

Status of the pre-series activities of the target elements for the W7-X divertor

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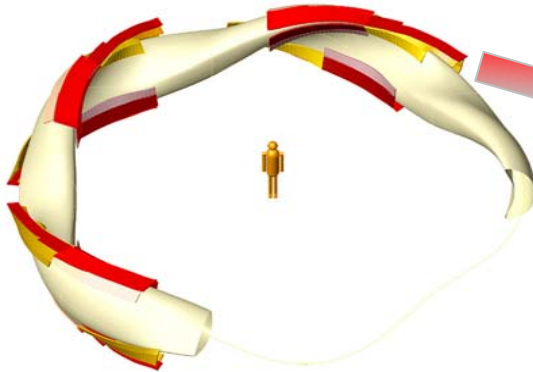


M. Missirlian, J. Schlosser



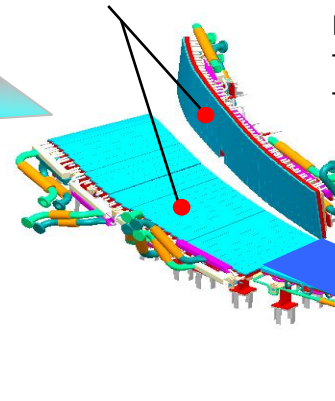
CEA-Cadarache, Euratom Association, 13108 St Paul lez Durance, France

- Design of W7-X target elements
- Fabrication of W7-X target elements
 - ◆ Characteristics of CFC NB31
 - ◆ Manufacturing route
- Pre-series activities
 - ◆ Results of HHF tests performed on GLADIS
 - ◆ Analysis of HHF tests
 - ◆ Heat load limits
 - ◆ Acceptance criteria
- Conclusion and outlook



Target plates arranged as
10 divertor units installed up down
symetrically along the twisted plasma column

10 MW/m²



Divertor total area : 25 m² = 19 m² + 6 m²

Heat loading (MW/m²)

10 **1**

Target modules

100 **20**

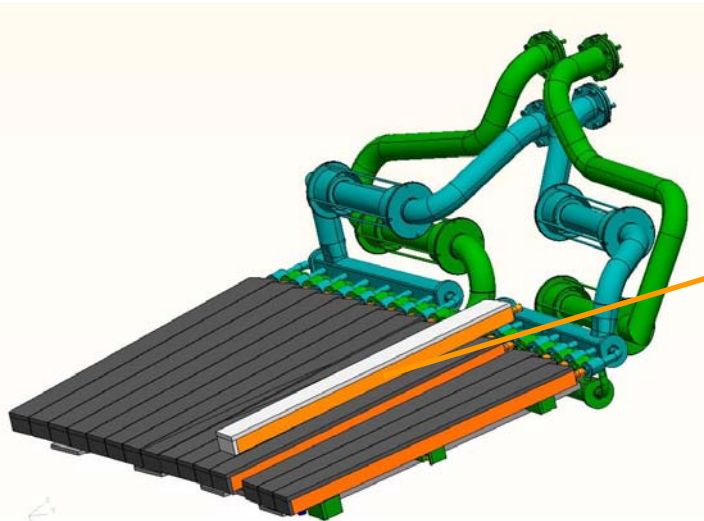
Target elements

890 **250**

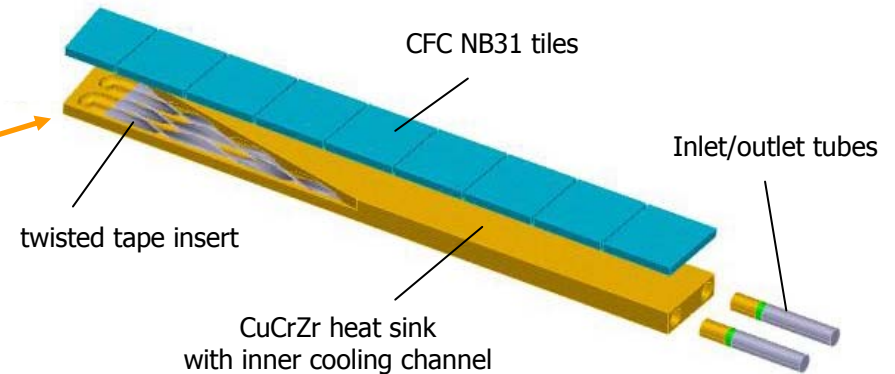
1 MW/m²

10 MW/m²

1 divertor unit: set of 12 target modules

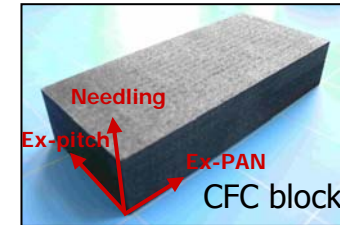


Target modules: sets of target elements



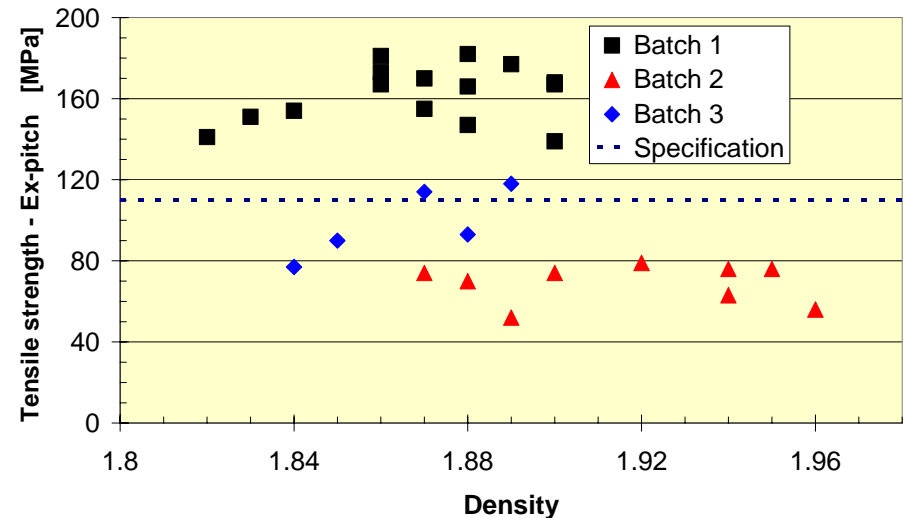
Target element designed for 10 MW/m²

- ♦ 3D-anisotropic material with complex manufacturing process
- ♦ Planned fabrication: end 2001/end 2003 (achieved in 2006)



Thermal conductivity	Temperature [°C]	Minimum [W.m ⁻¹ .K ⁻¹]	Average [W.m ⁻¹ .K ⁻¹]
Ex-pitch ☺	RT	260	300
	800	120	140
Ex-PAN ☺	RT	100	110
	800	48	55
Needling ☺	RT	85	100
	800	40	45

Tensile strength [MPa]	Minimum
Ex-pitch ☹	110
Ex-PAN ☺	20
Needling ☺	5



- ♦ Significant scattering of tensile strength in the ex-pitch fibre direction between delivered batches
- ♦ No clear identification of the origin during the manufacturing process
- ♦ Delivery accepted to avoid delay in the fabrication of target elements
- ♦ ~ 1000 kg available for pre-series and serial productions of target elements

Raw materials: CFC, CuCrZr, Cu, Ni, 316L

Chemical, mechanical examinations

AMC®-NB31 tiles



Visual, x-ray, ARGUS*

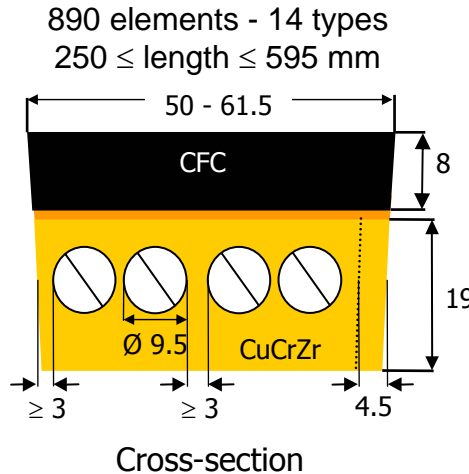
Bond between
AMC-NB31 tiles and CuCrZr block
EBW / HIP

Visual, ultrasonic, ARGUS*

AMC-NB31 tiles+ heat sink, lid, inlet outlet tubes
EBW - Machining - Heat treatment

Visual, ultrasonic, RT He leak test
Hardness and electrical conductivity,
Pressure drop, ARGUS*

TARGET ELEMENT



◆ Thermal performances

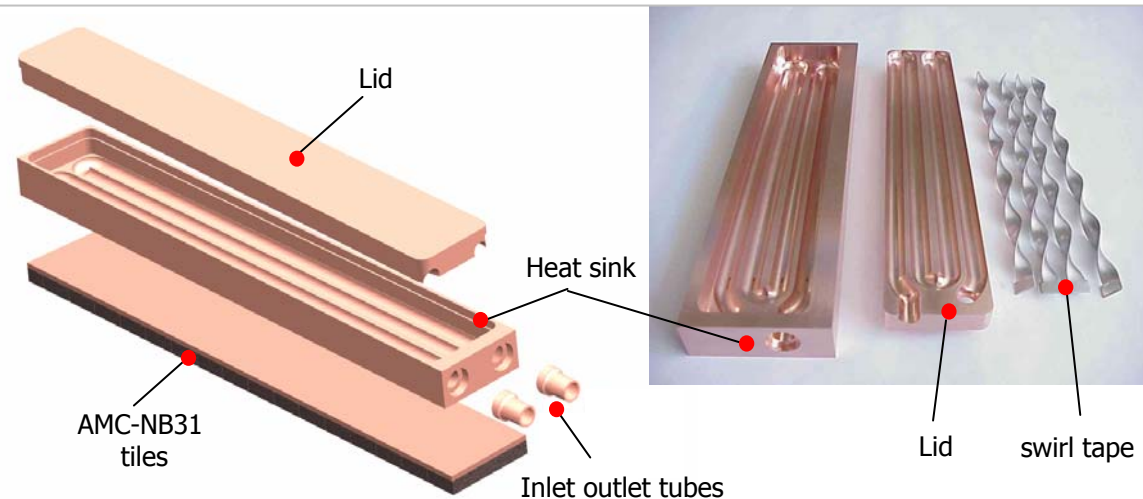
Max. stationary heat flux **10 MW/m²**
Max. power per element **100 kW**

◆ Technology

Heat sink	CuCrZr
Plasma facing material	CFC Sepcarb® NB31
Joining CFC-Heat sink	AMC® / EBW or HIP
Interlayer CFC-Heat sink	AMC®- Cu
Cooling	swirl tube

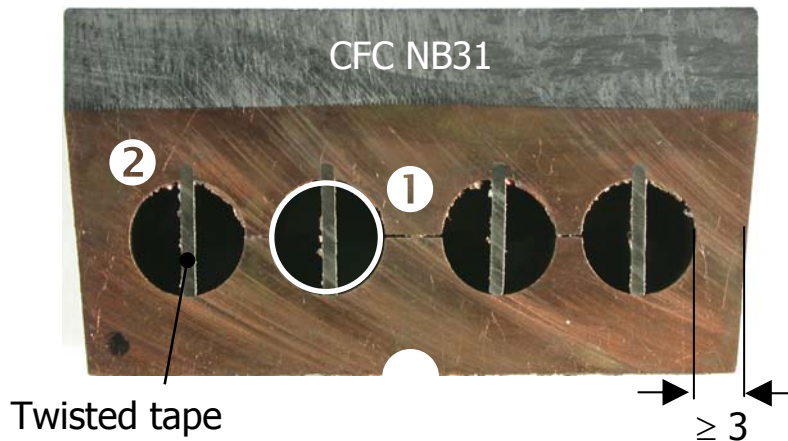
◆ Water-cooling characteristics

Axial velocity	8-10 m/s
Max. inlet/outlet temp	30°C/80°C
Static pressure	1 MPa

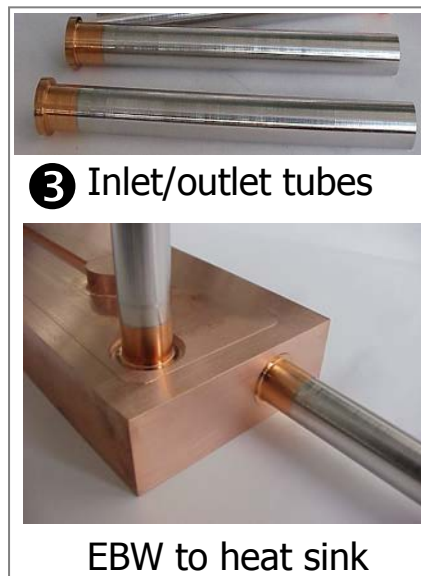
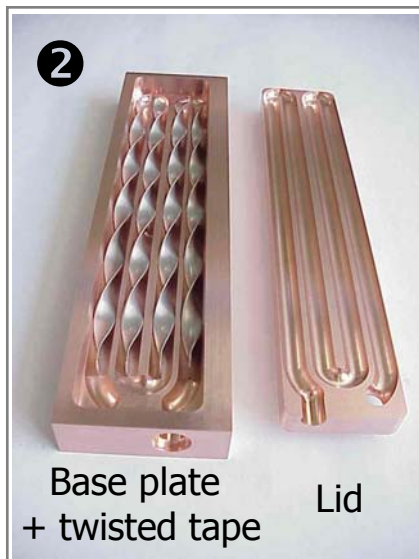


*Advanced infraRed thermoGraphy Unit for inSpection
developed by Plansee SE throughout pre-series phase

Each manufacturing step is qualified by the following relevant set of inspections



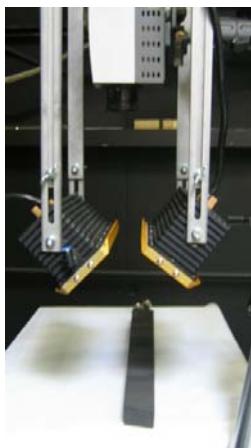
- ❶ **Heat sink = base plate + lid** [NDE: ultrasonic]
 - ⇒ EBW blind weld in central position
 - ⇒ Circular shape of the channel
- ❷ **Cooling channel**: twisted tape insertion
 - ⇒ Mechanical attachment with key-slots in base plate
- ❸ **Inlet/outlet tubes** [NDEs: dye penetrating, x-ray]
 - ⇒ EBW to stainless steel with Ni transition interlayer
 - ⇒ EBW to CuCrZr heat sink



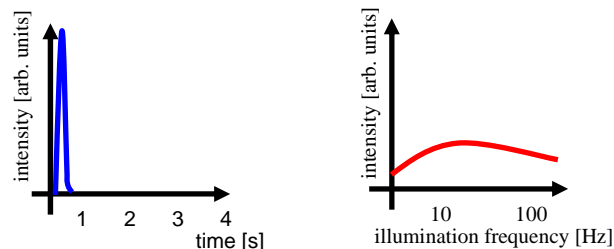
Reception tests

- ⇒ **No leak before and after HHF tests**
(35 full-scale pre-series TEs delivered)
- ⇒ Validation of the manufacturing route
- ⇒ Validation of the relevant NDEs
- ⇒ Validation of the acceptance criteria

ARGUS - Pulsed thermography mode - Preliminary results -

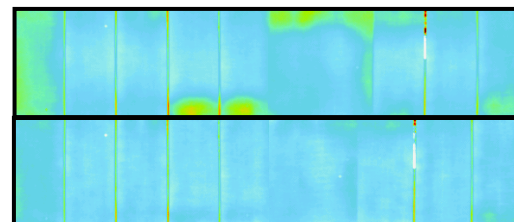


♦ Testing procedure

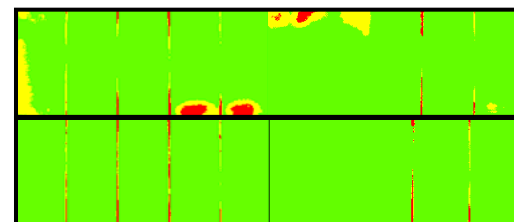


- **Heating:** one single flash of light (light source: 12 kJ)
- **Measure:** cooling-down recorded by IR camera

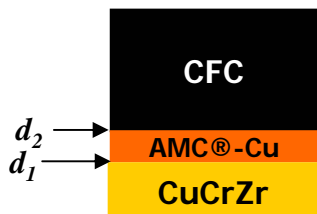
♦ Pre-HHF - Prediction mode



1 2 3 4 5 6 7 8 9 10

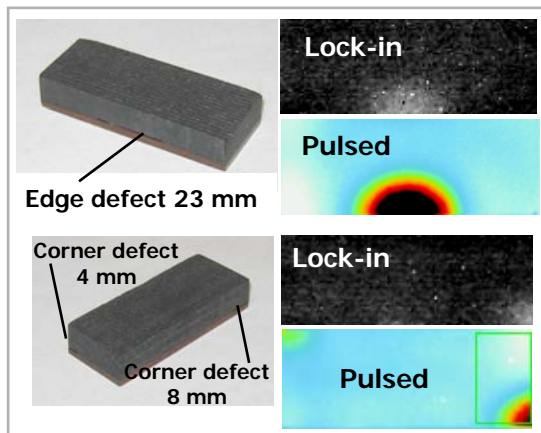


♦ Principle and application to AMC® tiles inspection



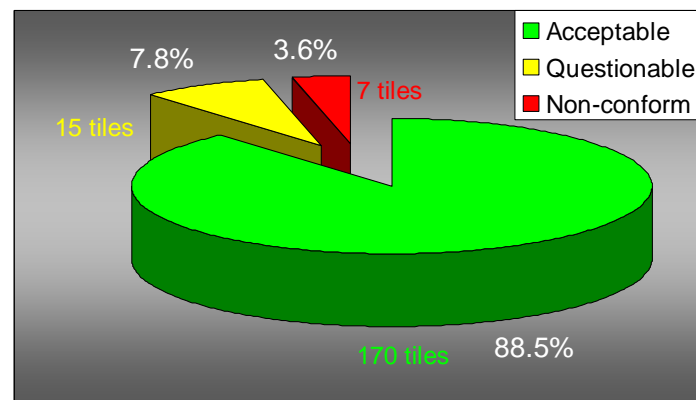
$$d_2 \propto \frac{1}{\sqrt{f_2}} \propto \frac{1}{\sqrt{2f_1}}$$

$$d_1 \propto \frac{1}{\sqrt{f_1}}$$



Calibrated defects Phase images

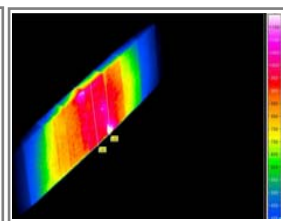
	Acceptable	Questionable	Non-conform
Rated phase shift 1	Min. $\Phi \geq 0.773$	$0.773 \leq \text{Min. } \Phi < 0.734$	Min. $\Phi < 0.734$
Rated phase shift 2	Min. $\Phi \geq 0.583$	$0.583 \leq \text{Min. } \Phi < 0.554$	Min. $\Phi < 0.554$



(See Poster H. Traxler et al.)

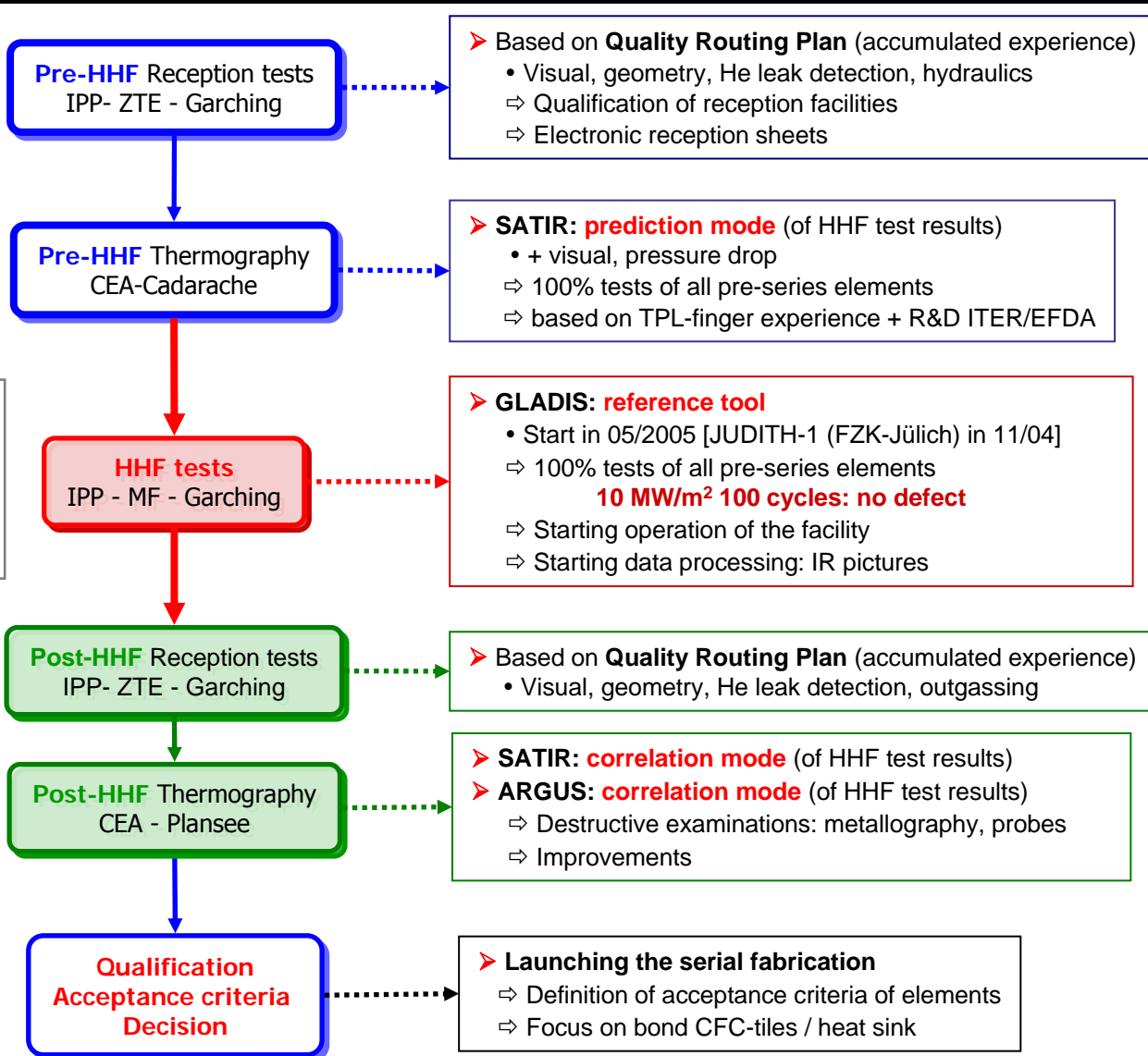
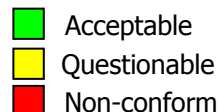
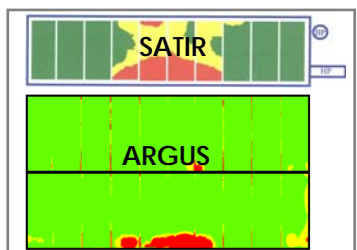


W7-X pre-series target elements



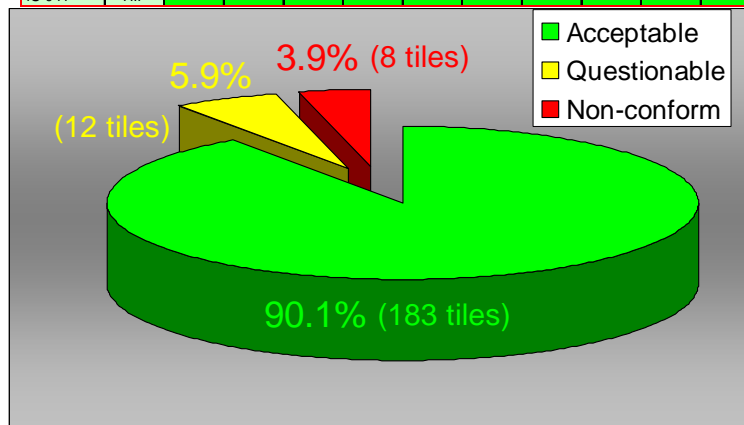
GLADIS ion beam

IR picture



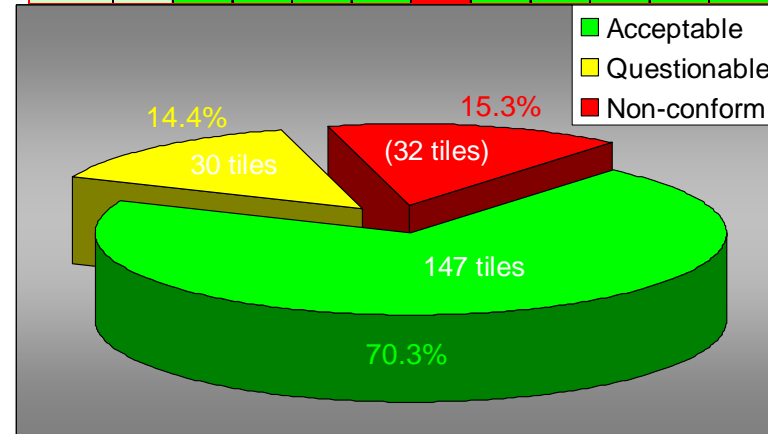
♦ HHF - Cycle 1 (10.4 MW/m²)

Name	Bond	t-1	t-2	t-3	t-4	t-5	t-6	t-7	t-8	t-9	t-10
4S-001	EBW										
4S-002	EBW	Reference SATIR									
4S-003	EBW										
4S-005 (3)	EBW										
4S-006	EBW										
4S-007	EBW										
4S-008	EBW										
4S-009	EBW										
4S-010	EBW										
4S-018	EBW										
4S-026	HIP										
4S-029 (3)	HIP										
4S-030	HIP										
4S-031	HIP	Reference SATIR									
4S-032	HIP										
4S-033	HIP/rep										
4S-034	HIP										
4S-037	HIP										
4S-038	HIP/rep										
4S-039	HIP										
4S-040	HIP										
4S-041	HIP										



♦ HHF - Cycle 100 (10.4 MW/m²)

Name	Bond	t-1	t-2	t-3	t-4	t-5	t-6	t-7	t-8	t-9	t-10
4S-001	EBW										
4S-002	EBW										
4S-003	EBW										
4S-005 (3)	EBW										
4S-006	EBW										
4S-007	EBW										
4S-008	EBW										
4S-009	EBW										
4S-010	EBW										
4S-018	EBW										
4S-026	HIP										
4S-029 (3)	HIP										
4S-030	HIP										
4S-031	HIP	Reference SATIR									
4S-032	HIP										
4S-033	HIP/rep										
4S-034	HIP										
4S-037	HIP										
4S-038	HIP/rep										
4S-039	HIP										
4S-040	HIP										
4S-041	HIP										

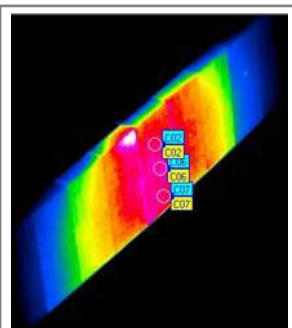


➤ GLADIS HHF test results after 100 cycles:

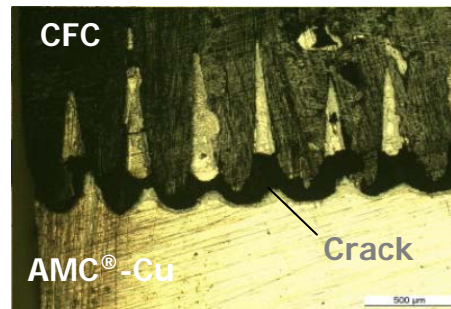
- ♦ 70% of tiles without defect: positive result
- ♦ 15% of tiles requires additional investigations
- ♦ 15% of tiles shows bond defects

➤ HHF test results (qualitative approach)

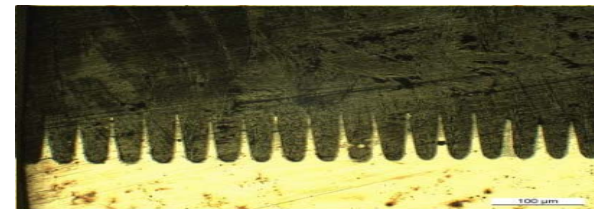
- ♦ **Hot spot growth** at the surface during cycling at 10 MW/m^2 - 10s visible after 10-25 cycles
- ⇒ **Visible initiation / propagation of cracks** at the interface CFC/AMC[®]-Cu



Typical hot spot



Typical crack propagation at the interface

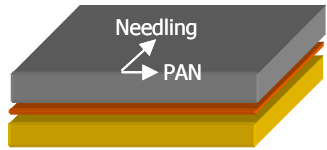


Typical good interface after HHF tests
~ 100 cycles @ 10 MW/m^2
~ 70% of tested tiles

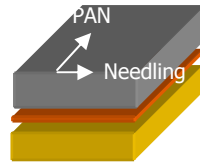
➤ Design improvement

- ♦ **Objective:** to minimize strain/stress at the interface
- ♦ **Tool:** simulations based on FE methods (Abaqus code, Plansee SE)
- ♦ **Outcome:** identification of design options compatible with fabrication
- ⇒ fabrication of additional pre-series target elements (phase III)

(See A. Plankensteiner et al. - SOFT 2006)



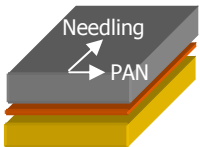
Option 1: bi-layer effect
0.4mm AMC + 2mm Cu



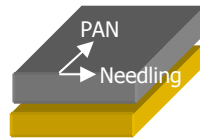
Option 3: effect of
90° in-plane fibre rotation
(PAN ↔ needling)

Improved design (phase III)

- ♦ CuCrZr heat sink: design kept
- ♦ Cooling geometry: **swirl tube with twist ratio 2**
- ♦ **Bi-layer** introduction: **0.4mm** AMC[®]Cu+ **2mm** OF-Cu
- ♦ Bonding technologies of AMC[®] tiles: **HIP**
- ♦ Repairing process: EBW (HIP-AMC[®]-tile to CuCrZr)

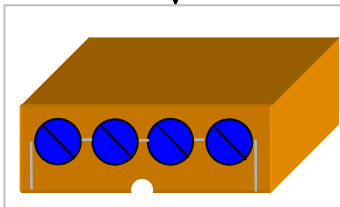


Option 2: effect of tile size
~62mm down to ~20mm



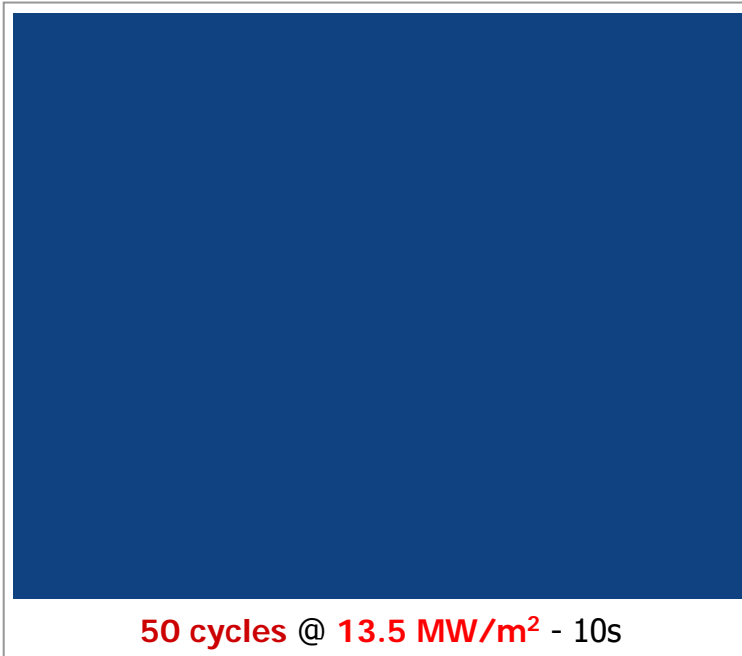
Option 4: effect of tile size
+ 90° in-plane fibre rotation

Phase III

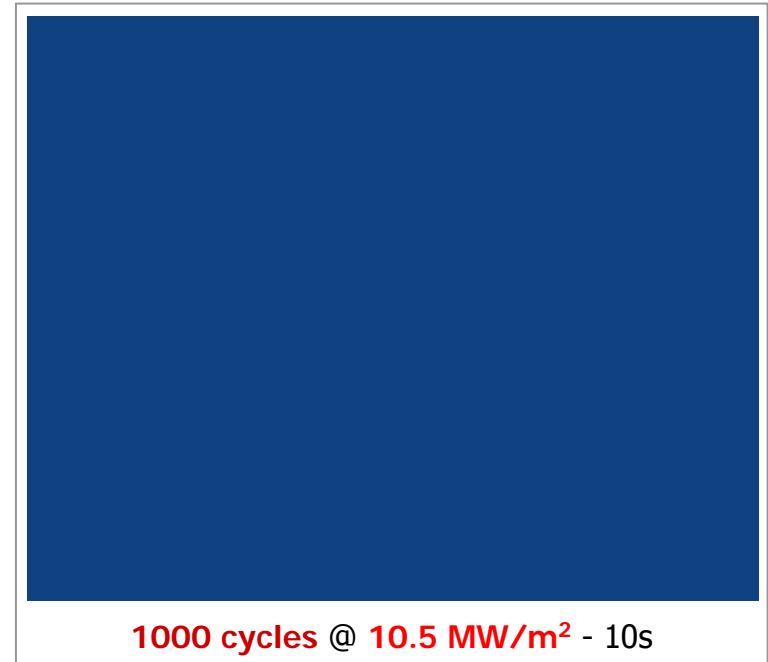


Options for pre-series phase III								HIP	EBW
Option 1	CFC NB31 tile Standard - Full size	+	AMC 0.4 mm	+	OF-Cu soft layer 2 mm	=		3 + 3	
Option 2	CFC NB31 tile Standard - Half-size	+	AMC 0.4 mm	+	OF-Cu soft layer 2 mm	=		3	
Option 3	CFC NB31 tile 90° rotated - Half-size	+	AMC 0.4 mm	+	OF-Cu soft layer 2 mm	=		4	2
Option 4	CFC NB31 tile 90° rotated - Half-size	+			AMC 2mm	=		4	2
							Total	21 elements	

- **Aim:** exploration of maximal allowed heat load on target elements



⇒ No catastrophic failure



⇒ No catastrophic failure

- **Aim:** exploration of maximal allowed heat load on CuCrZr cooling structure



Melted CuCrZr structure after burn-out

- Heat sink without CFC tiles
- ♦ Stepwise increase up to incident 31 MW/m²
- Burn out after 2.6s
- ♦ Design: 25 MW/m² (10 m/s, T_{in} = 20°C, P_{static} = 1 MPa)

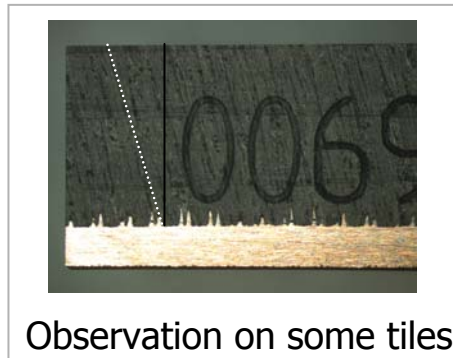
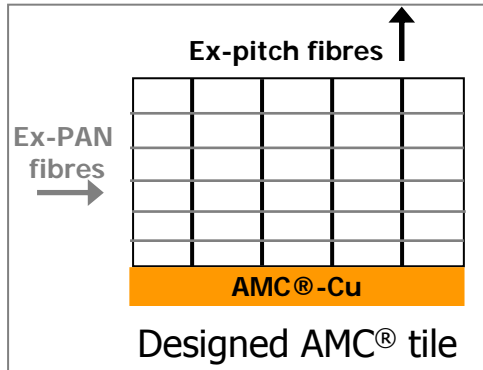
(See Poster H. Greuner et al.)

- ◆ **Need:** **Evaluation tool** of the impact of defects on the behaviour and lifetime of target elements
- ◆ **Outcome:** Identification of max. “**acceptable**” defect size (shape and location) **stable** under operation
- ◆ **Definition:** **method** (equipment, personal) + **value** (min., max., tolerance, *detection limit*)
= **decision** (accepted, repaired, rejected)
- **Most critical issue:** bond between tiles and CuCrZr heat sink
 - ◆ ~17000 tiles to manufacture ~900 target elements \Rightarrow ~19 tiles per element
 - ◆ 1 defective tile per target element \Leftrightarrow 1 defective target element
- **Strategy for pre-series activities**
 - ◆ 100 % HHF tests as reference for decision + 100% thermography test (ARGUS, SATIR)
 - \Rightarrow **Thermography:** examination of the **thermal transfer** of the bond
 - \Rightarrow **HHF test:** evaluation of the **thermo-mechanical performance** of the bond under heat load
- **Consequences**
 - ◆ **Correlation between HHF test and thermography NDE results**
 - \Rightarrow bond damage during cycling *difficult to be predicted with thermography*
 - \Rightarrow **independent** of thermography method performance
 - \Rightarrow post-HHF degradation of thermal performance to be correlated with post-HHF thermography NDEs
 - ◆ **Key issue:** **definition of acceptance criterion of HHF test results**

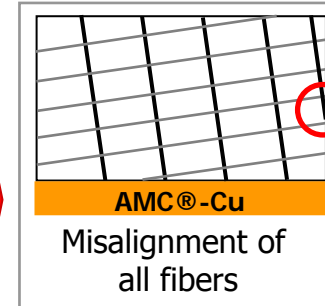
Bond defect detection = surface hot spot (IR), too high average surface temp (+ 20% *to be determined*)

 - **Increasing** hot spot: growing surface + increase T_{surf} + visible crack \Rightarrow **defective tile** (10-25 first cycles)
 - **Stable** hot spot: local $T_{\text{surf}} >$ average centre T_{surf} ($\sim > 100^\circ\text{C}$), no visible crack (100 cycl.) \Rightarrow quest. tile

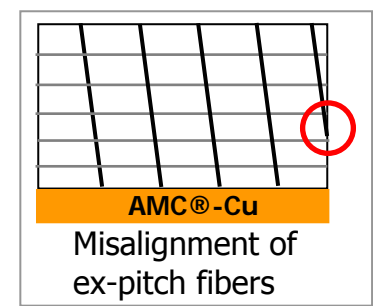
➤ Observation of Plansee SE



1st case

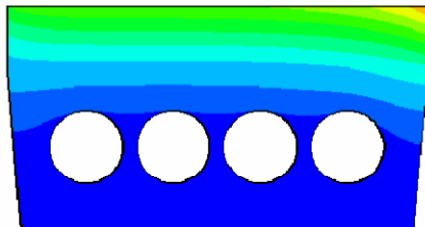


2nd case

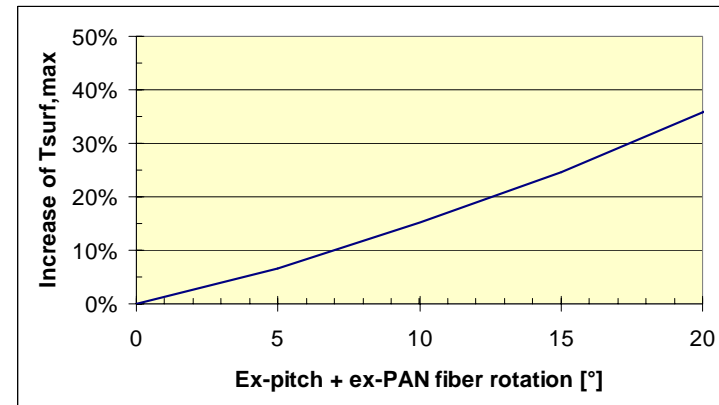


⇒ No direct contact fibers-Cu

➤ Simulation (Abaqus - S. Gerzokovitz - Plansee SE)



Typical temperature distribution
- Ex-pitch + ex-PAN rotation



➤ Conclusion

- ♦ Rotation of ex-pitch fibre direction may generate hot spot at the edge ⇒ interpretation
- ♦ **Next step:** comparison between ARGUS and GLADIS stable hot spots

➤ Pre-series activities phase I, II

- ♦ **Qualification** of the manufacturing route including NDEs ✓
- ♦ HHF test results in GLADIS: (→ *Poster of H. Greuner et al.*)
 - ⇒ 80-100 cycles @ ~ 10 MW/m² are sufficient to check the bond quality ✓
 - ⇒ 1000 cycles @ 10.4 MW/m² of 2 elements (EBW, HIP) without catastrophic failure ✓
 - ⇒ 50 cycles @ 13.5 MW/m² + Heat loads @ 24 MW/m²: "safety margin" in design ✓
 - ⇒ Thermal performance: CHF @ 31 MW/m² incident heat flux ✓
 - ⇒ **and no tile detachment occurred!**

➤ Pre-series activities phase III

- ♦ Design improvement compatible with industrial process to reduce stresses at the interface
- ♦ HHF tests in GLADIS of phase III elements (20 elements) will start in November 2006
 - ⇒ Positive results: start of fabrication by beginning 2007

➤ Acceptance criteria

- ♦ Significant improvement with ARGUS (pulsed-thermography mode) at Plansee SE ✓
 - ⇒ Cost-effective integration in manufacturing route (from AMC-tiles to completed element)
(→ Poster of H. Traxler et al.)
- ♦ SATIR has demonstrated it is a useful complementary reception facility for W7-X ✓
(→ Presentation of M. Missirlian et al.)

Time schedule (TE: Target element)	Amount	2001	2002	2003	2004	2005	2006	2007	2008	2009
Pre-series phases										
• Phase I ⇒ Qualification of design ⇒ Qualification of fabrication ⇒ Acceptance criteria	11 TEs									
• Phase II ⇒ CFC qualification	24 TEs									
• Phase III ⇒ Improvements ⇒ Acceptance criteria	21 TEs									
Series phase										
CFC NB31 (Snecma Propulsion Solide)	~1000 kg									
Target elements (Plansee SE) - <i>Draft</i>	890 TEs (+43)									