Development and testing results of water-cooled divertor target concepts for EU DEMO reactor

Third Technical Meeting on Divertor Concepts

IAEA Headquarters, Vienna, 4-7 November 2019

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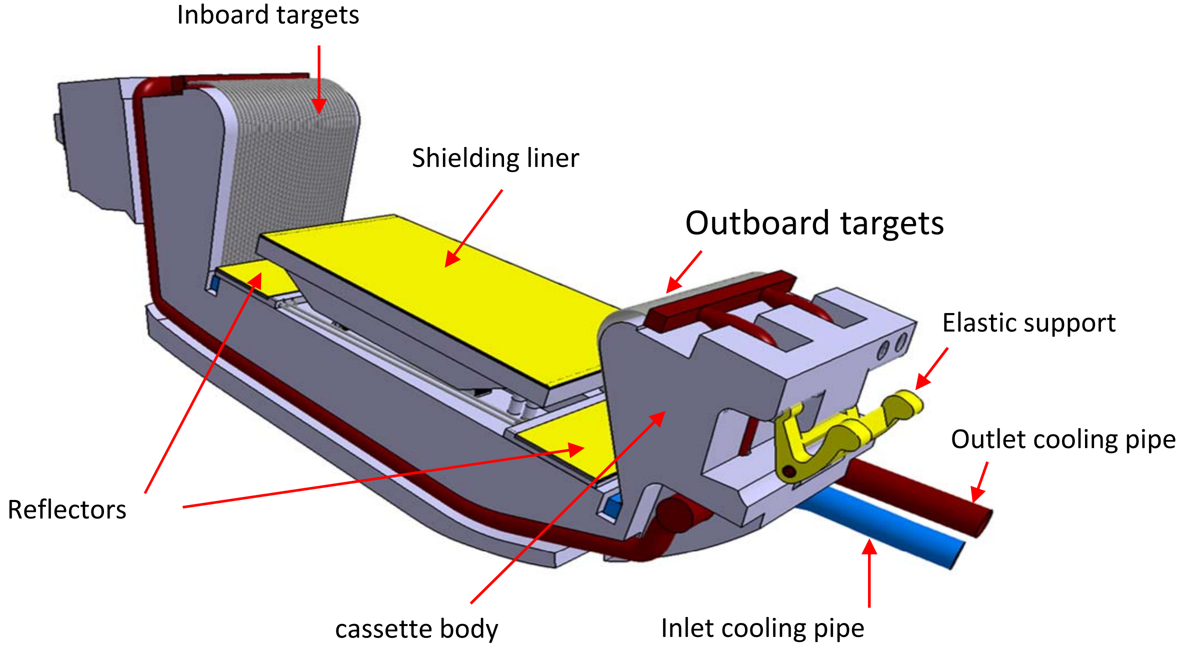
EU DEMO divertor: structure



- cassette body: Eurofer steel
- liner, reflectors: Eurofer steel (coated with tungsten)
- vertical targets: tungsten monoblock armor + copper alloy (or composite) pipe

❖ Power to exhaust: 251 MW in total

- Targets plates 138 MW
- cassette body: 113 MW

❖ Peak heat flux on targets (122 MW)

- stationary: 10 MW/m²
- transient: 20 (10s) - 50 (< 0.5s) MW/m²

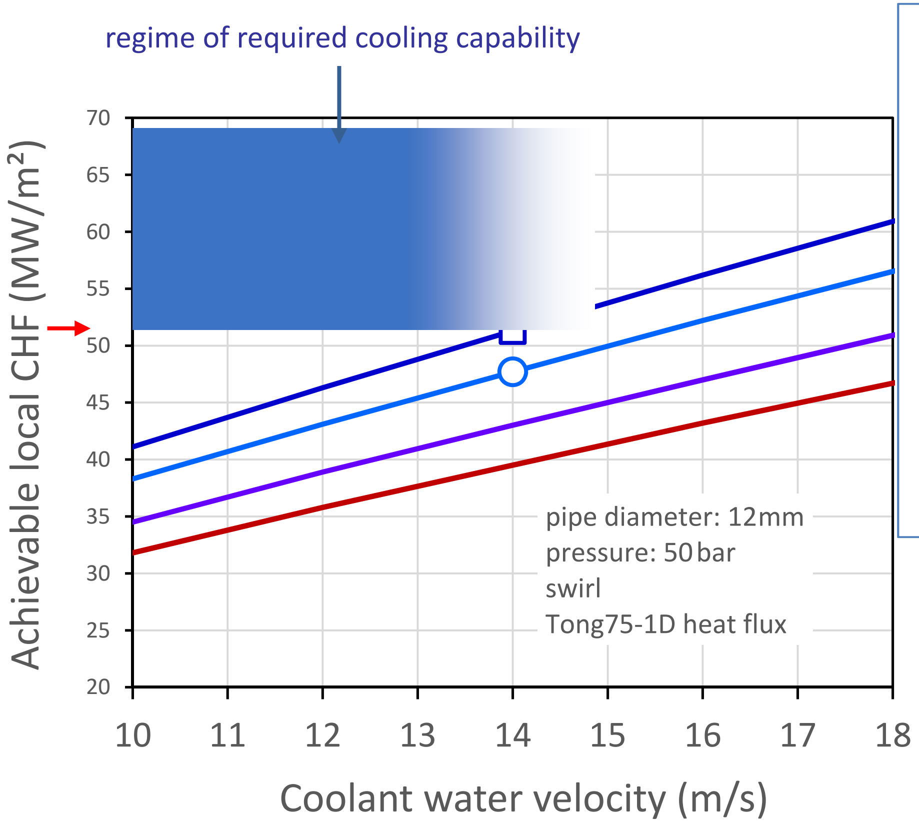
Design criteria:

- 10 MW/m², nominal steady-state operation,
- 20 MW/m², during slow transients up to 10 s
- 150 ° C water inlet, 50 bar, 16 m/s
- Applicable to a mass production of 625.000 W monoblocks arranged in ~ 70 cm long target units

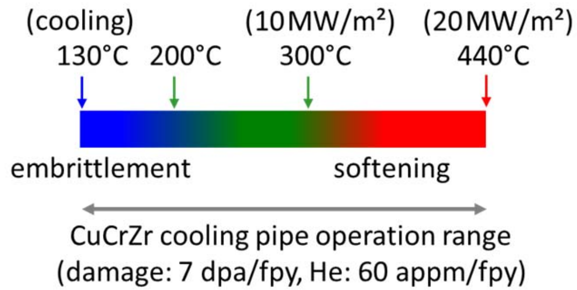
Expected neutron dose accumulated during 2 full power operation years:

- **4 dpa in W, 13 dpa in CuCrZr cooling tubes**

Heat flux loads and coolant parameters



- ✓ Heat flux load (at the strike point)
  - surface heat flux (stationary): ~10 MW/m²
  - surface heat flux (‘slow’ transient): ~20 MW/m²
  - heat flux peaking factor: ~1.6
  - margin to the CHF: ~1.4
  - local critical heat flux: ~45 MW
- ✓ Cooling condition (at strike point)
  - Local bulk temperature: ≤140 ° C
  - Coolant velocity: 14 m/s
  - Pressure (inlet): 5 MPa



Divertor Project: PPPT-WPDIV

WBS 1 - Cassette Development

Design, neutron irradiation calculations, hydraulic, RH

WBS 2 - Target Development

1) explore the design feasibility of various Vertical Target concepts
2) optimize the target design and technology
3) evaluate the individual target concepts by means of HHF test on real mock-ups,
4) select the best candidates with regard to:
   - the power exhaust removal capability
   - structural reliability
   - manufacturing technology suitable for industrial scale
5) qualify medium size prototypes under HHF fatigue and transient thermal loads.

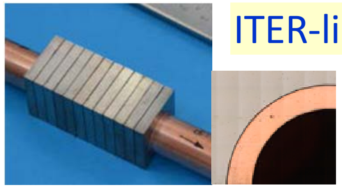
Target Concept technology qualification

1st phase R&D activities | **2nd phase R&D activities**

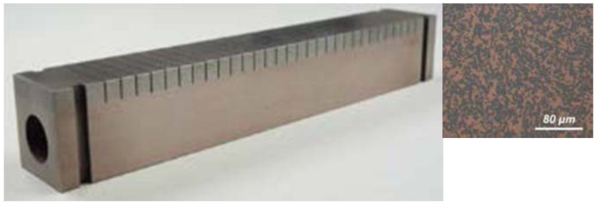
1. FEA for thermo-mechanical prediction and geometrical optimization
2. Mock-up fabrication
3. Non-destructive test (Ultrasonic ENEA-ULTRAS and SATIR-CEA)
4. Thermal fatigue tests in GLADIS cool (20° C) and hot (130° C) coolant temperature conditions (HHFT)
5. Post HHFT Non-destructive test (ENEA-ULTRAS and SATIR-CEA)
6. Post mortem destructive analysis (W, interlayer, pipe)

Technology R&D lines/concepts

ITER-like



- ✓ Fabrication technology fully established.
- ✓ Mock-up production completed.
- ✓ High-heat-flux testing performed



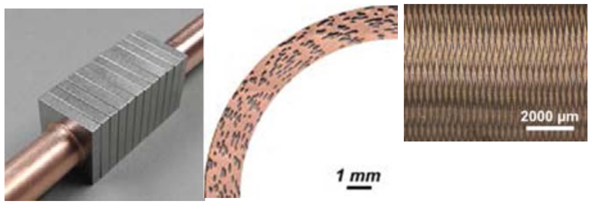
Composite block (W_p/Cu)

❖ Baseline:
- tungsten mono-block type

❖ Extra concepts:
- tungsten flat-tile type
- Helium jet injection (dual pipes)

Thermal break

Composite pipe (W_f/Cu)



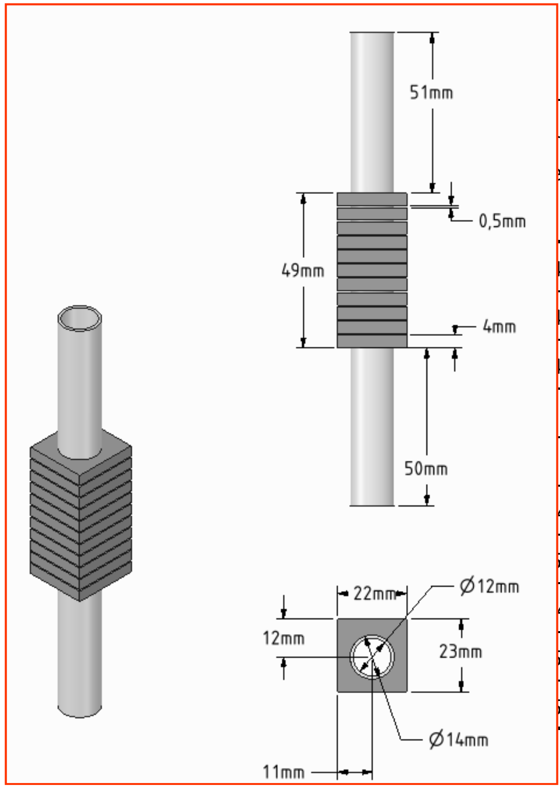
He jet injection (helium-cooled)

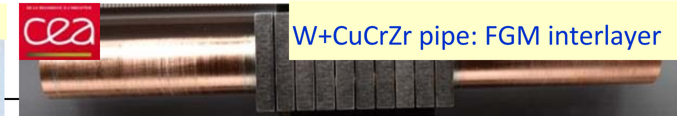
[23] New developments in the design of a helium-cooled divertor for the Europen DEMO

FGM- Functional Graded Material

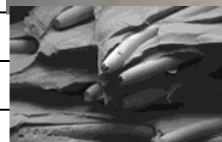
Thin graded interlayer (W/Cu)

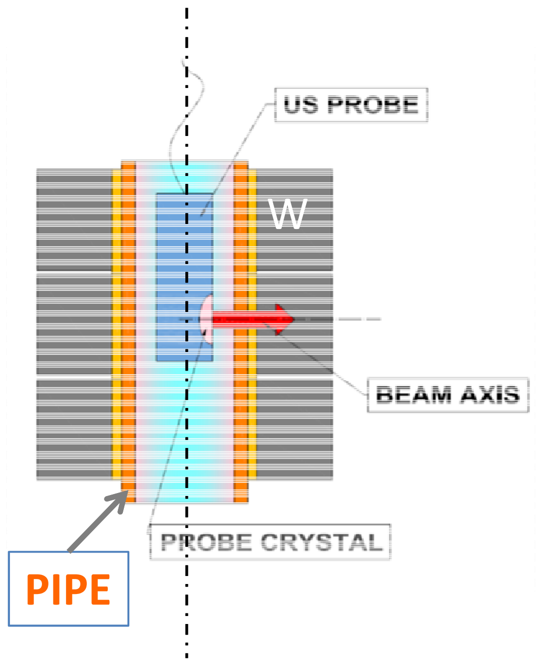
Fabrication plan 1st phase





...mo ...eng ...WL							...cks ...lat	block thickness (t)	Block width (w)	block height (h)	Armour thickness (a)	Shoulder thickness (b)	Bottom thickness (c)	Interlayer thickness (e)
...2,2							0	4	22	24	5	3	3	2
...2,2							0	4	22	24	5	3	3	2
...2,2							0							
30	no	15	12	-	W	Flat								
50	*?*	*14*	*16*	*?*	*W*	*block, 4*								
44,5														
...0,75											5	3	3	0,5
49,5											7	6	7	0,5
...0,75											5	3	3	0,5
...0,75							...2	4	22	26,3	5	3	3	0,5



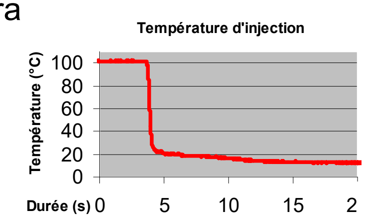


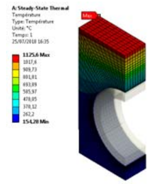
ULTRASONIC TECHNIQUE PRINCIPLE

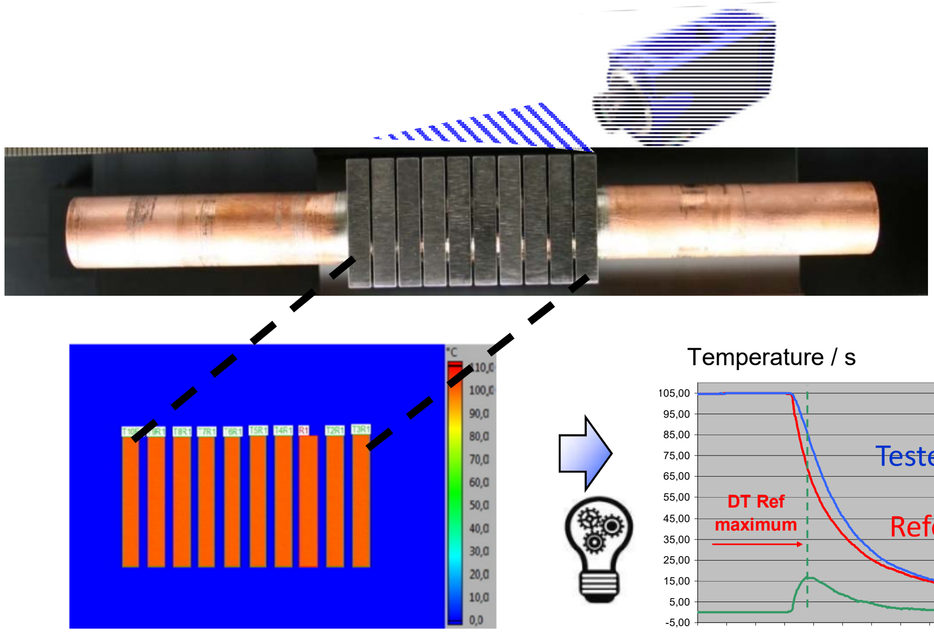
- **ultrasonic** pulse-echo technique: the probe is placed in the bore of the CuCrZr pipe with water fill
- echo signal is acquired for specific radial penetration by axial scanning
- joined interfaces map created (unwrapped cylindrical map: c-scan)
- calibration by reference component with known defect size

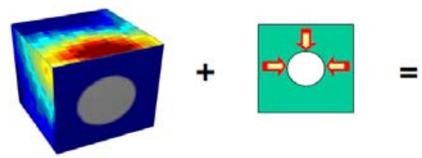
SATIR: fast thermal solicitation of PFC
to evaluate global thermal quality and thermal imperfection size

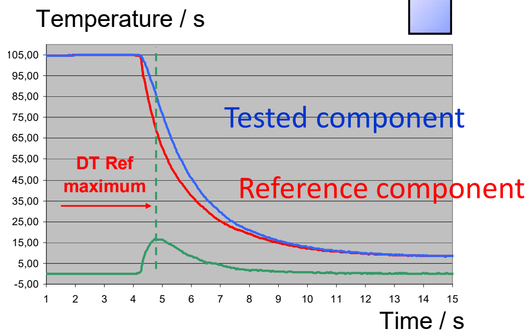
- Fast water cooling in pipe channel, abrupt variation of temperature (100° C to 10° C)
- Measurement of surface temperature by means of IR thermocamera
- Data treatment and thermal surface map analysis
- Identification, localization and sizing of thermal imperfection











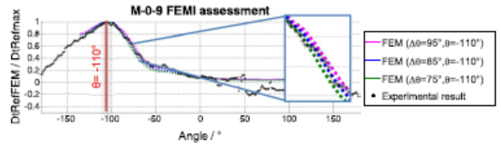


Figure 2. Normalized DtRef profiles obtained with finite element method (FEM) and with experimental data for monoblocks M0-1

F. Gallay et. al, Phys Scripta, 2017

HHF test strategy for concept assessment

H. Greuner, 17th, PFMC, 20.-24. May 2019, Eindhoven

Experimental validation of thermo-mechanical behaviour under DEMO relevant cyclic heat loads and cooling conditions

Aim: Identification of the most promising concept(s)

- cyclic heat loading in GLADIS (hydrogen neutral beam facility) to investigate fatigue and accumulation of plastic strain in materials

Uniform test procedure and typically 3 mock-ups for concept:

1.Step (each mock- up): cold-water, low pressure (20 °C inlet, 10 bar, 12 m/s) as "initial assessment"

1. **screening up to 25 MW/m²,**
2. **100 cycles 10 s at 10 MW/m² fatigue as quality assessment**

2. Step: hot-water, higher pressure (130 °C inlet, 40 bar, 16 m/s)

1. **screening up to 20 MW/m²,**
2. **cycling up to 500 (1000) cycl. at 20 MW/m², 10 s (one mock-up of each concept)**

3. Step: **cold-water,** high velocity (20 °C inlet, 16 m/s) overload screening and fatigue tests

1. **screening up to 32 MW/m², followed by 100 x 25 MW/m²**

Rationale for step 3: to test thermal limits close to the collapse of heat transfer (CHF).
Considering a safety margin of **1.4** , the heat flux on the components should be **limited to 22 MW/m² during hot water cooling**.
➔ Therefore we performed the tests at **cold water** and coolant high velocity for a safe heat transfer up to 32 MW/m².

Summary table of 1st phase mock-ups

<table>
<tr><th>RU</th><th>Design concept</th><th>CuCrZr tube condition as received</th><th>CuCrZr tube supplier</th><th>W grade</th><th>Interlayer</th><th>Tube Joining techn.</th><th>Brazing alloy (if brazed)</th></tr>
<tr><td>CEA</td><td>FGM</td><td>SAA</td><td>Le Bronze</td><td>ALMT Japan</td><td>Graded W</td><td>HIP/brazed</td><td></td></tr>
<tr><td>CCFE</td><td>TBCI-w27-split</td><td rowspan="2">SAA</td><td rowspan="2">Zollern</td><td rowspan="2">ALMT Japan</td><td>OFE Cu, Machined</td><td rowspan="2">brazing</td><td rowspan="2">CuAu</td></tr>
<tr><td>CCFE</td><td>TBCI-w22-split</td><td>OFE Cu, Machined</td></tr>
<tr><td>KIT</td><td>Flat W laminate (DB)</td><td></td><td></td><td>ALMT Japan</td><td rowspan="6">OFE Cu</td><td>D. bonding</td><td></td></tr>
<tr><td rowspan="2">IPP</td><td>W-Composite (particulate/flat)</td><td rowspan="5">SAAWcD</td><td rowspan="5">KME-DE</td><td>ALMT Japan</td><td>brazing</td><td>CuAu</td></tr>
<tr><td>W-Composite (W-fibre, monoblock)</td><td>ALMT Japan</td><td>brazing</td><td>CuAu</td></tr>
<tr><td rowspan="3">ENEA</td><td>DEMO (4 mm W)</td><td>ALTM+AT&M</td><td rowspan="3">HRP</td><td rowspan="3"></td></tr>
<tr><td>ITER-Optimized (12 mm W)</td><td>ALTM+AT&M</td></tr>
<tr><td>ITER-WPMAT x 1</td><td>KIT (PIM)</td></tr>
</table>

Grade CRM16 TER = Tempered Stretched Annealed
ELBRODUR-HF

Cold water HHF results 1st phase mockups

		NDT		COLD WATER - 20°C, 1 MPa, 12 m/s				
Design concept	**Comp.**	**Ultrasonic**	**SATIR**	**A -screening cold water 20 MW/m²**	**B, 100 x 10 MW/m²**	**C, 100 x 15 MW/m²**	**D, overload 25 MW/m² screening**	**E, overload +100 x 20**
TBCI-w27-split	**#001**	OK	OK	OK	OK		OK	
	#002	OK	OK	OK	OK			
	#003	OK	OK	OK		OK		
TBCI-w22-split	**#004**	OK	OK	OK		OK		
	#005	OK	OK	OK	OK			
	#006	OK	OK	OK	OK			
Flat tile-KIT	**no. ?**			failed				
Flat tile-KIT HIP	**H20 V 21**			failed				
Flat tile-KIT HIP	**H20 V 31**			only 17MW/m²		failed, #76		
FGM	**#3**	OK	OK	OK	OK		OK	OK
	#4	OK	OK	OK	OK		OK	
	#5	OK	OK	OK		OK		
	#6	**1**	**1**	OK	OK			
	#1	OK	OK	OK		OK	OK	
	#2	two defective outer tiles		-	-	-		
DEMO opt	***#005***	OK	OK	OK	OK			
	#007	***12***	***12***	OK	OK			
	#008	***1,11,12***	***1,11,12***	OK				
ITER-Optimized	***#009***	OK	OK	OK		OK		
	#011	OK	OK	OK	OK			
	#012	OK	OK	OK	OK			
W-Composite	***#1***			OK				failed #362
	#2			OK				OK
	#3			*22 MW/m², failed*				
Wfibre CuCrZr tube				OK				
WfCu Monoblock	***#1***	OK		OK	OK			

Hot water HHF results 1st phase mockups

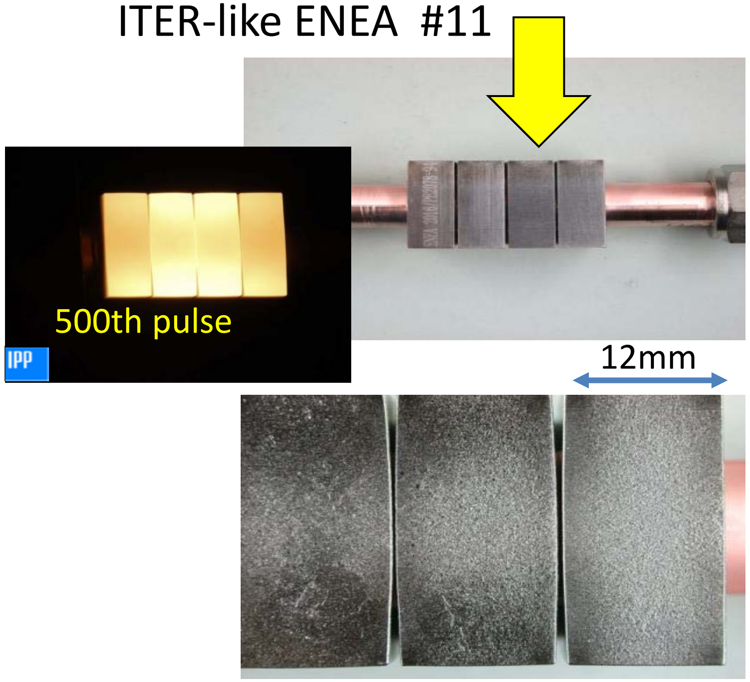
		NDT		HOT WATER 130°C, 4 MPa, 16 m/s					
Design concept	Comp.	Ultrasonic	SATIR	Screening 20 MW/m²	100 cycl 10 MW/m²	100 cycl 15 MW/m²	100 cycl 20 MW/m²	300 cycl 20 MW/m²	Result hot water tests
TBCI-w27-split	#001	OK	OK	OK			OK	STOP	degrad. of upper blocks, stop after cycl.150 1)
	#002	OK	OK						mup not selected for hot water tests
	#003	OK	OK	OK	OK	OK		PASSED	o.k., strong surface modification visible
TBCI-w22-split	#004	OK	OK						mup not selected for hot water tests
	#005	OK	OK	OK			PASSED		o.k., Swagelok damaged
	#006	OK	OK	OK			OK	PASSED	o.k. increase of Tsurf lam 2-5 lower central part, only minor surf. modification visible 2)
Flat tile-KIT	no. ?								based on cold water results,mup not tested
Flat tile-KIT HIP	H20 V 21								based on cold water results,mup not tested
Flat tile-KIT HIP	H20 V 31								based on cold water results,mup not tested
FGM	#3	OK	OK						mup not selected for hot water tests
	#4	OK	OK	OK			OK	PASSED	o.k., continous increase of Tsurf centre blocks 5-7 during cycling (IR ananlysis) 3)
	#5	OK	OK	OK	OK	OK	PASSED		100 x 10MW/m², 100x15MW/m², o.k
	#6	**1**	**1**			-			based on cold water results,mup not tested
	#1	OK	OK						
	#2	two defective outer tiles							no GLADIS tests
DEMO opt	*#005*	OK	OK	OK			OK	PASSED	o.k. no visible degradation
	#007	***12***	***12***						based on cold water results,mup not tested
	#008	***1,11,12***	***1,11,12***						based on cold water results,mup not tested
ITER-Optimized	*#009*	OK	OK						
	#011	OK	OK	OK			OK	PASSED	o.k., strong surface modification block swelling visible after ~200 cycl.
	#012	OK	OK						
W-Composite	*#1*								Mup not suitable for hot water cooling
	#2					-			Mup not suitable for hot water cooling
	#3								Mup not suitable for hot water cooling
Wfibre CuCrZr tube						-			only tube, not tested
WfCu Monoblock	*#1*	OK		OK			OK	PASSED	o.k. no visible degradation

W-surface after HHF testing

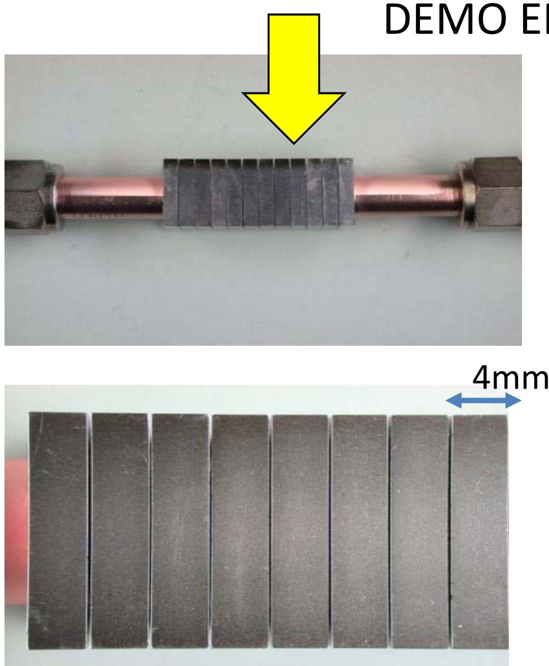
1st phase - HOT-WATER, 500 cycles @ 20 MW/m²

W-armor: 5mm

ITER-like ENEA #11



DEMO ENEA #5



1st phase - Post-mortem examinations plan

12.10.2018

39 blocks of 11 mock-ups

Selection of **damaged and undamaged blocks** after HHF tests

	Mock-up	Maximum heat flux	Cut	Blocks	Cut	Analysed	Reported
Iter-Like	CCFE#3	300x20 MW/m2 **hot water**	Axial & transversal IPP	CCFE#3-2	X		
				CCFE#3-7	X		
	CCFE#5	100x20 MW/m2 **hot water**	Transversal CEA	*CCFE#5-5*	X	X	X
	CCFE#6	500x20 MW/m2 **hot water**	Axial & transversal IPP	CCFE#6-4	X		
				CCFE#6-8	X		
				CCFE#6-9	X		
				CCFE#6-10	X		
	ENEA#5 (CASTING)	500x20 MW/m2 **hot water**	Axial cutting in IPP then Transversal cut in IPP/CEA	*ENEA#5-1 and #5-11*	X	X	X
				ENEA#5-12	X		
	ENEA#7 (HIP)	100x10 MW/m2 cold water	Transversal CEA	*ENEA#7-8*	X	X	X
	ENEA#8 (CASTING)	Scr. at 20 MW/m2 cold water	Transversal CEA	*ENEA#8-2*	X	X	X
				ENEA#8-8	X	X	X
	ENEA#11 (HIPING)	300x20 MW/m2 **hot water**	Axial cutting in IPP then Transversal cut in IPP/CEA	*ENEA#11-1*	X		
				ENEA#11-2	X		
				ENEA#11-3	X		
				ENEA#11-4	X		
FGM	CEA#2	1000x20 MW/m2	Transversal JULICH	CEA #2-4	X	X	X
		500x20 MW/m2		CEA #2-7	X	X	X
		Unloaded block		CEA #2-9	X	X	X
	CEA#4	500x20 MW/m2 **hot water**	Axial cutting in CEA then Transversal cut and analysis in IPP/CEA	CEA#4-2	**Sent to IPP 01.08**	**Sent to IPP 01.08**	**Sent to IPP 01.08**
				CEA#4-5	**Sent to IPP 01.08**	**Sent to IPP 01.08**	**Sent to IPP 01.08**
				CEA#4-6	X	X	X
				CEA#4-10	X	X	X
	CEA#6	100x20 MW/m2 **Cold water**	Transversal CEA	*CEA #6-10*	X	X	X
WfCu	IPP#1	500x20 MW/m2 **hot water**	Axial & transversal IPP	IPP#1-4→ IPP#1-9	??	??	??

1. Undamaged block taken from mock-up with min of solicitation
2. Undamaged block of a mock-up after hot water HHF tests
3. Mock-up used as a reference for SATIR (DTref~5°C)
4. Mock-up used to understand defect detected with UT
5. Damaged block(s) due to hot water HHF tests

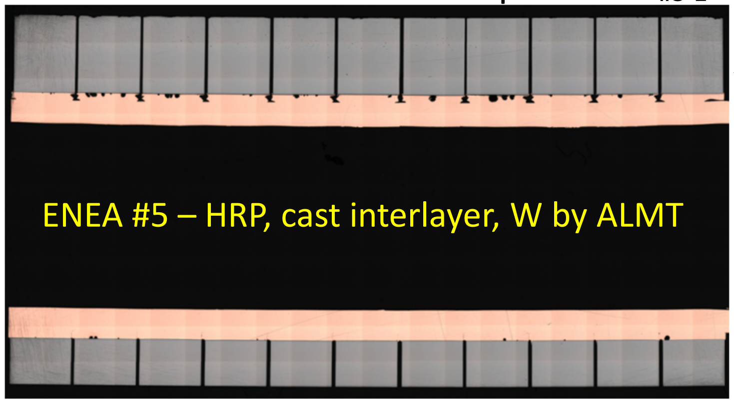
Metallographic examination + NDT and HHF correlations
to define NDT reliability nature o f thermal imperfection

Analyzed mock-ups which sustained
500c@20MW/m² :

CCFE#6 ENEA#5 CEA#4 ~~IPP#1~~

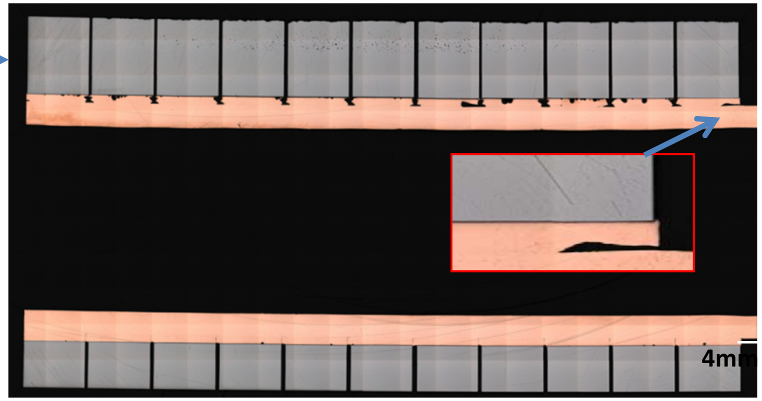
Example of micrographs post HHF testing

#5-11	L-L Left half mock-up	#5-1



HHF side

#5-11	R-R Right half mock-up	#5-1



Conclusion:

➔**No modification and deep cracks in W HHF-surface**

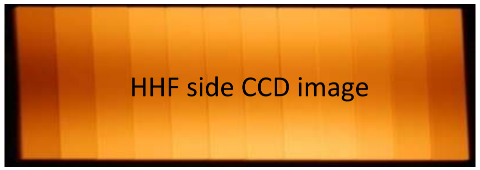
➔**Damages concentrated in the interlayer :**

1) voids in cast joints for 6 of 11 blocks

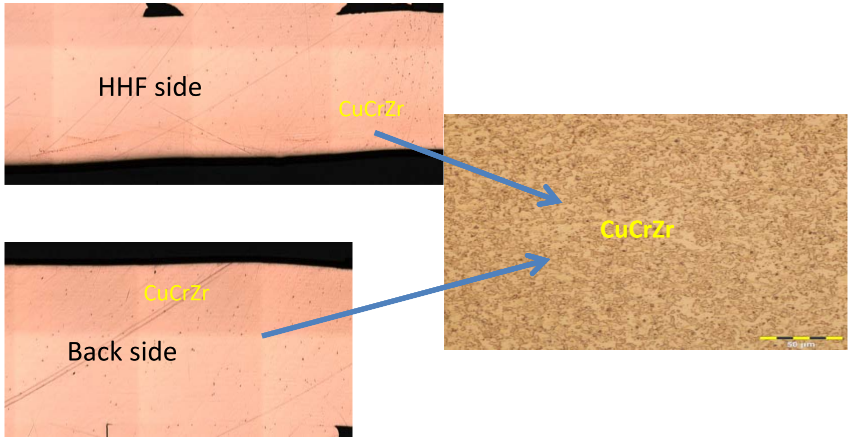
2) increased number of voids due to HHF tests

➔**Good agreement with NDT (ENEA-ULTRAS)**

Remark: results of metallographic analysis after 500c @20MW/m² hot water



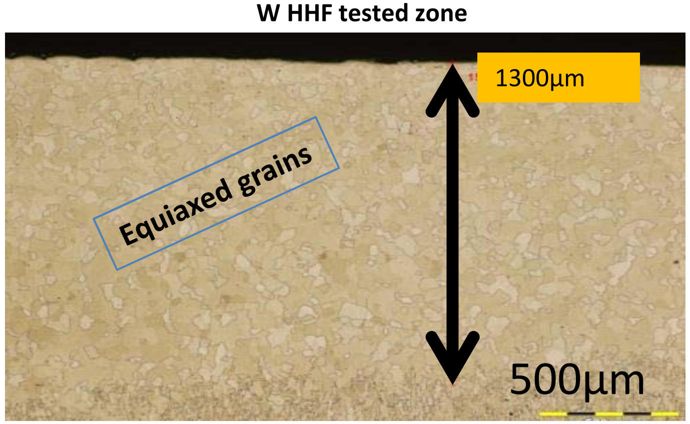
CuCrZr-pipe and W-block micrographs for ENEA#5

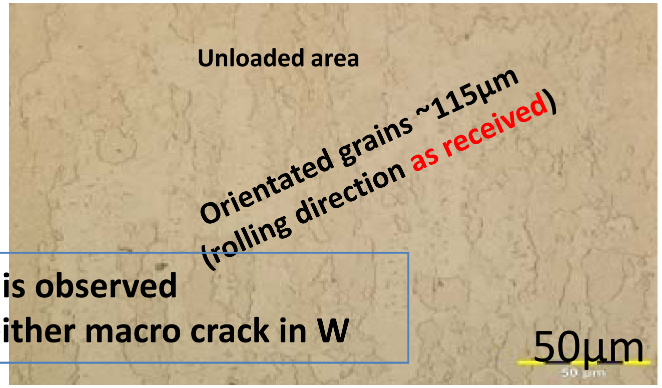


Micro-hardness 116 (HV 0.3)

Conclusion:

- **CuCrZr pipe keeps its fine grains aspect**
- **No softening of CuCrZr**





- **W recrystallization is observed**
- **No major defect neither macro crack in W**

1st phase - Summary and conclusion

Summary

- 1st Phase HHF completed with very good results
- 300 cycles at 20 MW/m² hot-water of all W monoblock concepts successfully performed
  - good agreement between FEM predicted and measured surface temperatures
  - Indication of recrystallization and grain growth of W surface after 500 cycles at 20 MW/m²

Outlook

- NDT performed before and after HHF loading
- Micrographs of selected mock-ups
  - Investigation of recrystallization depth, grain size
  - Investigation of W/Cu interface, plastic deformation, delamination, cracks

Conclusion

- **European labs are able to produce advanced W divertor water-cooled PFCs for DEMO application. These components withstand up to 20 MW/m² cyclic heat load**
- **Important R&D progress in the last years, improvements are still possible**
- **Standard mock-up geometry is required to enable concept comparison**

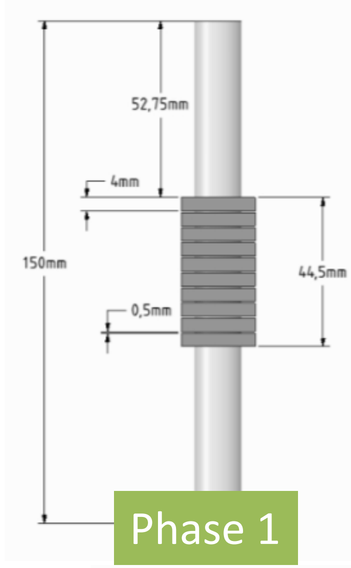
2^{nd} Phase R&D activities

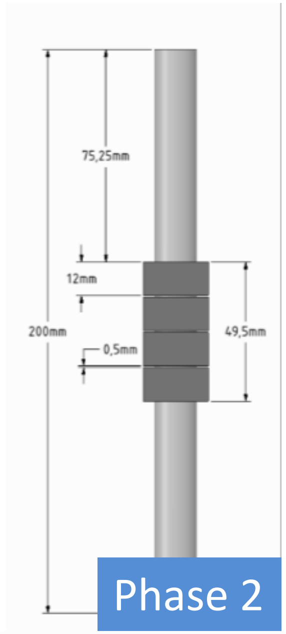
Started begin 2017 and concluded in 2018

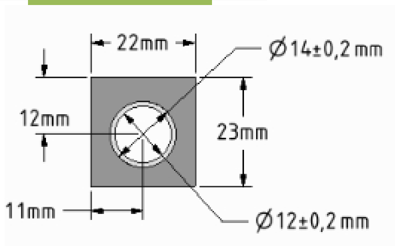
Standardized pipe and W-block dimensions for all design-concepts under development

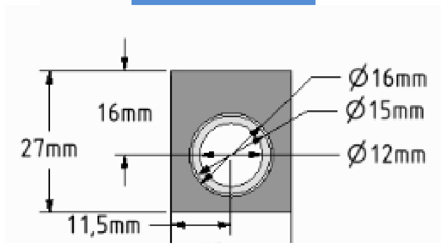
- ✓ Surface W thickness >= 8mm (erosion)
- ✓ Pipe wall thickness 1.5 mm (corrosion)
- ✓ W-block axial dimension 12 mm
- ✓ W-block width ~23 mm
- ✓ 4 W-blocks for mock-up
- ✓ Gap among W-blocks 0,5 mm

Final HHFT @ 20 MW/m²



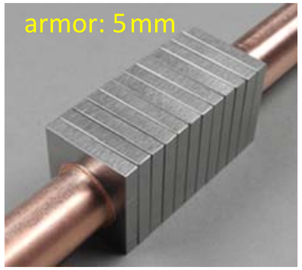






2nd phase R&D activity plan

1st R&D phase



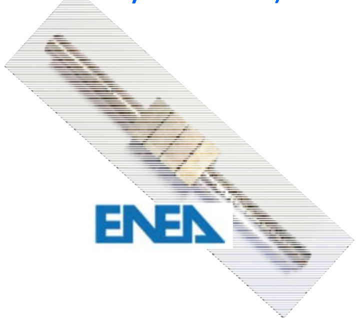
23 × 25 × 4 (mm³)

2nd R&D phase

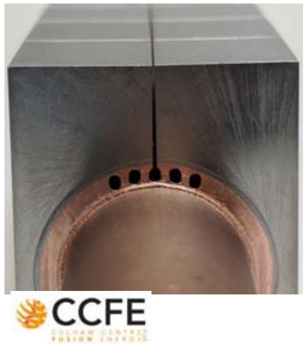
23 × 28 × 12 (mm³)

NDT → HHFT → NDT → Micro

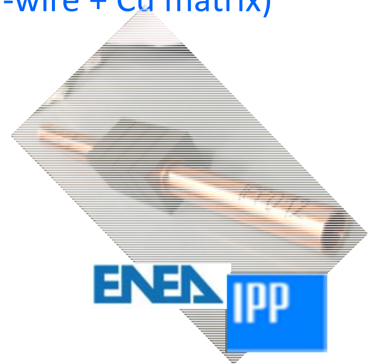
ITER-like
(Cu interlayer: 1mm)



Thermal break
(+vertical notch)



Composite pipe
(W-wire + Cu matrix)



FGM- Graded interlayer
(W/Cu: 20µm, 400µm)

2nd phase mock-up fabrication

Investigation of different interlayer thicknesses

	Design concept	Amount of mock-ups accord. PM	Type block	#	Date	Technique
ENEA	ITER LIKE (AT&M)	3	AT&M 1mm Cu	16	30/11/17	HRP
				23	01/02/18	HRP
				24	19/02/18	HRP
ENEA	ITER LIKE (ALMT)	3	ALTM 1mm Cu	25	11/04/18	HRP
				28	24/04/18	HRP
				29	27/04/18	HRP
ENEA	25 micron Cu coating by CEA	2	AT&M	30	10/07/18	HRP-Failure
				31	01/08/18	HRP-Failure
ENEA	100 micron Cu	2	AT&M	20	17/01/18	HRP
				21	17/01/18	HRP
				22	30/01/18	HRP-Failure
				26	18/04/18	HRP
ENEA	300 micron Cu	2	AT&M	18	20/12/17	HRP
				19	12/01/18	HRP
				27	20/04/18	HRP
ENEA-IPP	W-Fibre Composite	3	AT&M 1mm Cu	5	06/03/18	CuAu
				10	07/03/18	CuAu
				12	10/05/18	CuAu
				14	04/10/18	CuAu
IPP	W-Particulate Cu	3	? flat			
CEA	20 micron Cu-HIP	2	AT&M 2016	7	17/11/17	PVD+HIP
				8	17/11/17	PVD+HIP
CEA	FGM thin	2	AT&M 2016	9	17/11/17	PVD+HIP
				10	17/11/17	PVD+HIP
			AT&M 2018	14	18/10/18	PVD+HIP
				15	18/10/18	PVD+HIP
CEA	FGM 500µm	2	AT&M 2016 and AT&M 2018	11	20/06/18	CS+HIP
				12	20/06/18	CS+HIP
				13	20/06/18	CS+HIP
CCFE	Thermal break	4	4off ALMT	7	04/06/18	CuAu Braze
			4off ALMT	8	25/06/18	CuAu Braze
			4off ALMT	9	25/06/18	CuAu Braze
			4off ALMT	10	25/06/18	CuAu Braze
KIT	Flat/saddle tile	3		1 tile	01/06/18	HIP
				2 tiles	01/06/18	HIP
				4 tiles	01/06/18	HIP
				1 tile	01/06/18	HIP
				2 tiles	01/06/18	HIP
				4 tiles	01/06/18	HIP

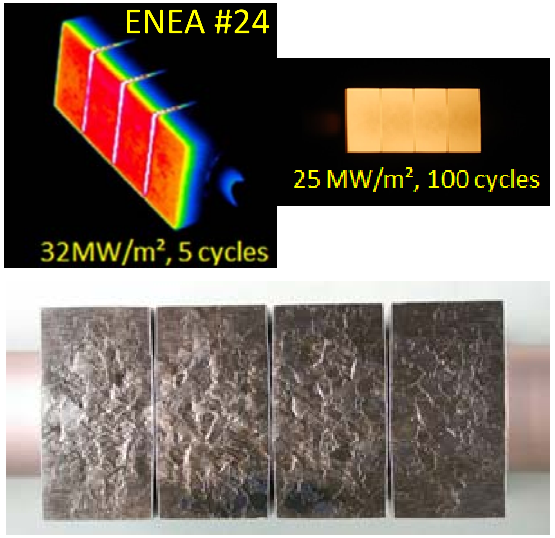
NDT results for 2nd phase mock-ups after fabrication

	Design concept	Type W block	#	UT ENEA Results	SATIR Results	GLADIS Arrived
ENEA	ITER LIKE (AT&M)	AT&M 1mm Cu	16	OK	Thermal imperfection block 1	12/04/18
			23	OK	No thermal imperfection	12/04/18
			24	OK	OK (Ref)	12/04/18
ENEA	ITER LIKE (ALMT)	ALMT 1mm Cu	25	OK	No thermal imperfection	25/06/18
			28	OK	OK (Ref)	25/06/18
			29	OK	No thermal imperfection	25/06/18
ENEA	25 micron Cu coating by CEA	AT&M	30	Failure during manufacturing		
			31			
ENEA	100 micron Cu	AT&M	20	NC to UT		
			21	OK	Thermal imperfection block 4	10/07/18
			22	Failure during HRP	-	-
			26	OK	No thermal imperfection	10/07/18
ENEA	300 micron Cu	AT&M	18	NC		
			19	OK	No thermal imperfection	25/06/18
			27	OK	OK (Ref)	25/06/18
ENEA-IPP	W-Fibre Composite	AT&M 1mm Cu	5	NC		
			10	OK	OK (Ref)	25/06/18
			12	OK	Thermal imperfection all blocks	25/06/18
			14	Small defect at block #2	Thermal imperfection all blocks	22/10/18
IPP	W-Particulate Cu	?				
CEA	20 micron Cu-HIP	AT&M 2016	7	OK	OK (Ref)	04/06/18
			8	NO #4 (inside W)	Thermal imperfection block 4	22/02/18
CEA	FGM thin	AT&M 2016	9	OK	OK (Ref)	22/02/18
			10	NO- All (inside W)	Thermal imperfection all blocks	22/02/18
		AT&M 2018	14	large defect at block 1	Thermal imperfection block 1	14/11/18
			15	0k	OK (Ref)	14/11/18
CEA	FGM 500µm	AT&M 2016 and AT&M 2018	11	N#2 detaced at Cu/W	Thermal imperfection block 2	28/11/18
			12	N#2-small defect	OK (Ref)	28/11/18
			13	N#2 #3 detaced at Cu/W	Thermal imperfection blocks 2 & 3	28/11/18
CCFE	Thermal break	4off ALMT	7	0k	OK (Ref)	26/07/18
		4off ALMT	8	0k	No thermal imperfection	26/07/18
		4off ALMT	9	0k	No thermal imperfection	26/07/18
		4off ALMT	10	0k	No thermal imperfection	26/07/18

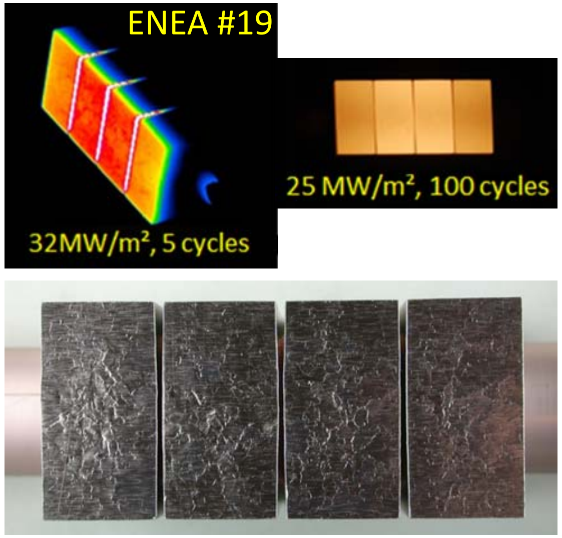
HHF qualification: impact of the Cu interlayer thickness

ITER-like (2nd phase, W: 8mm), W: AT&M -> 32 MW/m² (5 pulses) + 25 MW/m² (100 pulses)

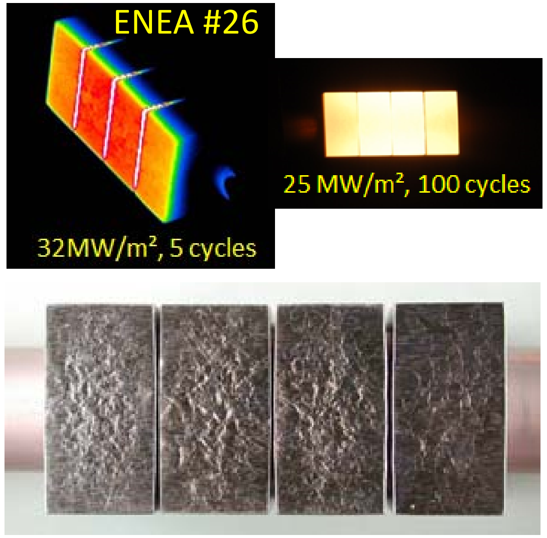
Cu interlayer: 0.1 mm



Cu interlayer: 0.3 mm

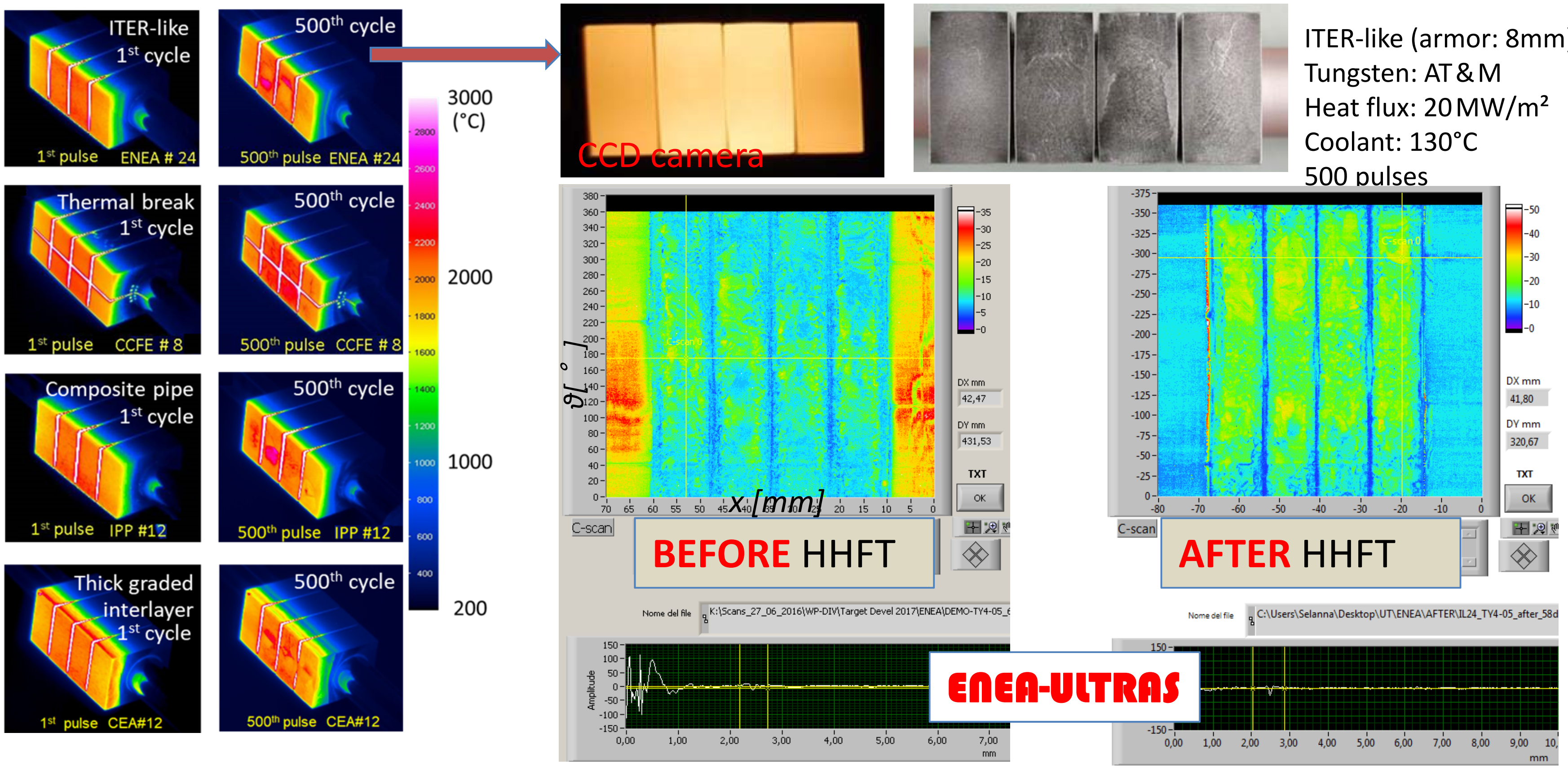


Cu interlayer: 1 mm



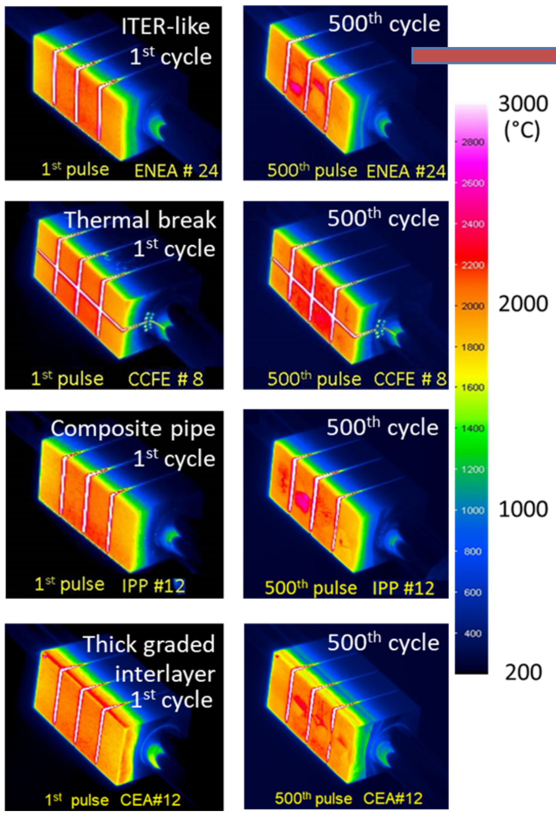
No cracks, intact joint in all cases

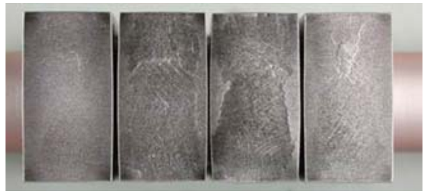
2nd phase mock-ups qualification testing



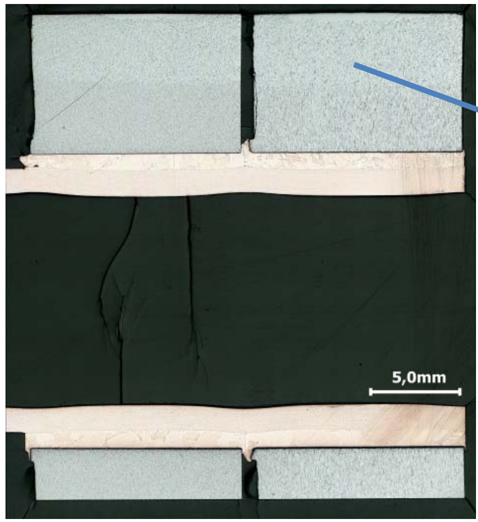
ITER-like (armor: 8mm)
Tungsten: AT & M
Heat flux: 20 MW/m²
Coolant: 130°C
500 pulses

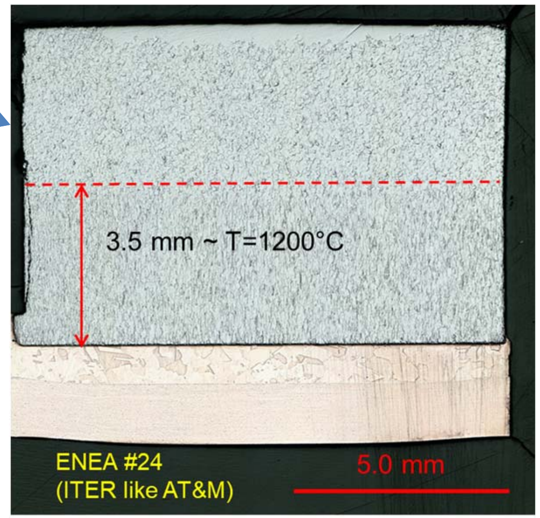
2^{nd} phase mock-ups qualification testing





ITER-like (armor: 8mm)
Tungsten: AT & M
Heat flux: 20 MW/m²
Coolant: 130°C
500 pulses





Summary

- 1^{st} and 2^{nd} R&D phases completed with very good results in agreement with calculations
- R&D activities performed for all concepts to improve reliability and performances
- NDT performed before and after HHF loading of all W monoblock concepts
- HHF testing campaign completed for all concepts

Conclusion

- **Only slight differences in the HHF behavior due to the concept design solution adopted**
- **Important outcome R&D progresses for novel technologies (W/Cu composites for heat-sink and pipes, FGM interlayer, new ENEA-HRP furnace,)**
- **No critical damage features found (no armor cracking, intact joining, no structural failure)**
- **Week points to be further investigated: interlayer thickness (is 1 mm really necessary?), standards and codes for novel materials of pipes (WfCu), neutron damage on materials, possible scale-up of selected concepts, performances under long-pulse thermal loads**

Thank you