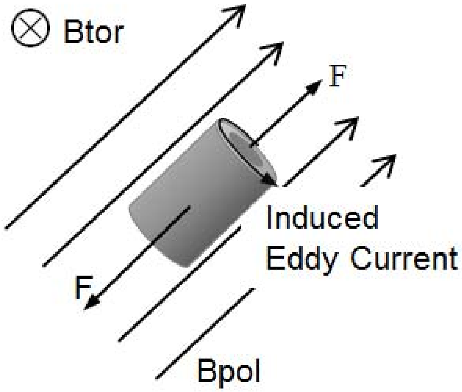


Parameters:
- P ~ 100 MPa
- T ~ 900 °C
- T ~ 1 h

SEM results:
Good diffusion-bonding between Ti and W

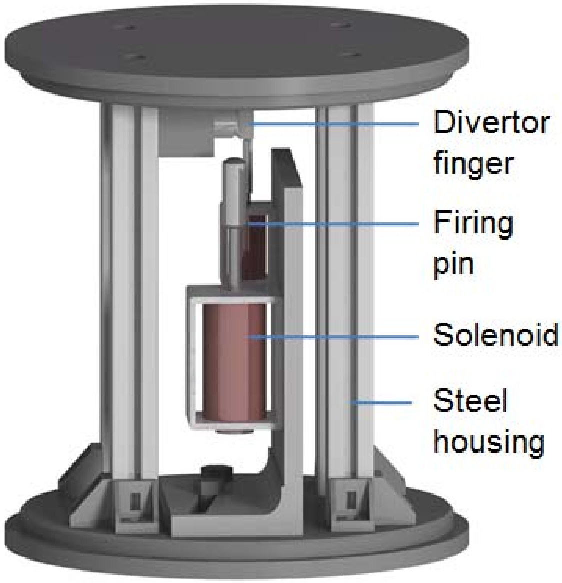
Assessment of induced electromagnetic load on a divertor finger and impact tests

[P. Norajitra et al., Fus. Eng. Des. 87 (2012) 932–934]



Electromagnetic model

[I. Maione]



Experimental setup

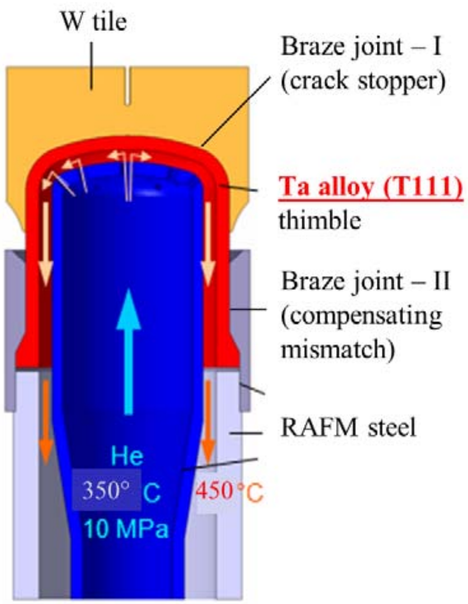
Experiments

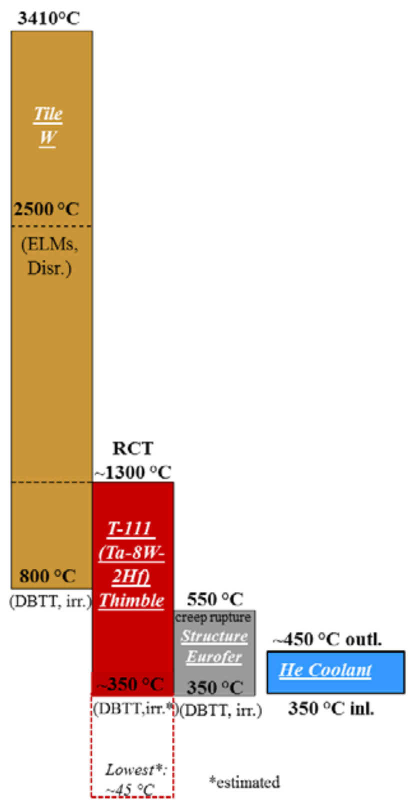
Description	Variable name	Value using Wres	Value using EUROFERres	unit
Plasma magnetic field	|B| Brad Btor Bpol	0.501 -0.411 $2.81 \cdot 10^{-9}$ 0.287	0.501 -0.411 $2.81 \cdot 10^{-9}$ 0.287	T @ (prad,ppol)
Eddy current	I_{Eddy}	20.6	4.96	A
Induced magnetic force	F	1.75	0.42	N
Induced torque	M	0.028	0.0067	N·m

- EM impact load by disruption on the HEMJ cooling finger was estimated to be small due to the small size of finger.
- Simulating tests with 30 times higher impact load on real W finger module showed no damage after 1000 impact strokes.

Study on alternative Low-Temp. Design using Ta Alloy as Thimble Material

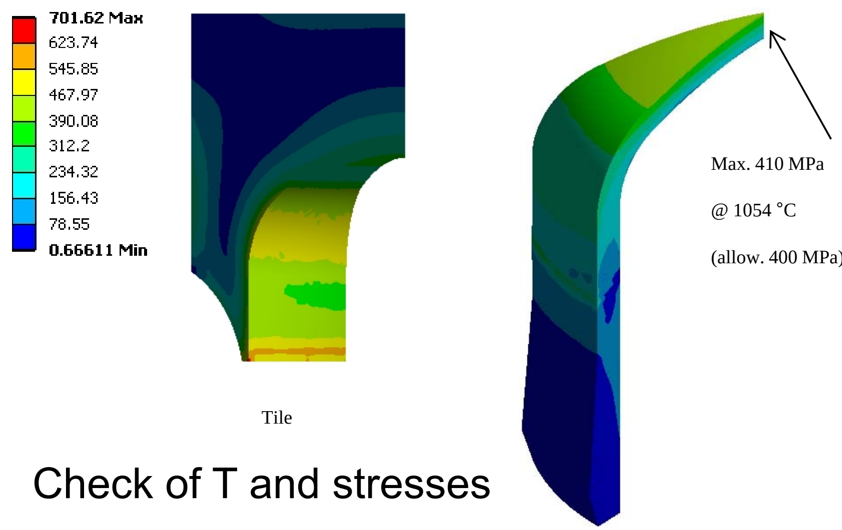
[P. Norajitra et al., proc. SOFE-25, San Francisco, USA, 2013]





Motivation:

- Unknown irradiated data for W materials
- T111(Ta-8%W-2%Hf): extremely low DBTT (-196 °C) and high creep resistant at 980 – 1310 °C,
- → may satisfy the requirements on the ductility of thimble structure.
- Working temp. 350 °C allows for the simplistic use of Eurofer instead of ODS version.



Check of T and stresses

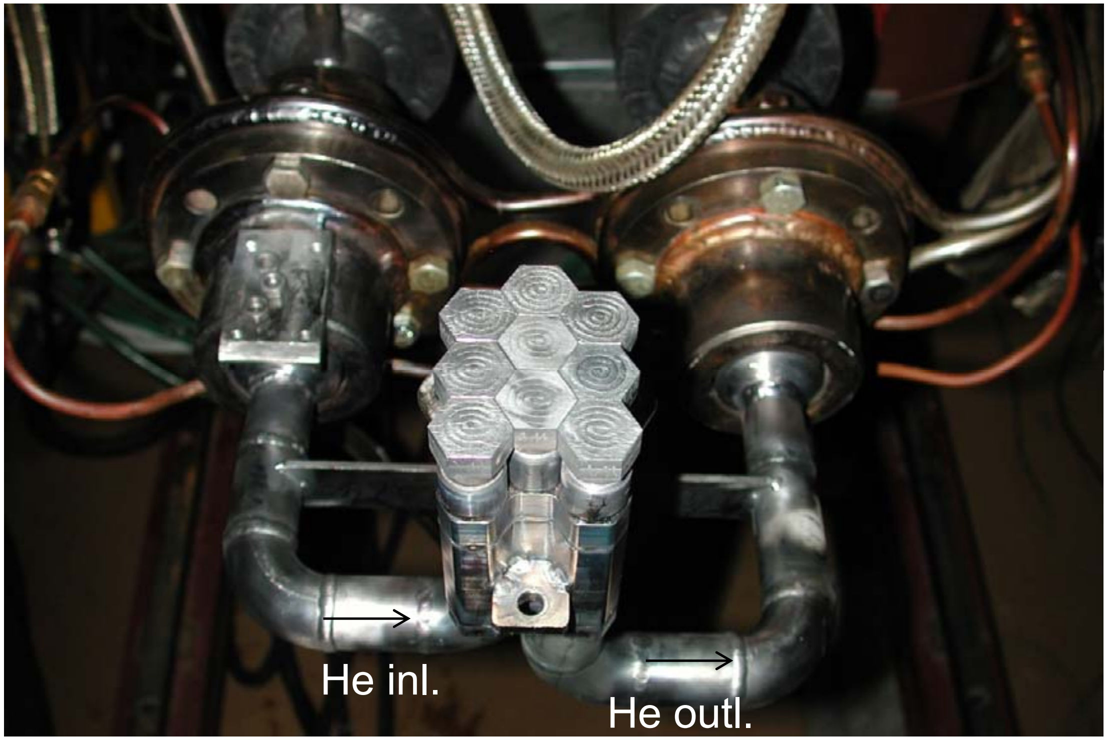
→ design is useful

[W. Basuki, B. Koncar]

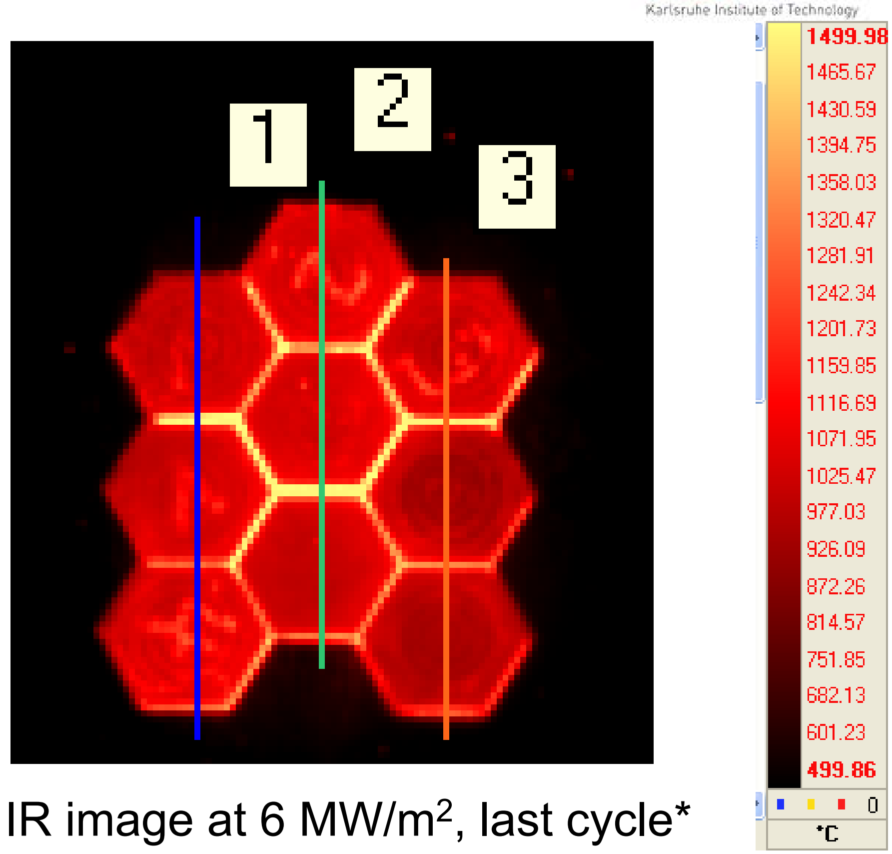
Design:

- T111 as thimble material
- $q = 10\ MW/m^2$
- $p_{He} = 10\ MPa$
- $T_{in/out} = 350/450°C$
- He mfr = 6.8 g/s

1st HHF tests on W 9-finger module at Efremov (Sep. 2013)



9-finger module mounted to the He loop

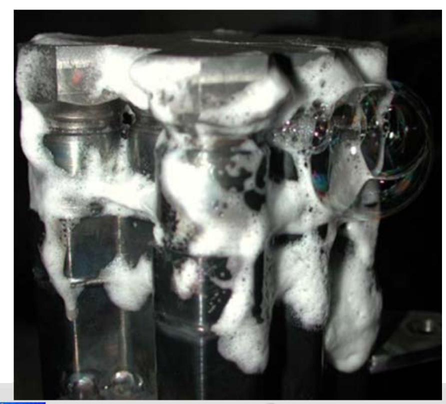


IR image at 6 MW/m², last cycle*

Mock-up has seen:

- 3 MW/m² (75 cycles 15/15 s; 25 cycles 20/20 s) @10 MPa, 26 g/s
- 5 MW/m² (3 cycles, 20/20 s) @10–9.5 MPa (tank-to-tank), 50 g/s
- 6 MW/m² (3 cycles, 20/20 s) @10–9.5 MPa, 50 g/s (*before leak was detected at TP)
- T_{He} in/out = 500/~540 – 550°C

[V. Kuznetsov]



Conclusion and Outlook

- The performance of HEMJ to carry heat load ≥ 10 MW/m² has been confirmed by HHF tests at Efremov.
- Crack-free manufacturing quality of tungsten fingers has been achieved.
- High temperature brazing of divertor parts using Pd based fillers was successfully performed.
- Advanced joining technology of W-W parts with diffusion bonding using LA Ti interlayer is promising.
- Divertor integration study has confirmed the feasibility of assembling target plate from small modules.
- Satir NDT method (CEA) for HEMJ finger modules has been developed.
- Study on tungsten deep drawing of thimble shows useful results.
- Study on disuption EM load shows small impact on the HEMJ fingers due to their small sizes (also benefit for stress reduction)
- Study on alternative design shows that Ta alloy could be used as thimble material at low coolant temperature of 350°C, enabling the use of basic Eurofer without ODS.

- **Future plan:** HHF experiments on big divertor modules in HELOKA.
- The dilemma in divertor design is the unknown neutron irradiation data for W properties, especially DBTT.
- --> Needs for irradiation experiments of W structure materials in typical neutron environments.

List of HCD related publications

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Thank you for your attention!