MAX-PLANCK-INSTITUT
FÜR PLASMAPHYSIK

TKT

PART I: Definition of the plasma facing surface

PART II: Technology development & qualification

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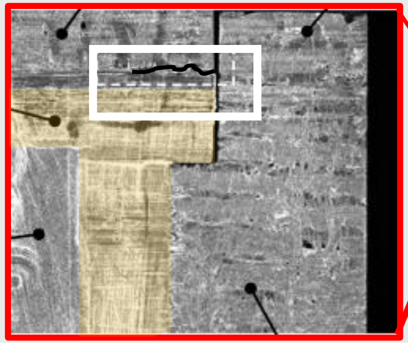
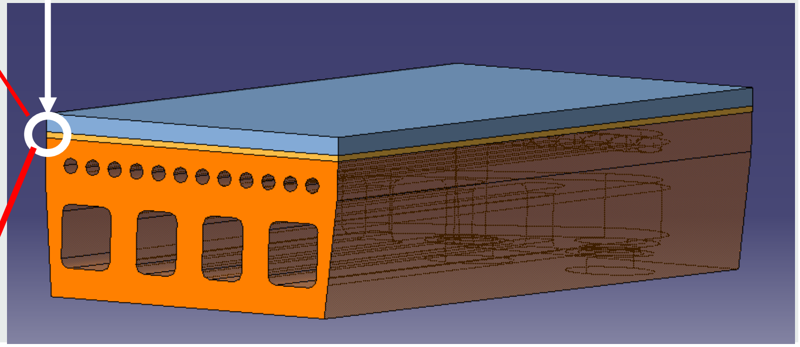
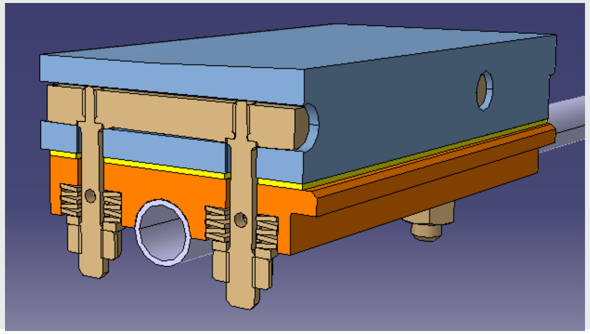
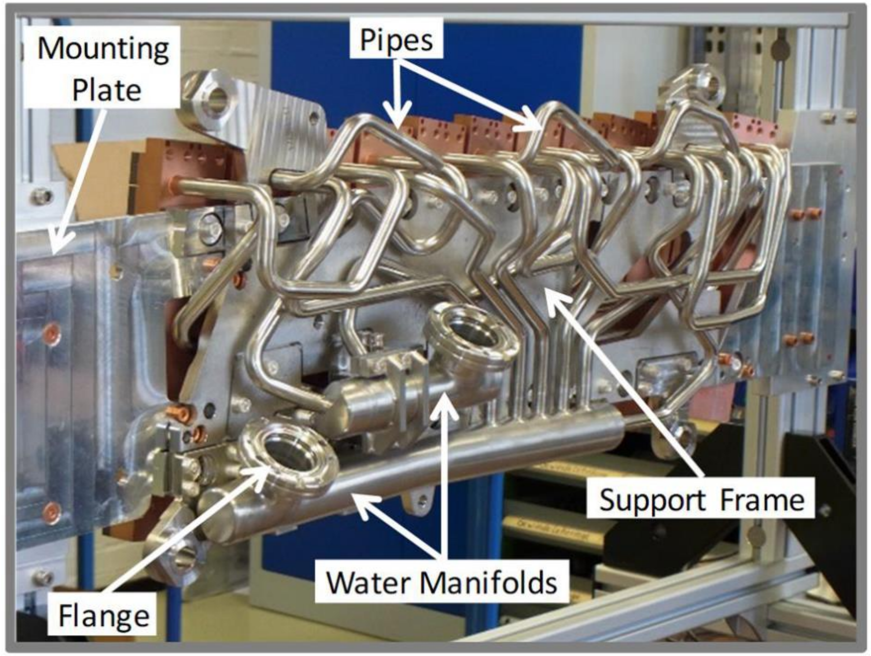
Fundamental differences divertor ⇔ baffle

	Divertor	Baffle
Plasma facing material	W or W_{95}NiFe	
Heat sink material	Cu or CuCrZr	
Heat load requirement	10 MW/m^2	< 1-2 MW/m^2
W-Cu Interface	Perfect thermal bond required	Cold contact sufficient
Connection type	continuous	Loose bolted connection allowed
Interlayer	1 mm OFE-Cu ΔT @ 10 MW/m^2 = ~25 K	Graphite foil ΔT @ 1 MW/m^2 = 500 K
Key design concern	Thermal expansion mismatch Interface stress singularity	Maximum W temperature Bolt design
CFC – OFE Cu crack example 		

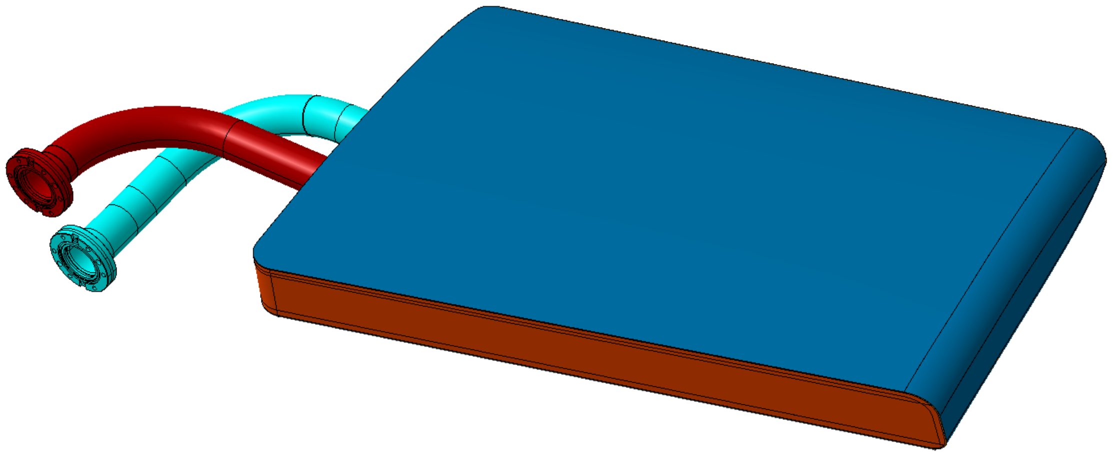
Technology qualification for target modules

- **Assumptions**
  - Similar plasma facing geometry as CFC divertor: 10 MW/m² design heat load
  - Use existing cooling water infrastructure: 5 l/s per target module, $\Delta p < 15$ bar, max 13 modules per unit
  - Limiting target module weight ~50 kg
  - Preferably increased design heat load for edge tile near pumping gap from 2-5 to 10 MW/m²
  - Accessible filter required in supply line outside UHV to prevent flow obstruction in cooling channels
- **Objectives**
  - Simplify manufacturing and inspection and installation
    - Minimize pipe work and number of weld seams
    - Minimize number of target elements per module (aim = 1)
    - Minimize number of manufacturing and inspection steps
    - Relax tolerance requirements
- **Design rules**
  - Hydraulic loss ⇔ heat removal: high velocity only where heat is removed
  - Heat sink deforms as result of competition between hot and cold side
    - Make cold side far more rigid than hot side
  - W-Cu interface closest to water to minimize temperature & stress
    - Including soft Cu interlayer to accommodate thermal expansion mismatch
  - Statically determined support system, free of thermal restraint forces



Simplifying target module geometry

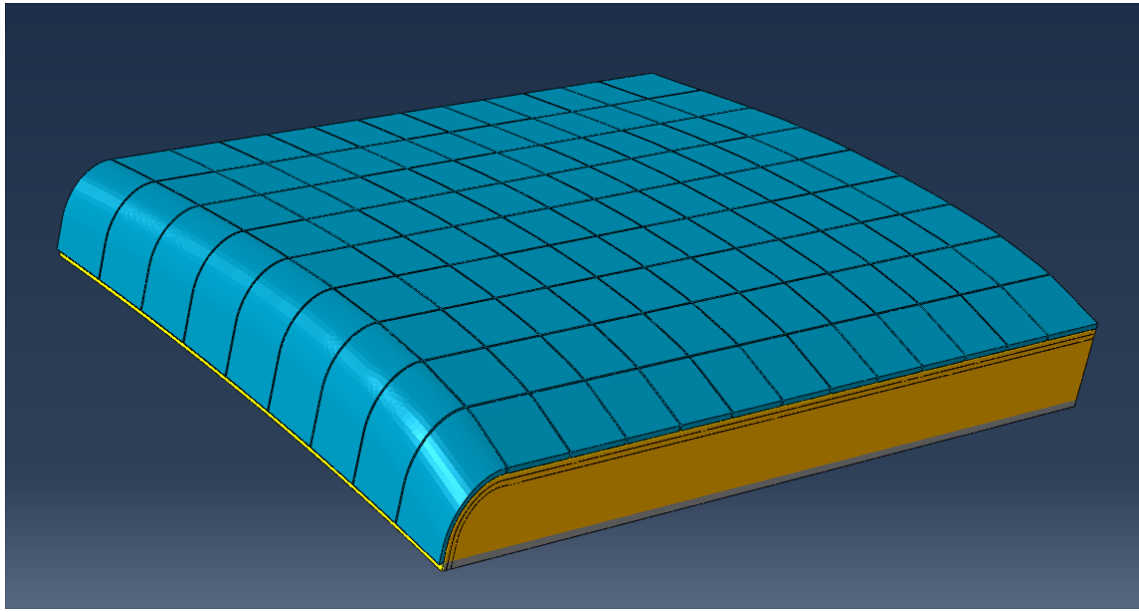
- Since the new plasma facing geometry is unknown, the largest and most curved CFC target module TM1h was selected as reference
- The edge tile problem is resolved by adding a smooth curvature, allowing cooling channels to closely follow the plasma facing surface

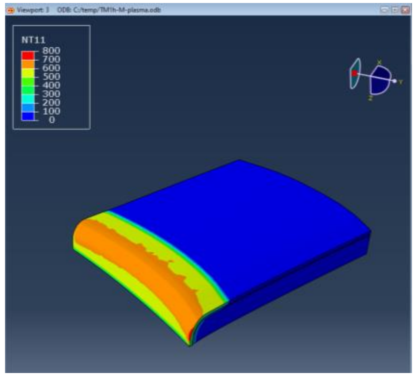


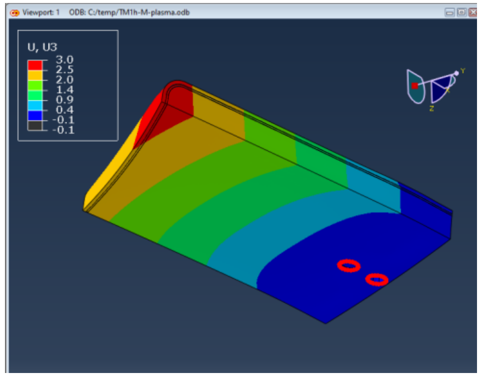
Size ~0.4x0.6 m x 50 mm

Conceptual layout of target module

- **Additive manufactured (LPBF) CuCrZr heat sink with integrated manifold**
  - Heat removal channels closely follow exposed side
  - Machining of plasma facing side after printing
- **Need for soft OFE-Cu interlayer**
- **W or WNiFe plasma facing surface**
  - WNiCu dissuaded since T_{limit} < 900 °C [Neu: 2017]
  - Coating (low pressure plasma spray or cold spray)
    - Thickness > 0.2 mm ➔ 0.3 mm targeted
      - To survive erosion over W7-X life (~300h)
    - Either on soft Cu interlayer or FGM on CuCrZr directly
  - Or mosaic of W/Cu sandwich tiles bonded by brazing
    - Sandwich tiles by galvanizing, casting or diffusion welding
    - Final machining after brazing process
    - Size < 30x30 mm
      - To limit manufacturing deformation
    - Thickness > 2-3 mm
      - to avoid Cu sputtering in slits
- **FEM show temperatures < 800 °C and displacements < 3 mm**



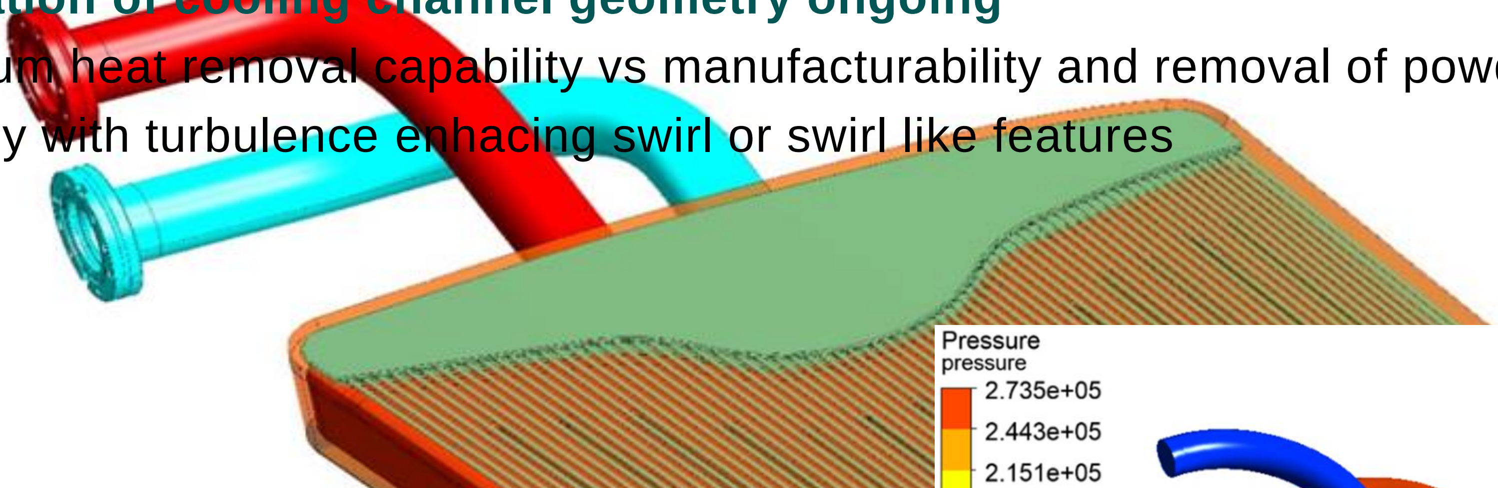


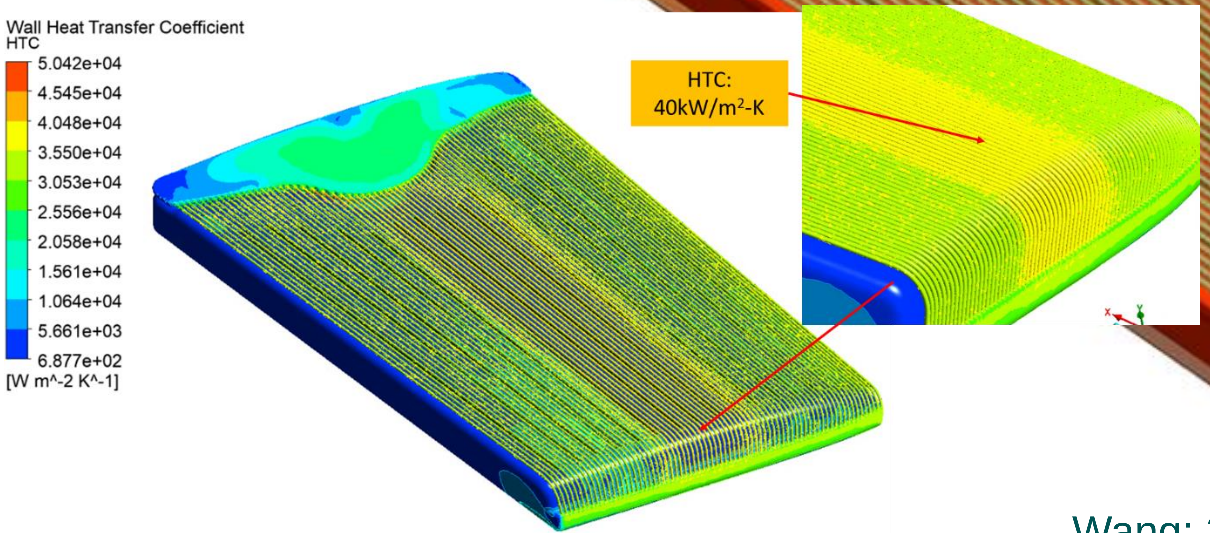


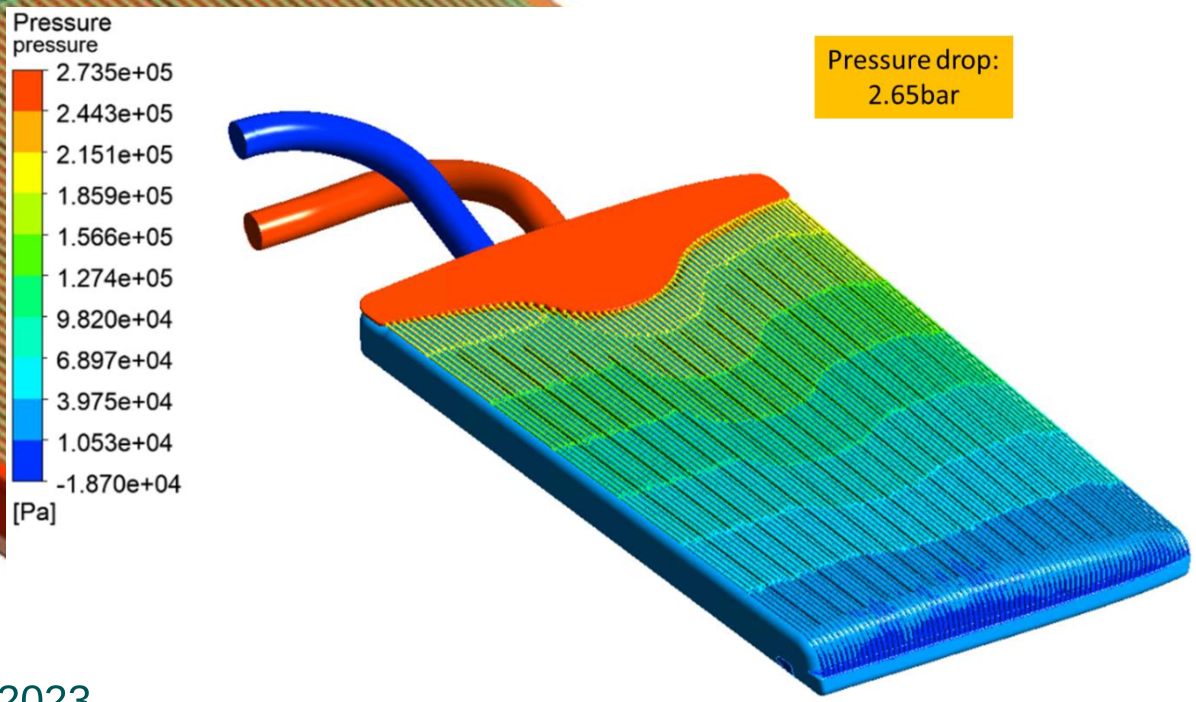
Cooling channel concept

- **HTC of ~40 kW/m²K at 10 m/s**
- **Δp 2.65 bar over entire target module at 4 l/s(compare to ~7 bar in CFC divertor)**
- **Optimisation of cooling channel geometry ongoing**
  - Maximum heat removal capability vs manufacturability and removal of powder remains
  - Possibly with turbulence enhacing swirl or swirl like features

Tretter: 2023







Wang: 2023

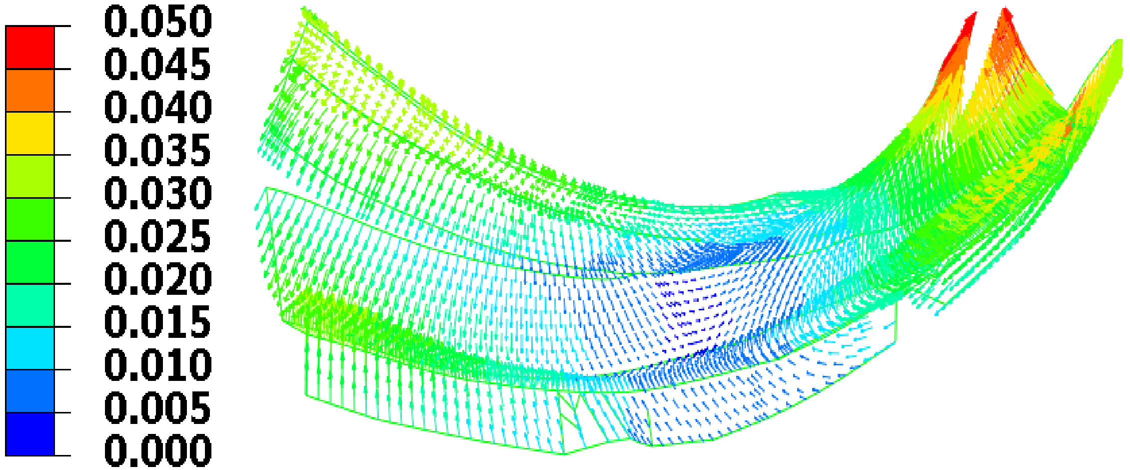
Large components ➔ large Lorentz forces

- **Decay of plasma in 1 ms**
  - Pfirsch-Schlüter currents
  - Toroidal current (50 kA)

    VMEC ➔ Extender ➔ FLT: plasma induced field change on divertor
  - Diamagnetic current:
    - Field exclusively inside LCFS suddenly distributed inside vessel (ΔB_{tor} = ~20 mT)
    - Decay of superconducting coil system of 3T in 3 s is less critical: $3/3 < 20 \cdot 10^{-3} / 1 \cdot 10^{-3}$
- **Change of magnetic field perpendicular to modules B_{perp} causes eddy currents**
  - Induced currents limited by inductance and resistance of module

$$I_{ind} = A_{enclosed} \cdot \Delta B_{perp} \min\left(\frac{1}{R\Delta t}, \frac{1}{L}\right)$$

    - $\Delta B_{perp} < 22$ mT ➔ $I_{ind} < 6$ kA ➔ $F_{support} < 6$ kN
    - $\Delta\sigma < 72$ MPa for M12 bolt
    - Slits can further reduce eddy currents
- **Avoid current sharing with vessel**
    - Supports must be electrically isolated

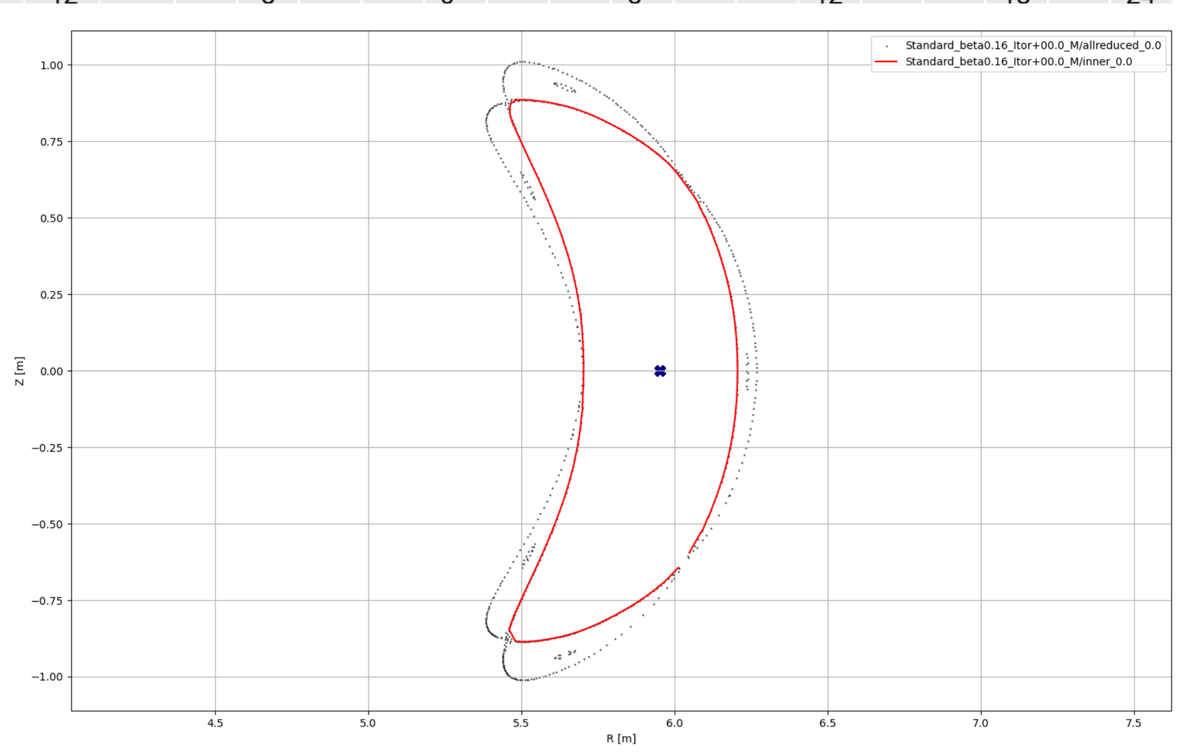


Fellinger et al.: NME 37, 2023

Engineering the plasma facing surface

- **Calculate separatrix**
  - Start points with intermediate connection length traced without target geometry [Kharwandikar: 2023]
  - More than 200 finite beta cases run with VMEC/extender/EMC-lite [Geiger/Fellinger: 2024]
- **Divertor d**
  - Safe distan
- **Divertor i**
  - Intersectior
- **Baffle doe**
  - No intersec
  - Only after c baffles cou
- **Use contr**
  - to limit sepa
- **Engineeri**
  - Magnetic tc
  - High mirror
  - DE: Fast tra
  - Fast creatic

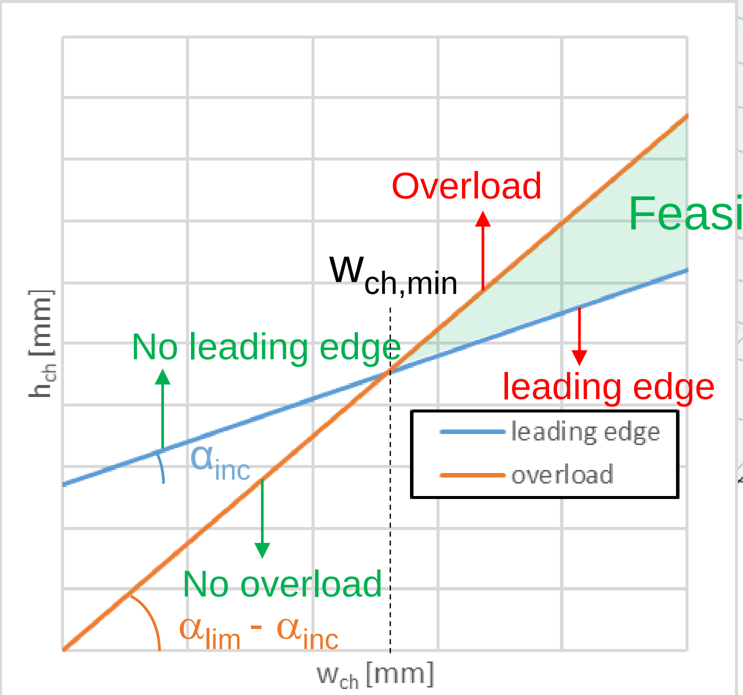
Config	Beta[%]	Itor [kA]																										
Standard	0.16%	-30	-28	-26	-24	-22	-20	-18	-16	-14	-12	-10	-8	-6	-4	-2	0	2	4	6	8	10	12	14	16	18	20	
	0.65				-24			-18			-12			-6			0			6			12			18		24
	1.32				-24			-18																				
	2				-24			-18																				
	2.69				-24			-18																				
	3.4				-24			-18																				
	4.13				-24			-18																				
High Iota	0	-70	-60	-50	-40	-30	-20		-15																			
	0.4						-20		-15																			
	0.8						-20		-15																			
	1.2						-20		-15																			
	1.6						-20		-15																			
	2.0						-20		-15																			
	2.4						-20		-15																			
	2.8						-20		-15																			
High Mirror	0.0						-20		-15																			
	1.0						-20		-15																			
	2.0						-20		-15			-10		-5			0		5			10		15			20	
	3.0						-20		-15			-10		-5			0		5			10		15			20	
	4.0						-20		-15			-10		-5			0		5			10		15			20	

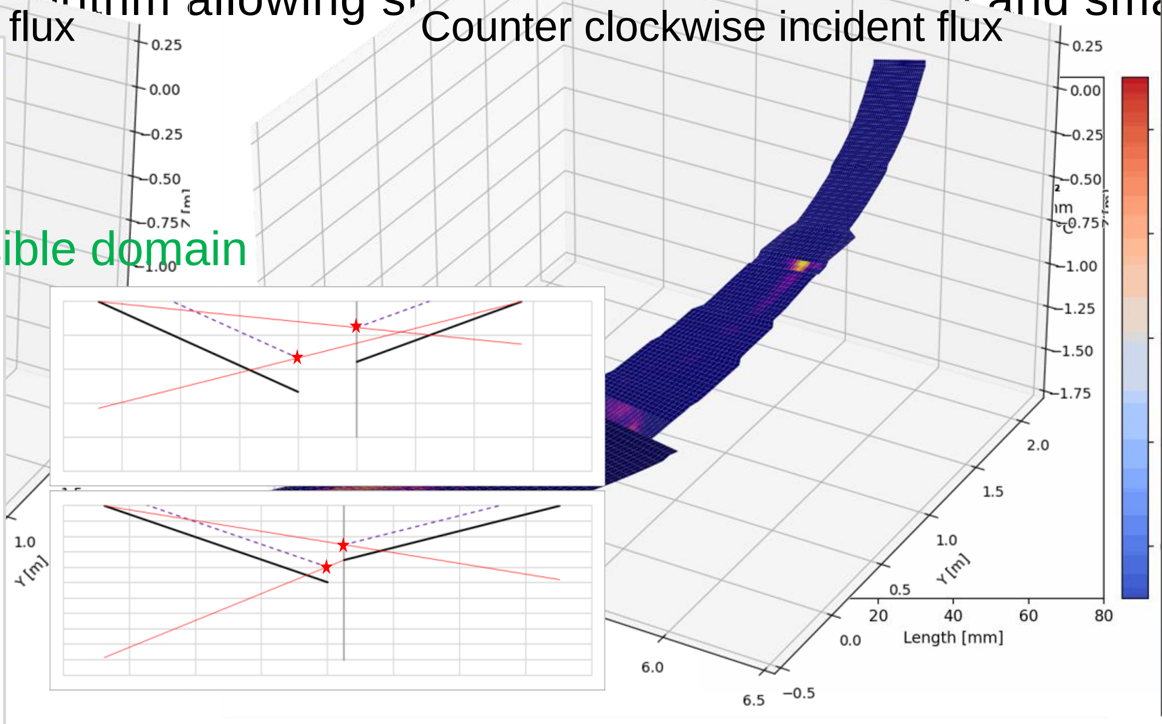


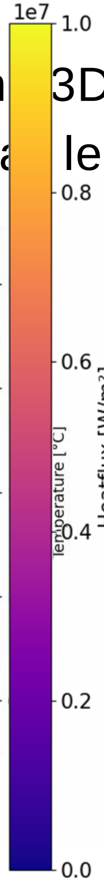
Leading edges [Antara Menzel]

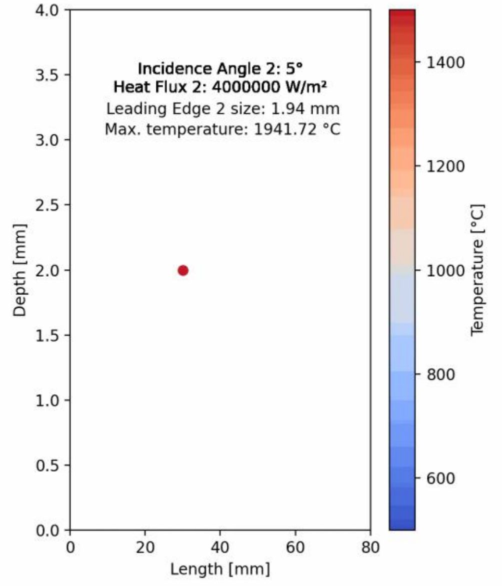
- **W-based plasma facing surface is less forgiving as CFC with regard to leading edges**
  - Need for final machining of mosaic of sandwich tiles after brazing
  - Large module size allows for shallow chamfering between modules
- **Tool developed to identify plasma facing area with high loads at incident angles of opposite sides**
- **Tool developed to optimize chamfer geometry to mitigate edge loads**
  - Simple solution for symmetric case avoiding leading edge
  - Simple ... tool for asymmetric case avoiding l... edge and assuming n... 3D effects
  - Ad... algorithm allowing st... and sma... leading edges

q_{max} over ST, HI and HM, 0%/ 1%, 3%, 5% beta/ 10 kA, 20 kA current



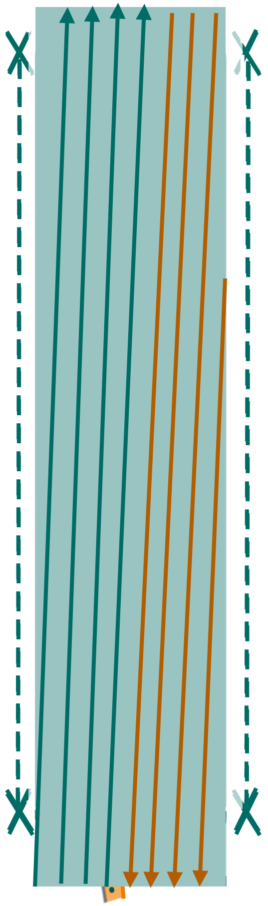


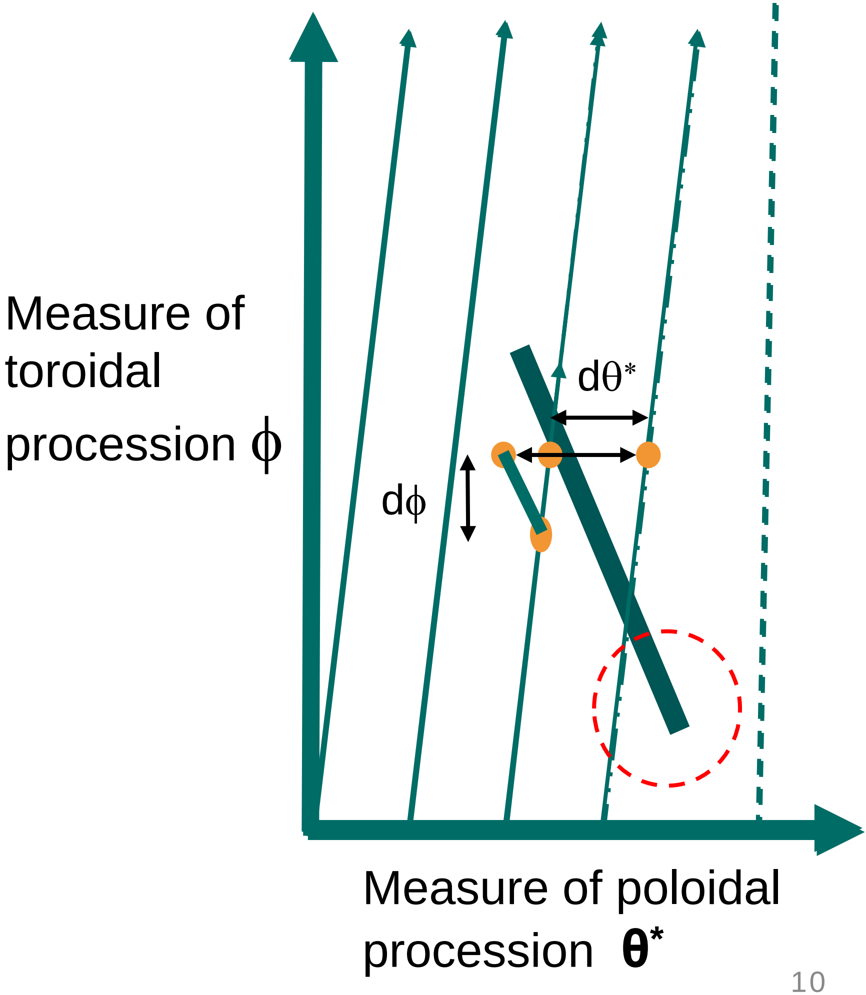




Robust leading edge free design [Menzel]

- **Unfold power shell of one island with global toroidal and local poloidal procession**
- **Choose a starting section of divertor in toroidal section ϕ_0**
- **Trace section for $d\phi$**
- **Trace section for 2π to find local poloidal procession $d\theta^*$**
- **Create new divertor section in $\phi_0+d\phi$**
  - using shift in opposite direction $s \cdot d\theta^*$
  - s is chosen to tune incident angle and heat load
- **All heat load can be designed to arrive from one side only**
- **Front edge is in shade**
- **<u>Closed divertor for standard configuration</u>**





Qualification tasks target element

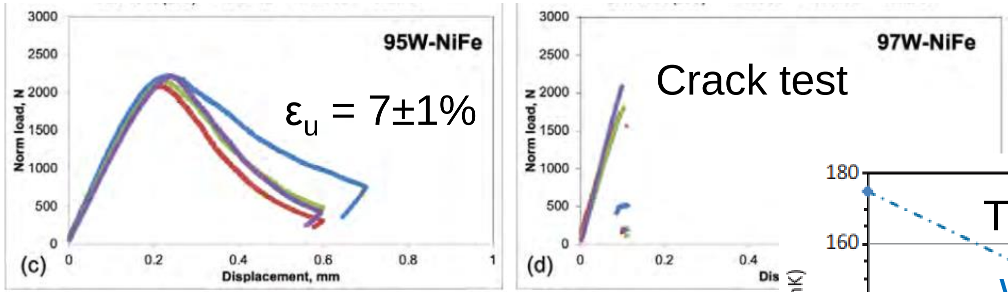
- **Measurement of properties of W, W heavy alloys, AM CuCrZr, and OFE Cu (cast/galvanic/plate)**
  - Porosity, stress-strain relation, magnetization, machinability
  - Cast Cu is very soft, galvanic copper needs annealing
  - LPBF CuCrZr needs age hardening to increase thermal conductivity – overaging must be avoided
- **Cooking recipes for manufacturing processes**
  - Additive manufacturing of CuCrZr heat sinks (LPBF)
  - Coating W or WNiFe onto heat sink
    - Low pressure plasma spraying or cold gas spraying
    - Pure W(NiFe) onto soft copper interlayer or functionally graded W(NiFe) + Cu coating directly onto heat sink
  - Manufacturing of sandwich tiles of W or WNiFe with soft OFE Cu interlayer
    - Bonding W and WNiFe to OFE Cu by diffusion welding (DW), cast Cu or galvanic Cu
  - Bonding sandwich tiles onto heat sink
  - Galvanic connection of stainless steel connectors to CuCrZr heat sink
- **Demonstration of robust and reliable performance**
  - He leak tightness of heat sinks
  - Cyclic HHF resistance

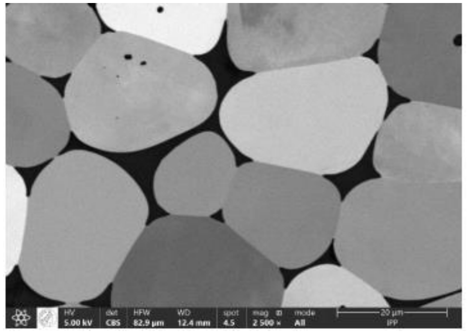
$W_{95}Ni_{3.5}Fe_{1.5}$ properties

- **Magnetic permeability:** $\mu = 1 + \frac{J*rho}{H} = 1 + \frac{J*rho*4\pi}{B*1000}$

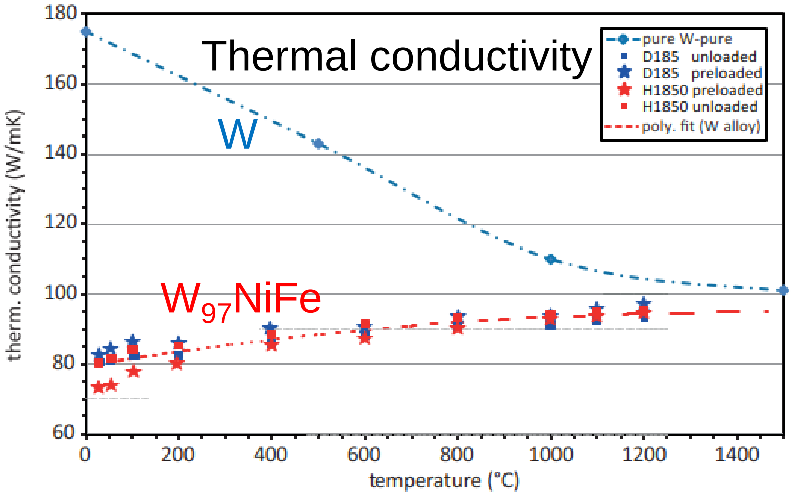
Material	density [kg/m³]	Supplier	B [T]				J [A/m / (kg/m³)]			
			1.4	1.7	2	2.5	1.4	1.7	2	2.5
W97NiFe	18500	D185	1.038	1.032	1.027	1.022	2.3	2.33	2.35	2.4
	18500	HPM185	1.031	1.026	1.022	1.018	1.85	1.87	1.88	1.9
W95NiFe	18000	Litty	1.056	1.047	1.040	1.032	3.45	3.5	3.52	3.55

- **Saturation at elevated temperature ➔ μ_R = 1 at 500°C**
  - Risk of amplification of initial asymmetric heat loads

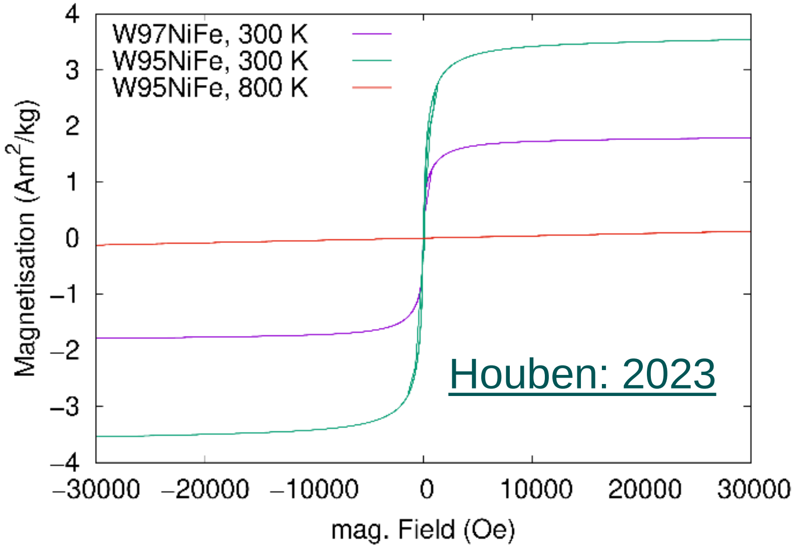


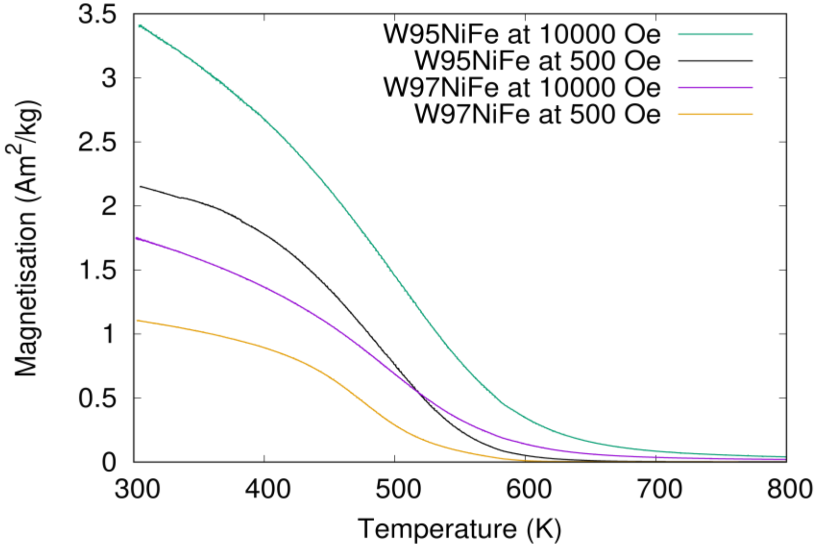


Two-phase: W-grains in WNiFe matrix



Magnetisation

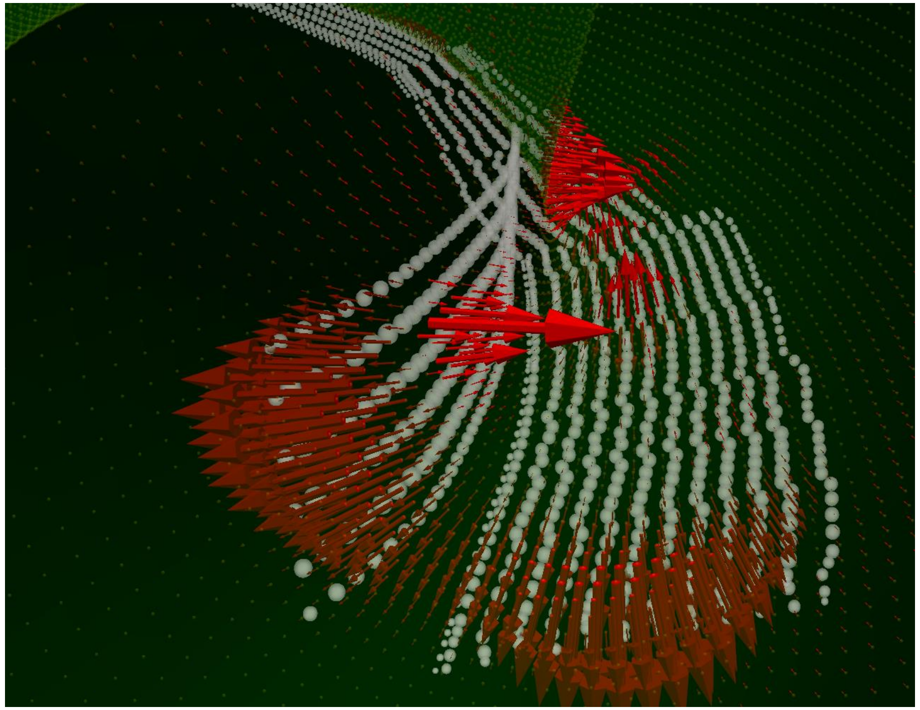


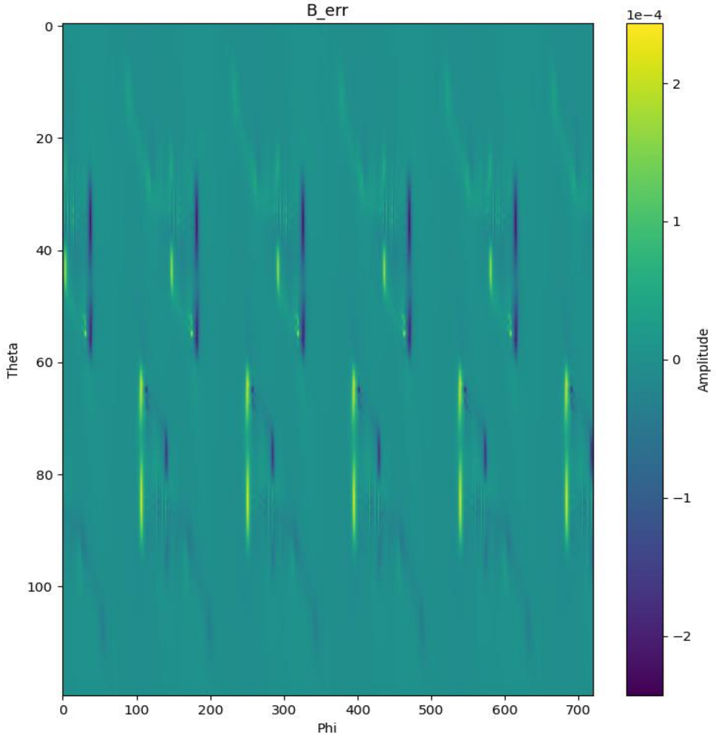


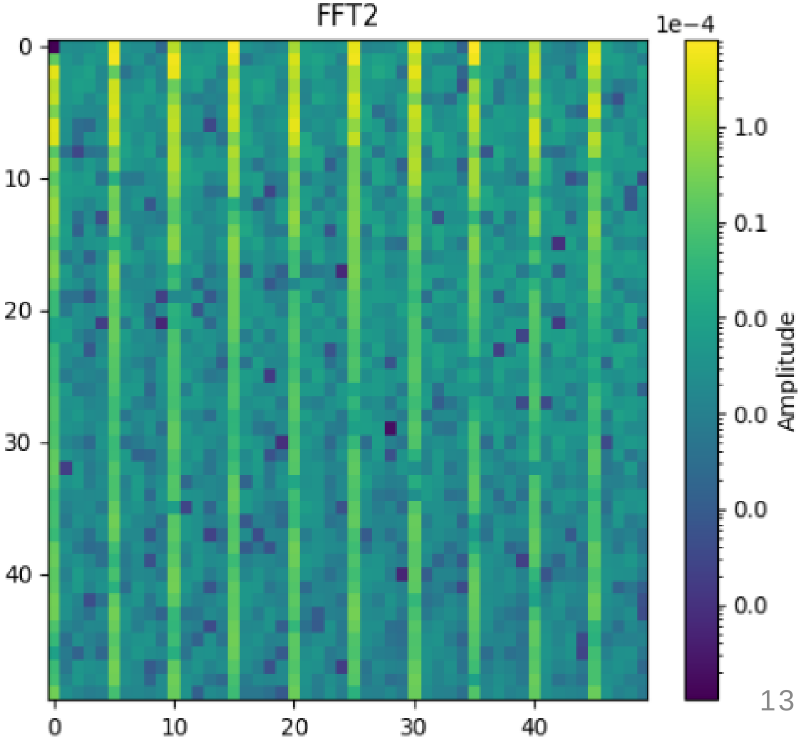
Error field calculations [Thomas Fornal]

- $\mu_R > 1.01$ ➔ MATLAB tool of M. Köppen
  - 4 mm thick WNiFe surface modelled with spheres with same volume and same μ_R
  - Calculation of LCFS with VMEC
    - 720 x120 points as function of toroidal and poloidal angle
  - Calculation of disturbed and undisturbed error field at LCFS
  - Calculation of relative error projected onto normal of LCFS
  - Calculation Fourier components: $B_{err} = \sqrt{B_{11}^2+B_{22}^2+B_{33}^2+B_{44}^2} = 1.1\cdot10^{-6} \ll 2\cdot10^{-4}$ ✔

Rel. field error	
B_{11}	$4.0\cdot10^{-7}$
B_{22}	$5.7\cdot10^{-7}$
B_{33}	$7.2\cdot10^{-7}$
B_{44}	$4.0\cdot10^{-7}$
B_{55}	$3.6\cdot10^{-4}$

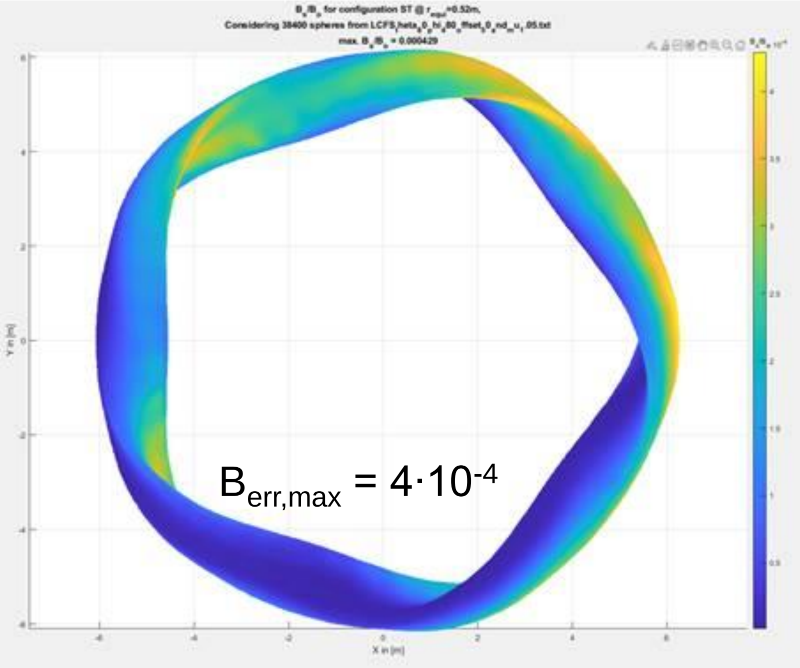


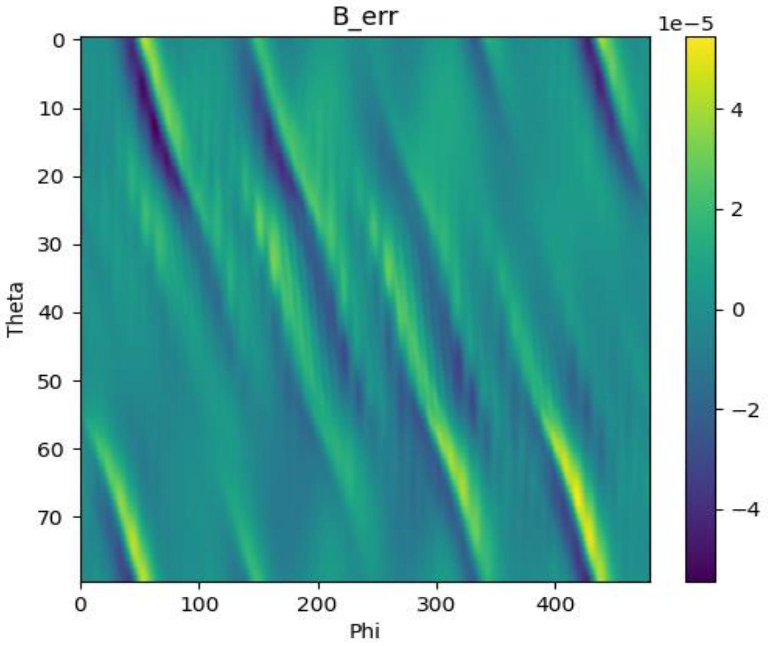




Validation for arbitrary divertor geometry

- **Background: saturation of WNiFe at elevated temperature may increase asymmetry**
- **Virtual plasma facing surface of WNiFe at 50 mm from LCFS with 4 mm WNiFe**
- **Apply 1-1 variation of μ_R over the plasma facing surface: $\mu_R = 1.025 + 0.25 \cdot \cos(\alpha_{tor} - \alpha_{pol})$**



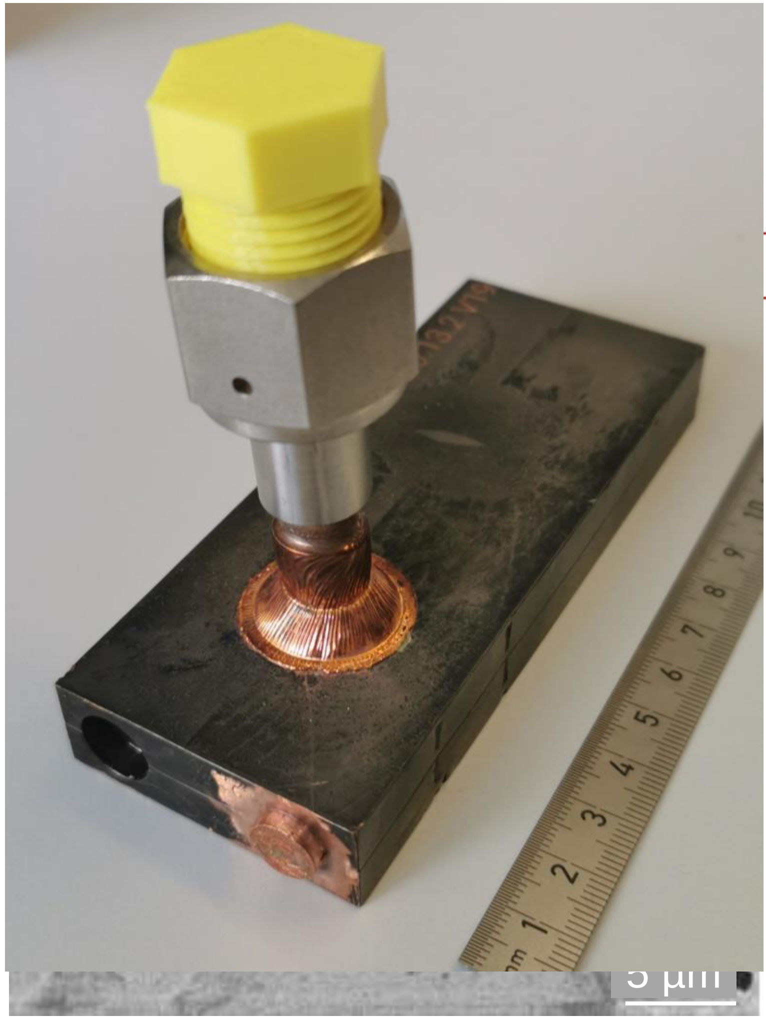


Rel. field error	
B_{11}	$1.7 \cdot 10^{-4}$
B_{22}	$1.7 \cdot 10^{-7}$
B_{33}	$8.5 \cdot 10^{-8}$
B_{44}	$2.0 \cdot 10^{-5}$
B_{55}	$1.3 \cdot 10^{-5}$
B_{66}	$1.1 \cdot 10^{-6}$

- **$B_{err} = \sqrt{B_{11}^2 + B_{22}^2 + B_{33}^2 + B_{44}^2} = 1.7 \cdot 10^{-4} < 2 \cdot 10^{-4}$ ➔ OK even for extreme unfavourable μ_R distribution**
- **Conservative approach: In reality saturation at elevated temperature will reduce attraction of field by surface material and thus reduce heat load**

Diffusion welding

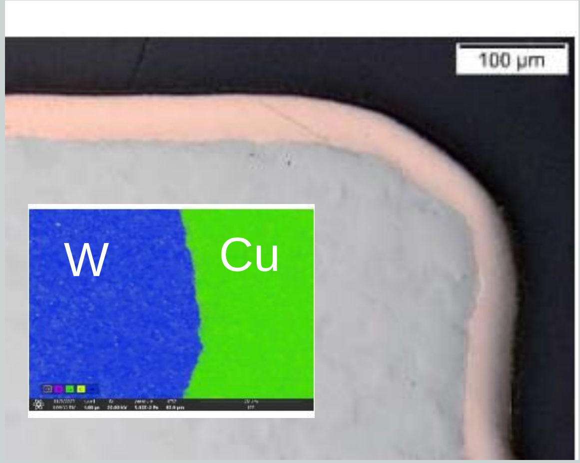
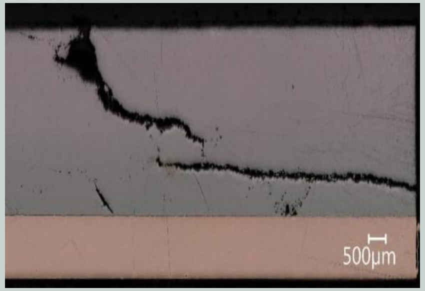
- **Diffusion welding of CuCrZr**
  - *Rationale: No added constituents, no liquid phase transformations*
  - 800-950°C @ 4-17 N/mm² for 30-60 minutes
  - 100% bonding
  - residual deformation ⬄ initial tolerance requirements
    - Initial flatness < 15 µm, R_z < 15 µm, no scratches
    - < 5% reduction of height feasible
  - He tightness achieved at 160°C / 30 bar
    - for diffusion welded flat plates with half-pipe cut out channels at both sides
    - 8/10 samples OK at residual deformation of >= 0.1 mm
    - 2/10 samples not ok at residual deformation 0.05 mm

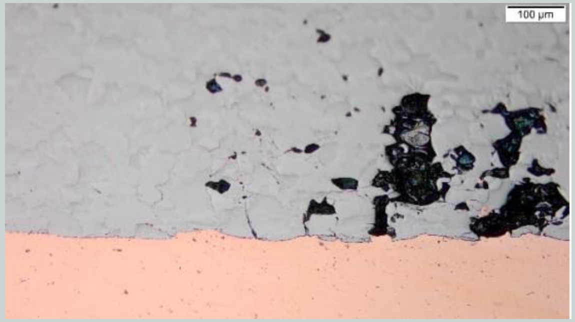


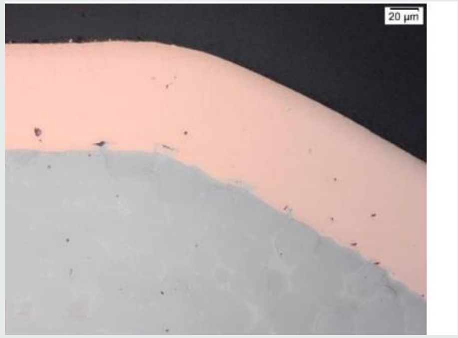
Bonding Cu to W and WNiFe

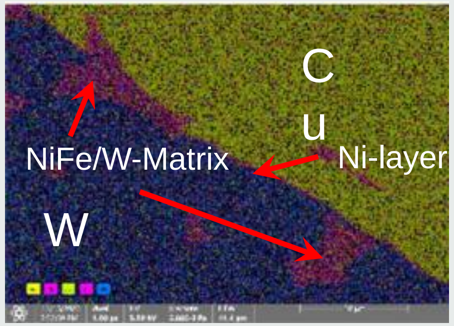
Courtesy Katja Hunger – IPP Garching

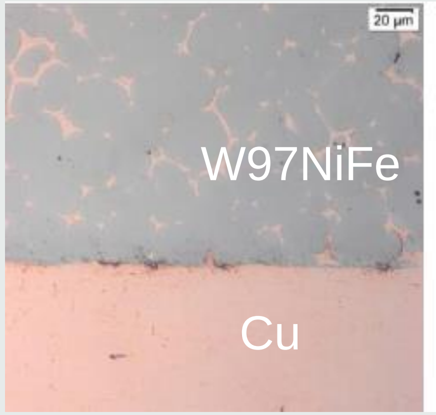
<table>
<tr><th></th><th>Galvanised copper</th><th>Cast copper</th></tr>
<tr><td>W100</td><td>

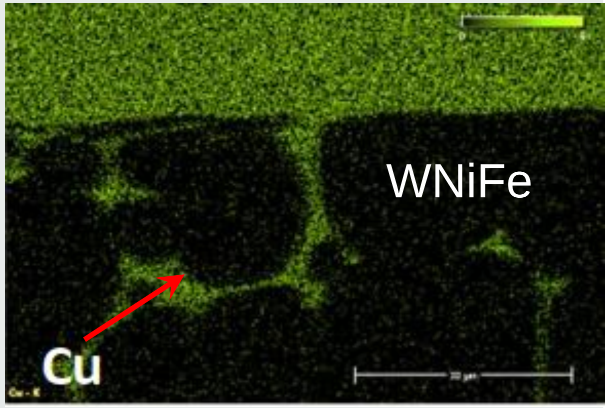
Initial issue
Local lack of bonding
Resolved for series

</td><td>



Cracking of W limits tile size to 40 mm</td></tr>
<tr><td>WNiFe</td><td>



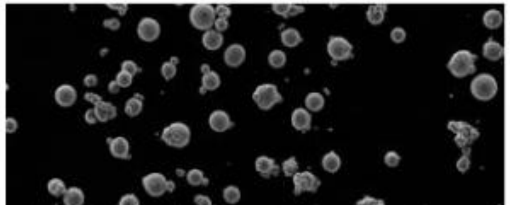
No diffusion of Cu in WNiFe matrix</td><td>

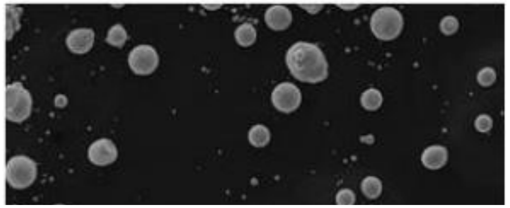


Diffusion of Cu in WNiFe matrix</td></tr>
</table>

Additive manufactured CuCrZr

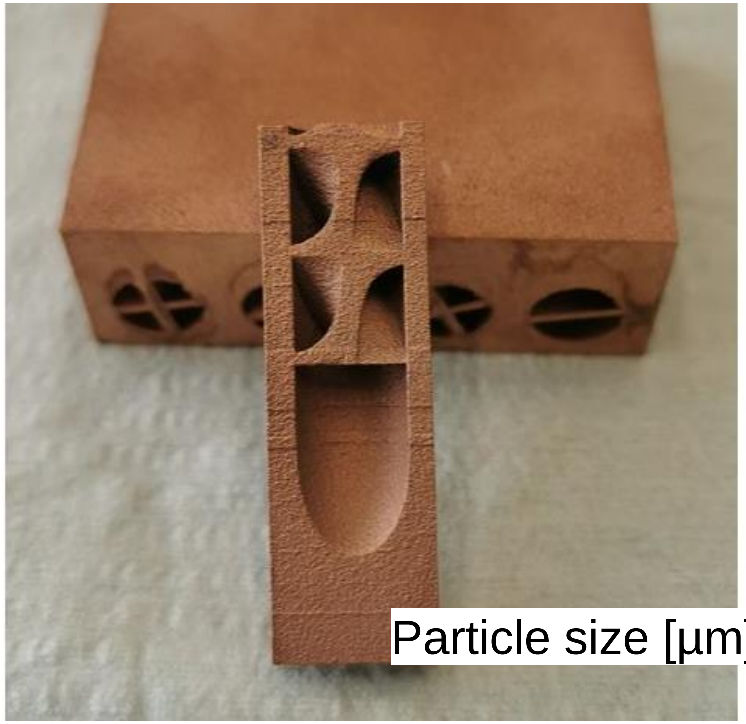
- **Additive manufacturing CuCrZr**
  - *Rationale: Increased geometric design space, single manufacturing process*
  - 4 commonly available powders compared ➔ all four applicable
  - Integrated swirl tape feasible
  - Density 99.8 %
  - He leak tightness 10^{-9} mbar·l/s for wall thickness of 1-3 mm
    - First 28/28 samples successful with and without heat treatment



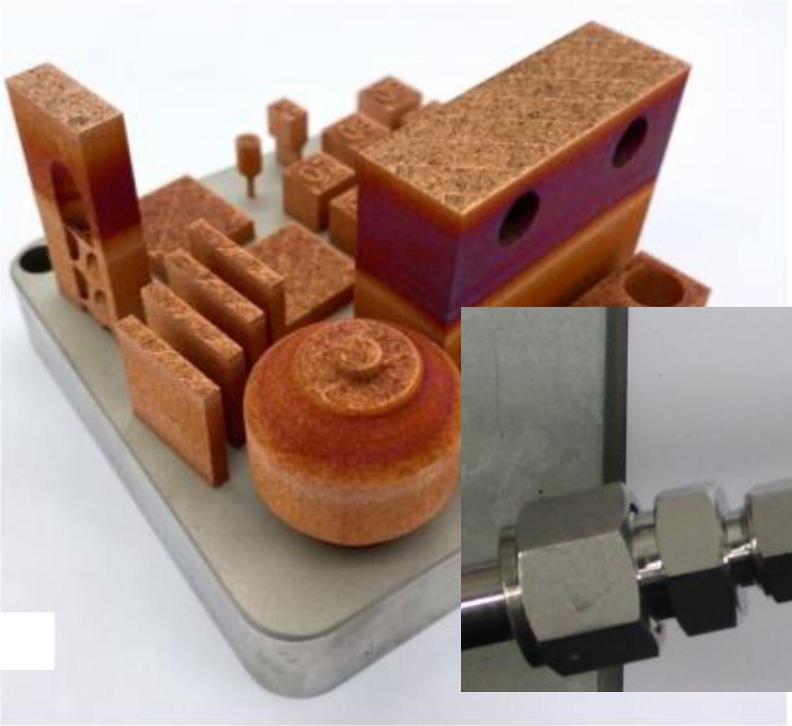


Volume fraction [%]

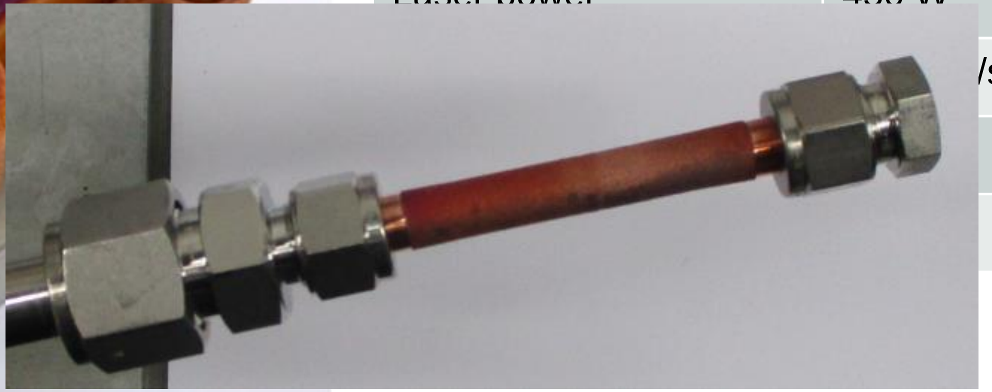
30
25
20
15
10
5
0



Particle size [µm]

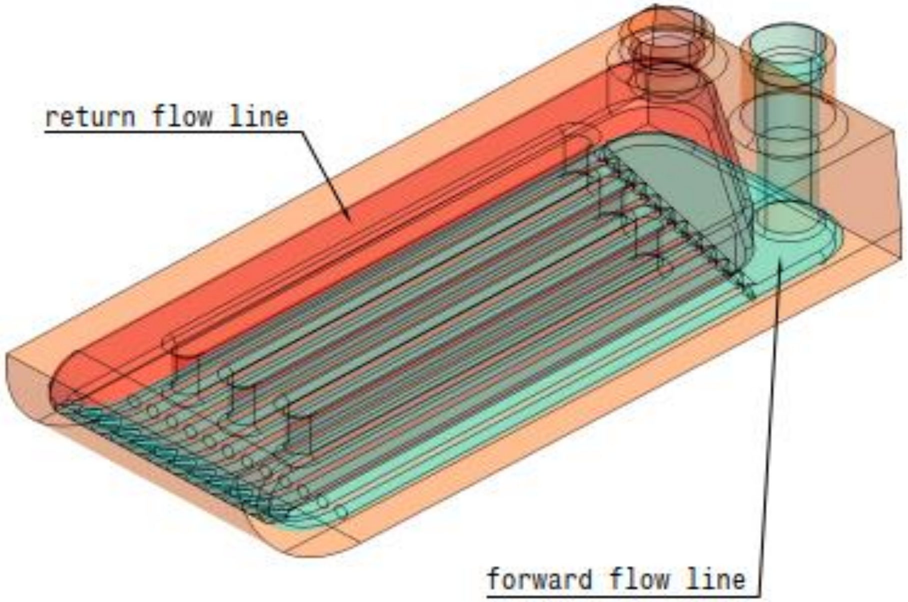


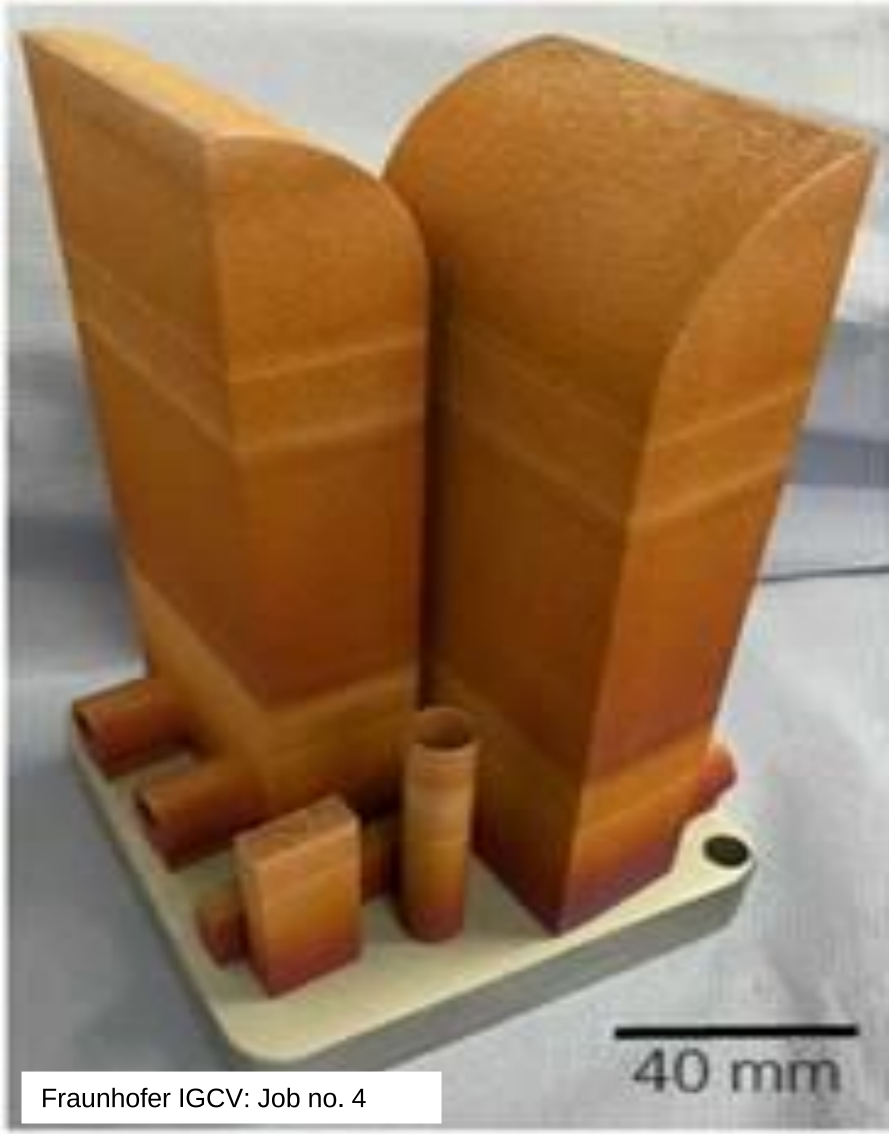
Process parameters	
Laser power	450 W
	/s



Small scale heat sinks with cooling channels

- **Issues with de-powdering**
  - Mechanical shaking / Cyclic nucleation
  - Pressurized liquid flow through channels
    - Measuring powder rests in the liquid
    - First 2 heat sinks of interrupted print job fully blocked
      - Hirtisation not applicable if flow is fully obstructed
    - Next 2 heat sinks cleaned without issues
- **CT-scan mandatory**
- **He leak test mandatory**
  - 1 leak found near base plate ➔ design & process improvements
  - 1 heat sink leak tight





Fraunhofer IGCV: Job no. 4

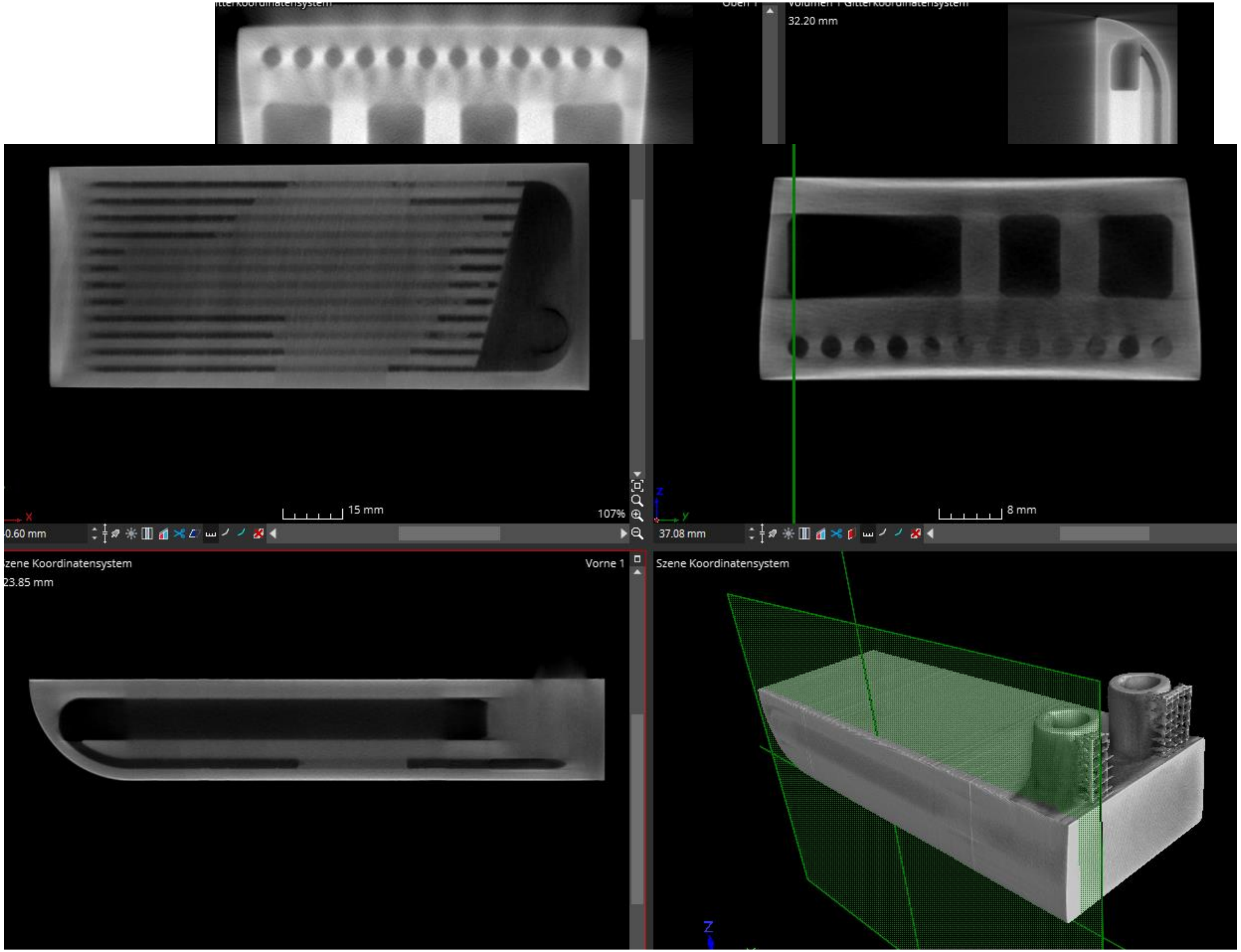
CT scan of heat sinks

General

- **80 µm resolution**
- **Max size: ~900 x Ø600 mm**
- **Boundaries suffer from reflections**
  - Line scan with higher contrast at boundaries possible
- **Cost depends on resolution**

Objective

- **Detection of remaining powder**



Interrupted print job

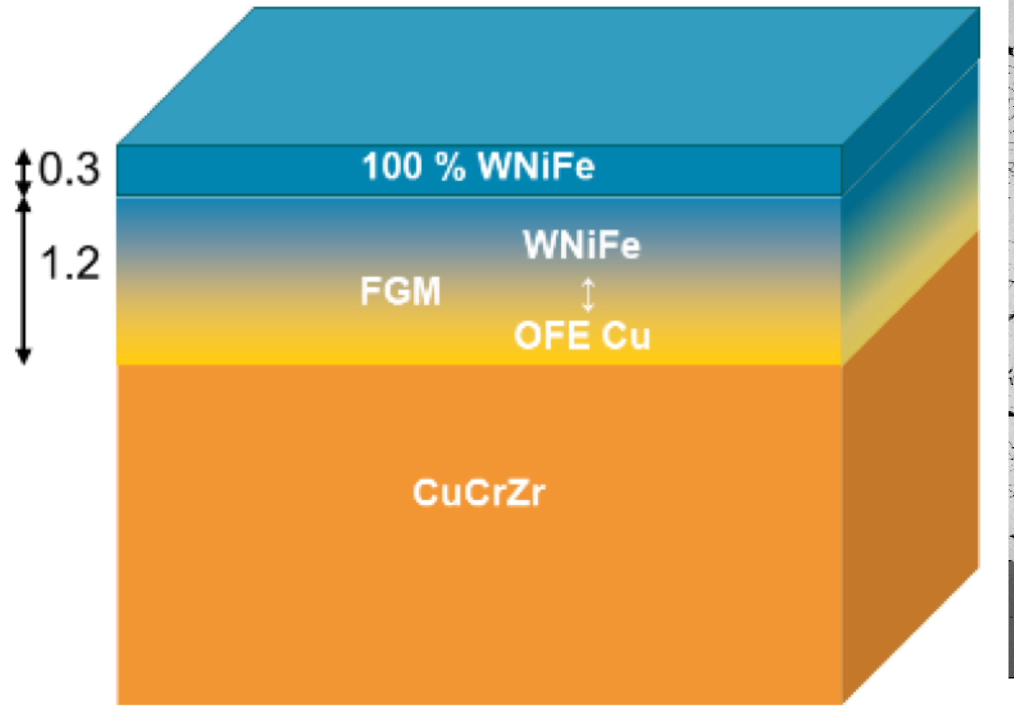
- **Powder remains clearly visible**

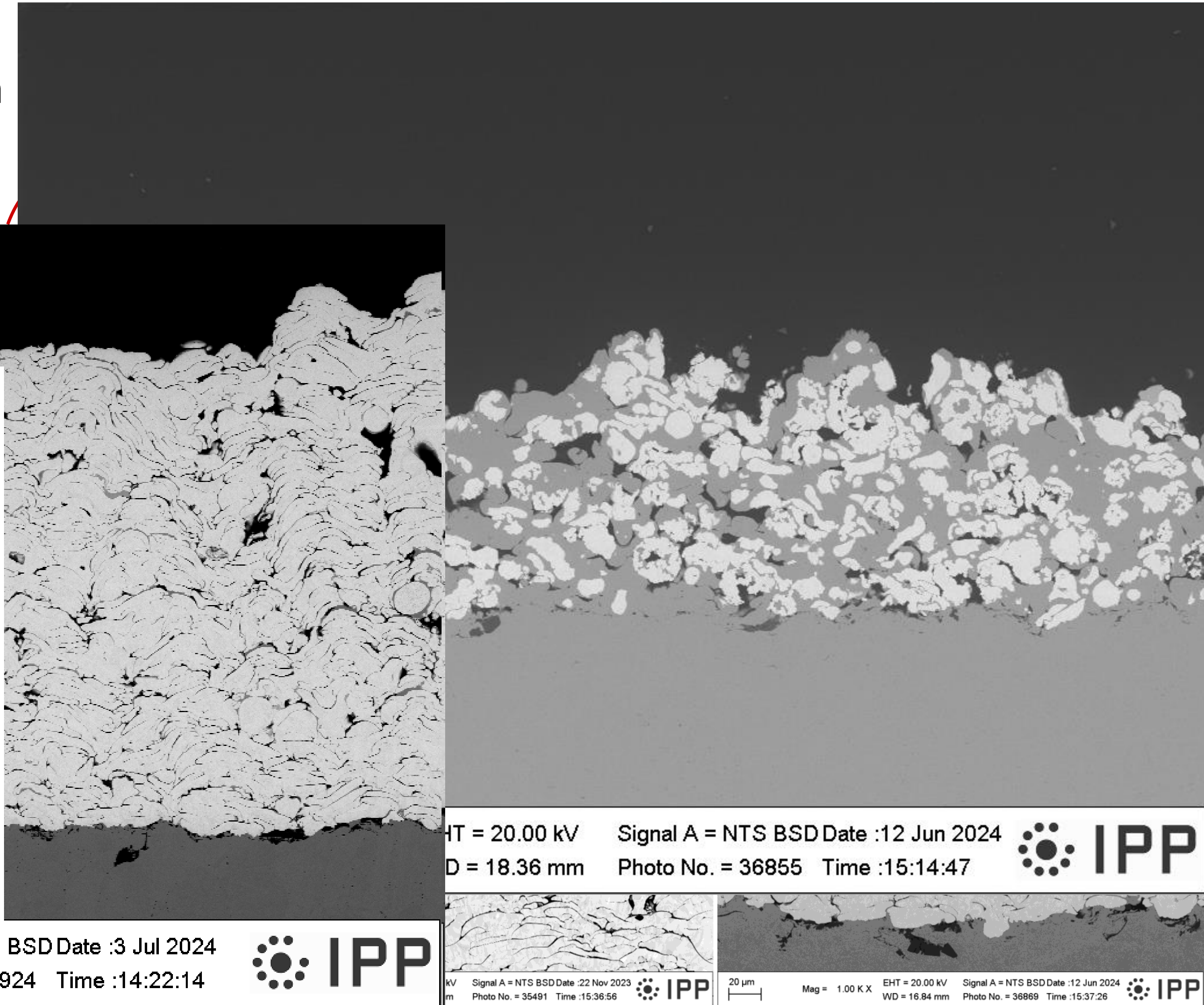
Smoothly run print job

- **No powder remaining**

Coating

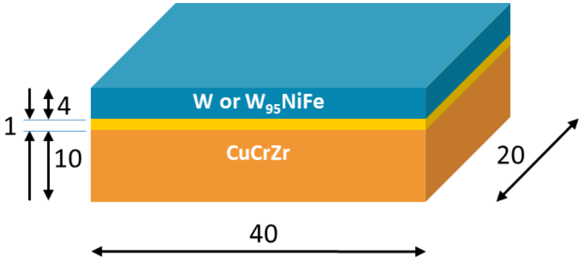
- **Low pressure plasma spraying**
  - Small scale: substrate of 73x20x10 mm
  - W or WNiFe on OFE Cu
    - Very low porosity

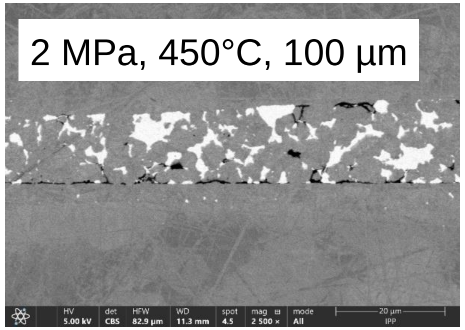


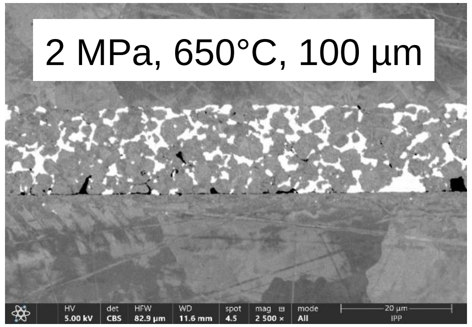


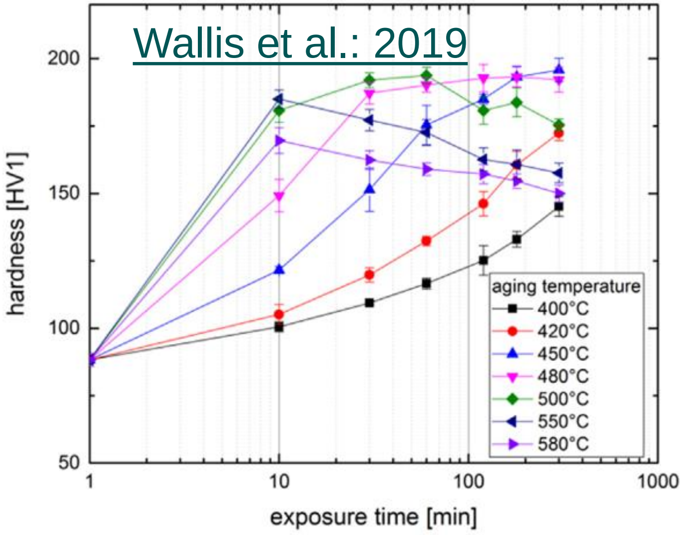
Brazing sandwich tiles onto heat sink

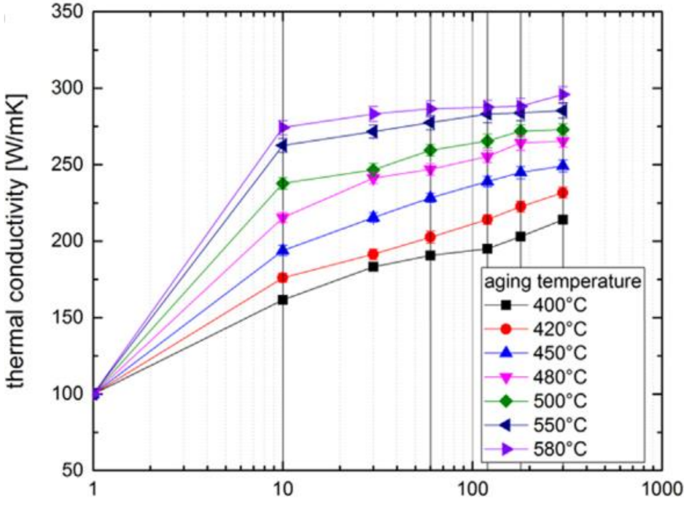
- **Aim**
  - Bond OFE Cu to CuCrZr with reduced diffusion welding parameters:
    - low pressure (~ 0.5 MPa) to avoid need for external contact pressure
    - low temperature (< 580 °C) for short time (< 30 min.) to ensure CuCrZr properties
  - Moderate tolerances: 50 µm planarity / parallelism / Rz5
  - High thermal conductance
  - Sufficient strength to survive thermal stress from nearby W-Cu interface
- **3 types of paste with µm or nm Cu particles under investigation**
  - 1x µm particles
    - 2 MPa, 650°C, 100 µm thickness shows promising result
    - No compression or 450°C or 250 µm thickness not satisfactory
    - including Ag ➔ not compatible with W7X
  - 1x µm particles but poor viscosity ➔ only feasible with preprint process
  - 1x nm particles with better viscosity and no Ag ➔ next test





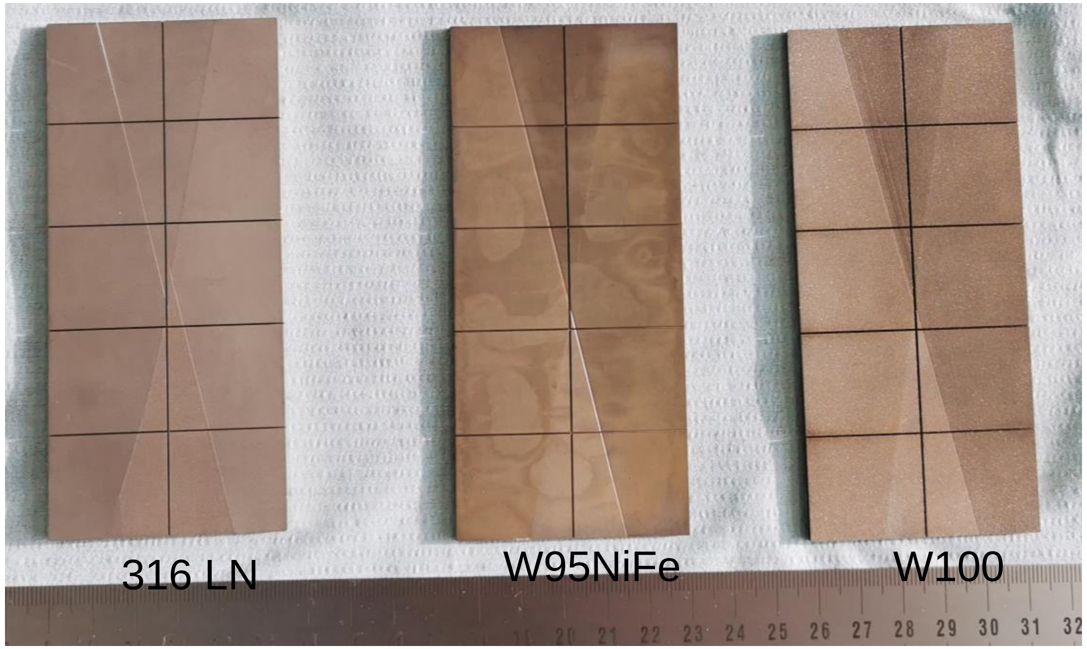


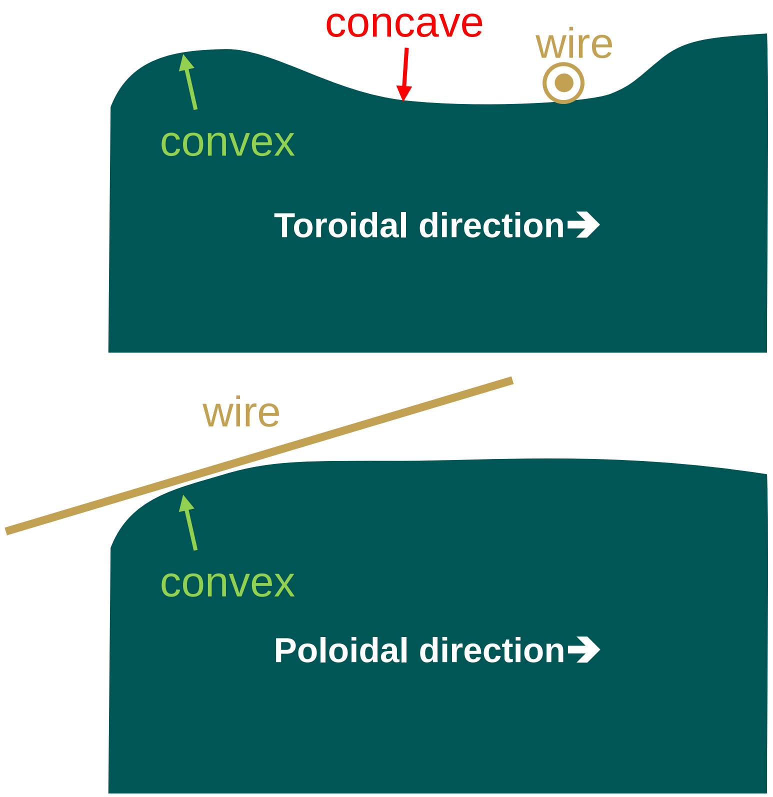




Machining the plasma facing surface

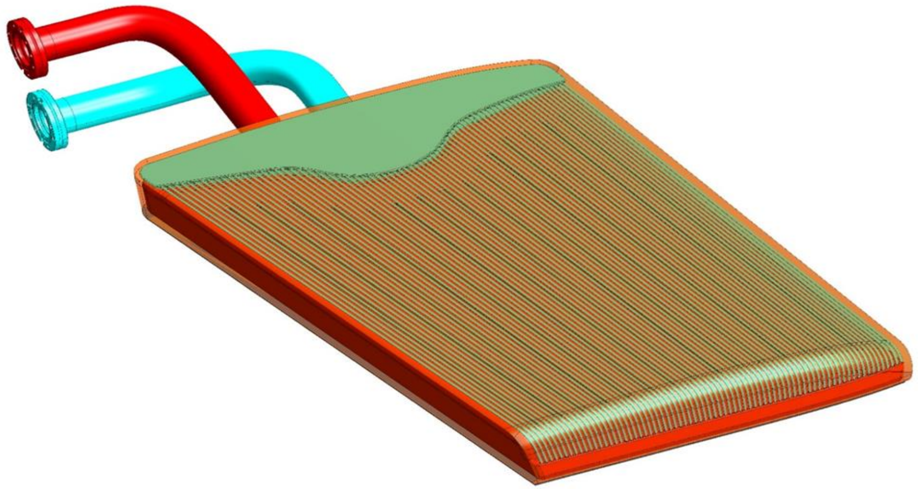
- **Machining by wire erosion and milling**
  - Trials with same surface shape as most complex CFC target elements successful
  - WNiFe easier to machine than pure W
  - Machined surface gets contaminated by wire constituents: requires cleaning
- **Straight wire used for wire erosion limits surface shape**
  - Toroidal curvature will be both convex and concave
  - Poloidal curvature must be flat or convex

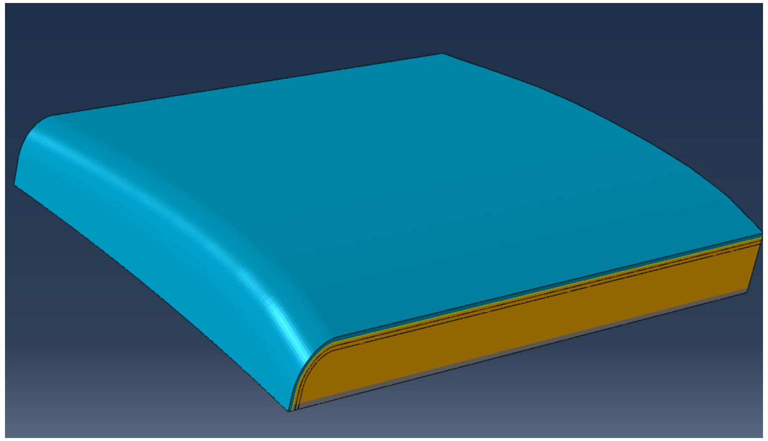


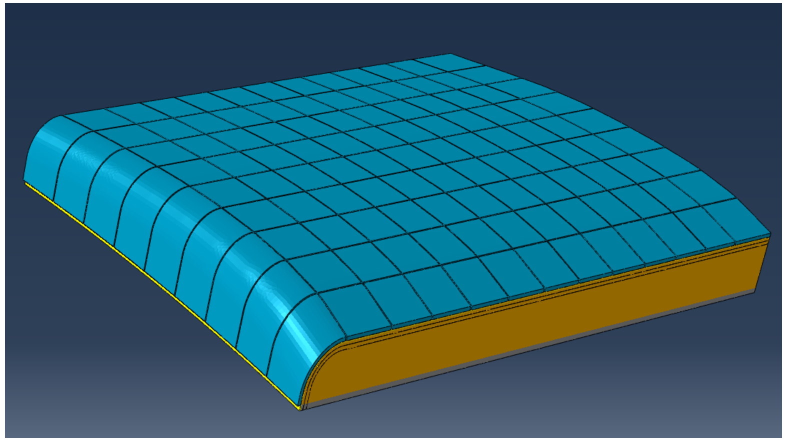


Resume

- **Technology qualification for divertor**
  - Focus on simplifying and minimizing manufacturing and inspection steps
    - Additive manufactured CuCrZr heat sink
    - Plasma facing surface
      - W-based coating or
      - Mosaic of W-based sandwich tiles brazed onto CuCrZr
  - First qualification results very promising
    - Leak tightness of heat sink / low porosity of coating / high quality bond W/Cu and WNiFe/Cu
    - HHF tests pending
  - Pursued heat load on divertor edge tile and baffles seems feasible







Outlook

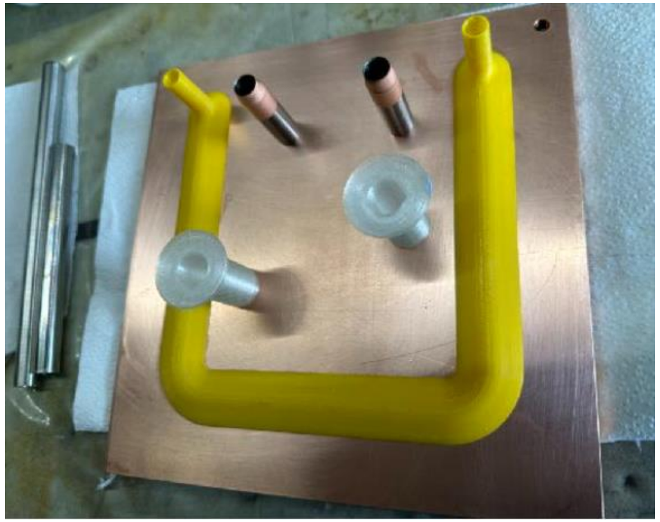
- **2024**
  - Manufacturing sandwich tiles 40x20x(4+10) mm
    - W/Cu and WNiFe/Cu: galvanic, cast, diffusion welded
    - Cyclic HHF tests to determine best bond between W/Cu and WNiFe/Cu
  - Triple product HHF samples 40x20x(4+1+10) mm
    - Brazing trials Cu on CuCrZr
    - Best sandwich tiles brazed on CuCrZr
  - Additive manufacturing small series of A4 size CuCrZr heat sinks by 3 loan manufacturers
    - Optimization of cooling channel geometry (by CFD)
    - Improvement of technology of galvanic connection to stainless steel pipe
    - He leak tests, hydraulic test, critical HHF test
  - Coated HHF samples 40x20 mm
    - Low pressure plasma coating 0.3 mm W or WNiFe on 10 mm Cu
    - Low pressure plasma coating 0.3 mm W or WNiFe + 1.2 mm FGM on 10 mm CuCrZr
    - Cold gas coating 0.3 mm W or WNiFe + 1.2 mm FGM on 10 mm CuCrZr

Outlook

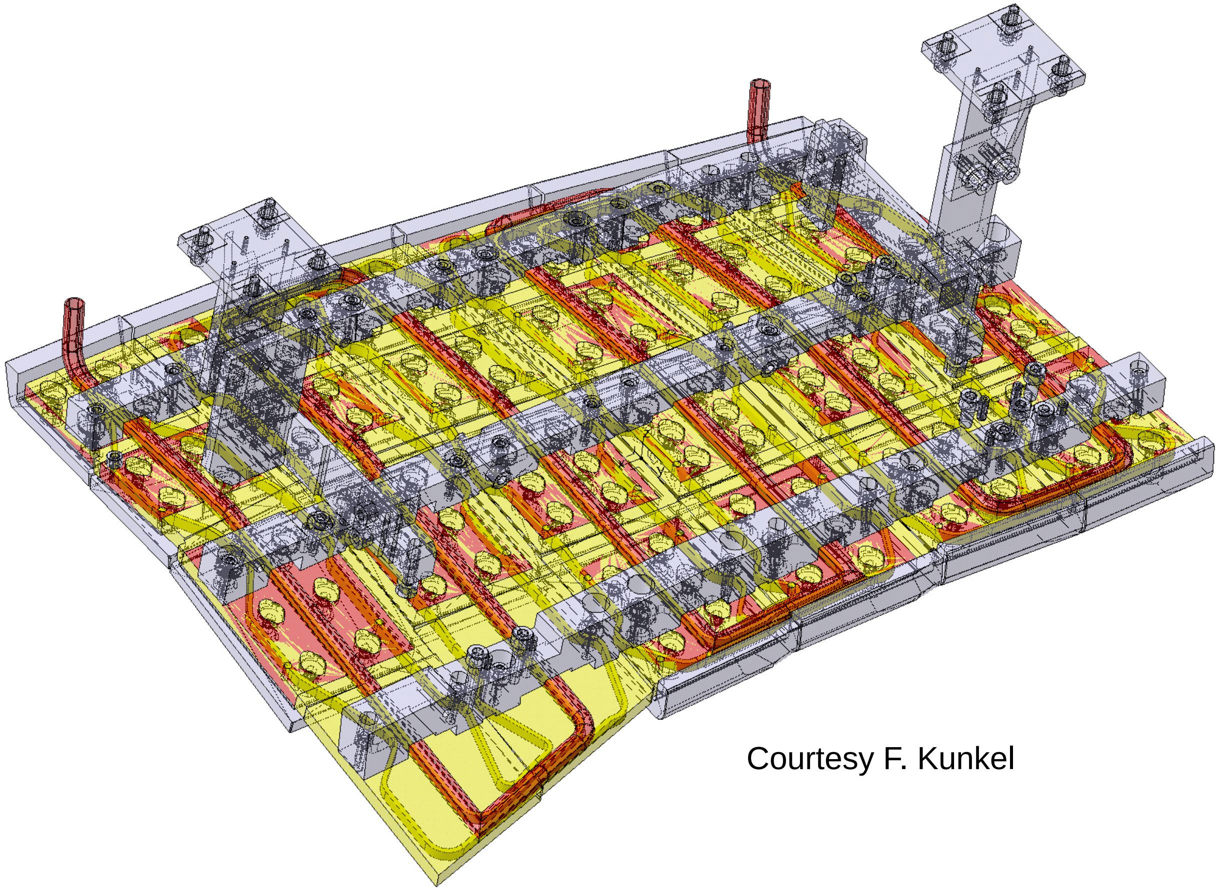
- **2025**
  - Brazing mosaic of sandwich tiles onto heat sinks
  - Coating of heat sinks
  - HHF testing of brazed and coated heat sinks
- **2026**
  - Upscaling qualification to full size (A2 format)

Baffle reinforcement and simplification

- **Stainless steel meander with partially brazed CuCrZr heat sinks replaced by single CuCrZr block**
  - Water channels machined and sealed by galvanisation
  - First 3 samples He leak tight
- **6x larger cooling area than in current design**
  - No need for steel support structure
  - Braze with high thermal stress avoided

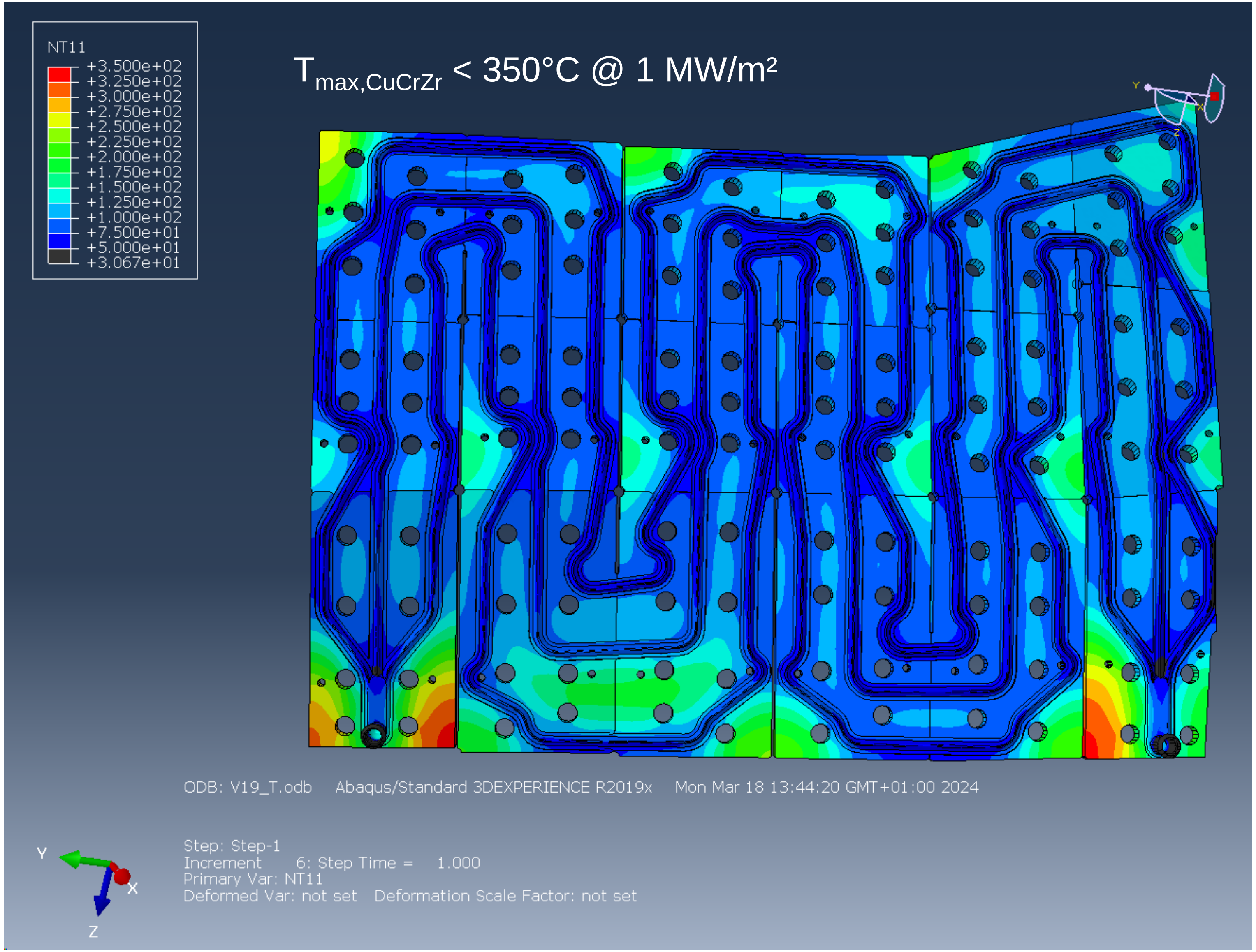


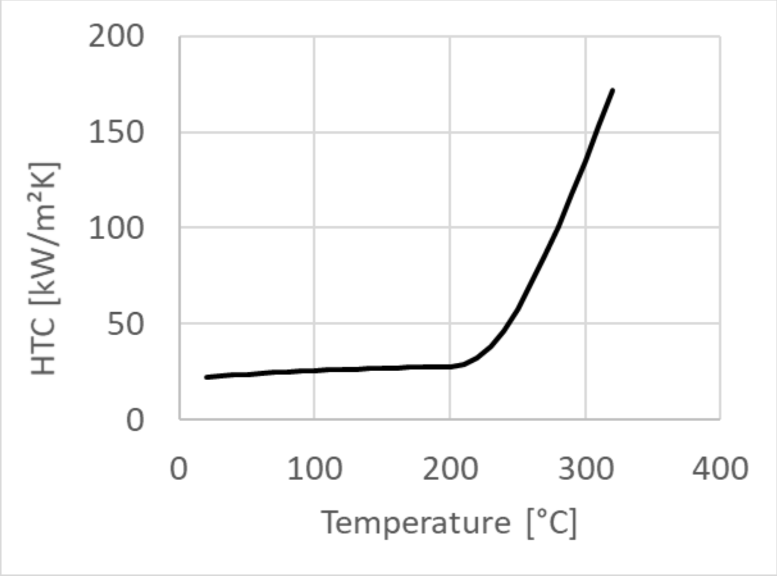
Size ~0.4 x 0.8 m

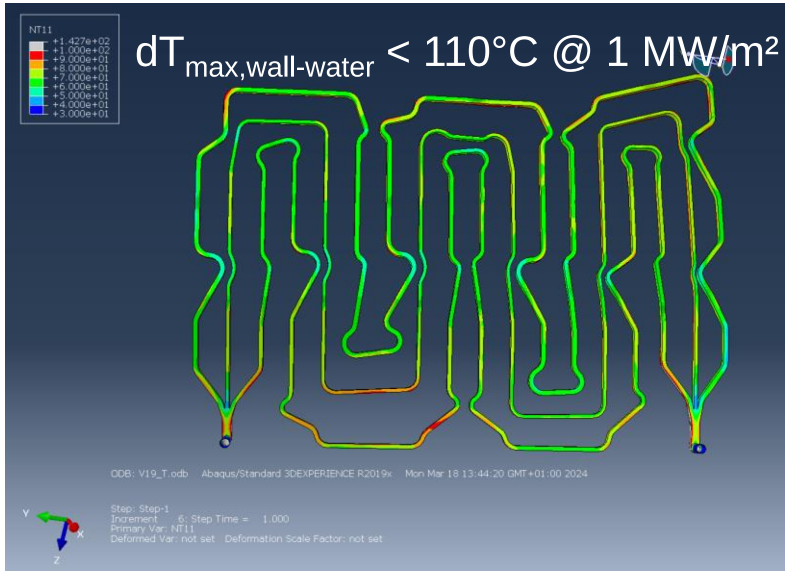


Courtesy F. Kunkel

Thermal results new baffle design

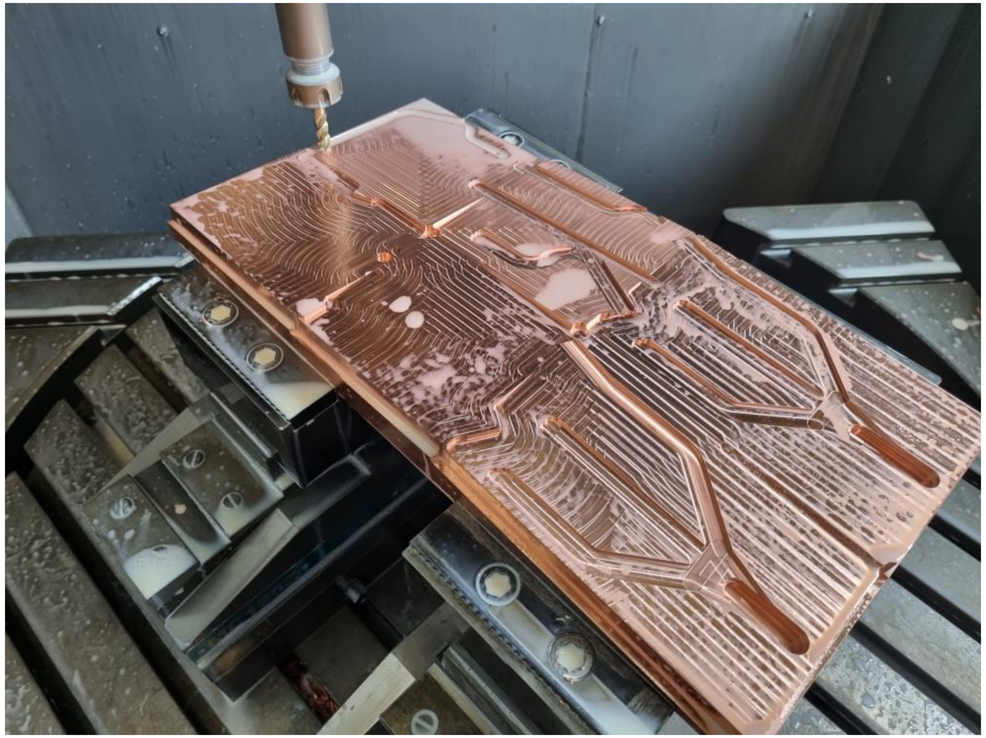






Manufacturing of 1/3 module

- Leak tightness shown
- 160°C /30 bar test pending
- Hydraulic test pending
- HHF test pending



Resume and outlook baffle technology

Resume

- **1 MW/m² over entire plasma facing surface feasible**
  - Locally (2 tiles) 2MW/m² acceptable, limited by water temperature rise
  - Also suitable to improve heat load capacity of TM56h
- **Cost of 14 k€ for manufacturing and material**
- **Robust cooling plate allows for in vessel mounting onto support structure**

Outlook

- **Technology for galvanic connection to stainless steel to be improved**
- **Hydraulic and thermal test**
- **Improvement of bolting technology of tiles open to avoid galling (“fressen”)**
  - W-coated graphite tiles
  - W-coated heat sink if coating process for divertor will be successfully qualified
    - W-coated Cu plates could also be used to replace graphite tiles of heat shields
- **Further channel geometry enhancement possible if bolt pattern is changed**

Back up slides navigator

Main slides

Divertor concept W7-X

Outline

Divertor ⇔ baffle

Particle exhaust issues

Tools

Technology qualification

Target module concept

Diffusion welding / machining

Additive manufacturing

Baffle concept

Outlook

Backup slides

Particle exhaust need

Wall source and sink vs pumping

Thermal stress

Thermal and deformation FEM results TM1h

Parametric FEM thermo-mechanical results

Current thermal overload issues

Leading edges

W and WNiFe

Galvanic heat sink

Divertor type strategy

- Current divertor: CFC-based – cooled – open – well diagnosed
- W-based – cooled – open – well diagnosed
- C- or W-based – (un)cooled – closed – limited diagnosed
- Reactor relevant divertor: W-based – cooled – closed – well diagnosed

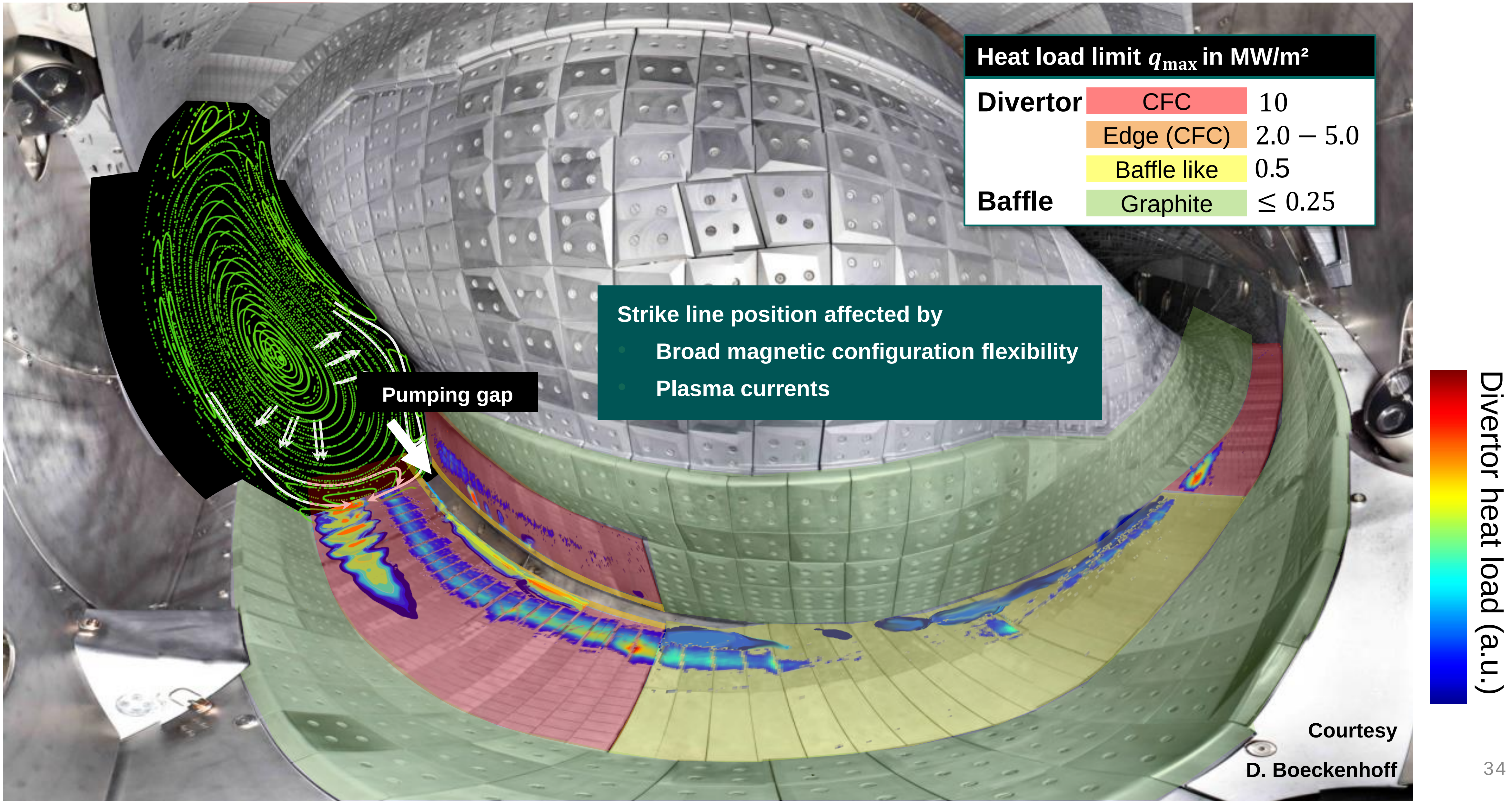
Background

- **2020 TWG W7-X strategy 2030 identified need for transition to all metallic PFC in W7X**
  - New design of W-based cooled divertor required
    - Keep current cooling water supply
    - Respect weight and space restriction
  - Option of uncooled divertor was rejected
  - Option of in-situ coating of CFC divertor was shifted as parallel research program to FZJ
- **2021 EUROfusion funded project was awarded for W-based target element development**
- **2022 W-Based divertor project was approved in RSR**

W based divertor project

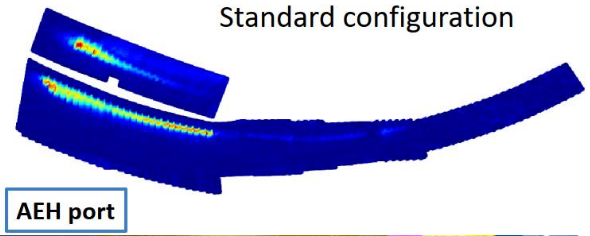
- **Goal**
  - Transition of W7-X to reactor relevant plasma facing materials
    - To prove that the stellarator concept can meet the requirements of a future carbon-free fusion reactor
    - By demonstrating high-performance, steady-state HELIAS operation
  - Include lessons learnt from manufacturing, installation and operation

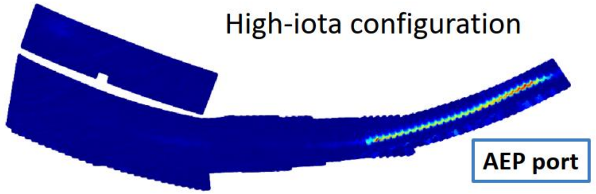
Current divertor layout Wendelstein 7-X

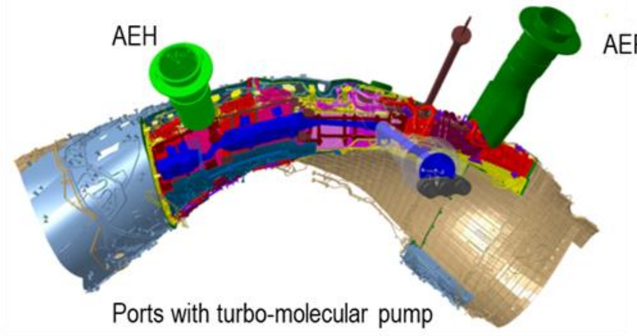


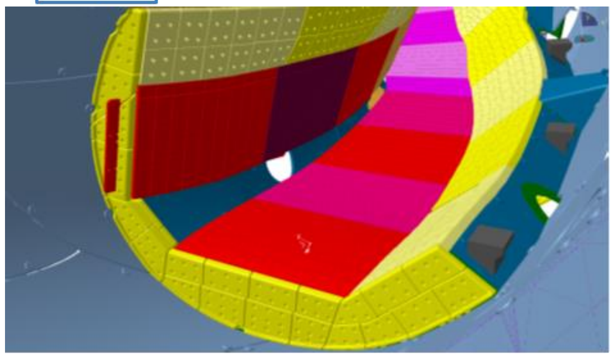
Particle exhaust issues

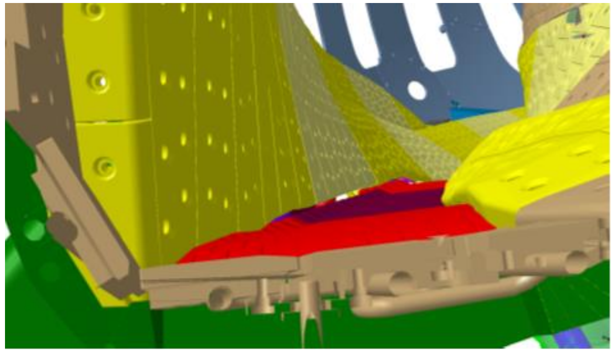
- **Large pumping gap (Standard) less efficient than small gap (High iota) in OP1.2**
  - Standard configuration: $p_{AEH} = 0.4 \cdot 10^{-3}$ mbar. Ratio p_{AEH}/p_{AEP} = 1-3
  - High iota configuration: $p_{AEP} = 1.0 \cdot 10^{-3}$ mbar. Ratio p_{AEP}/p_{AEH} = 13-20
- **Need to change geometry of large pumping gap and orientation of pumping gap panels**
- **Demand to improve heat load capacity of edge tiles to allow strike line (recycling zone) close to pumping gap**

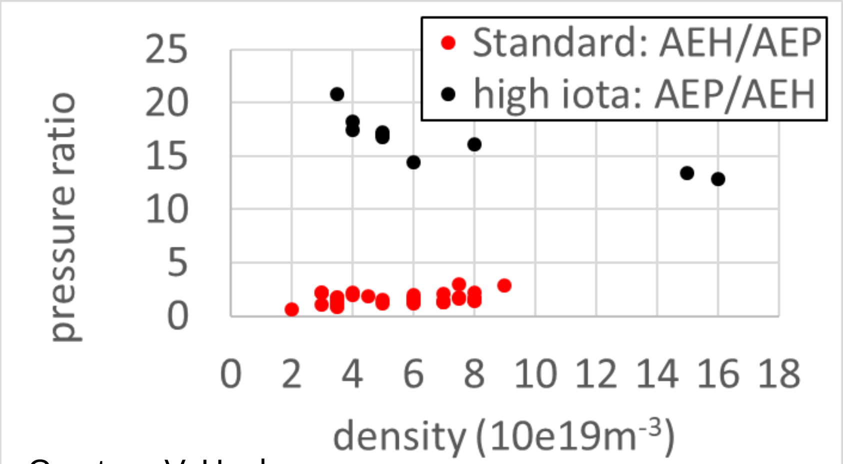












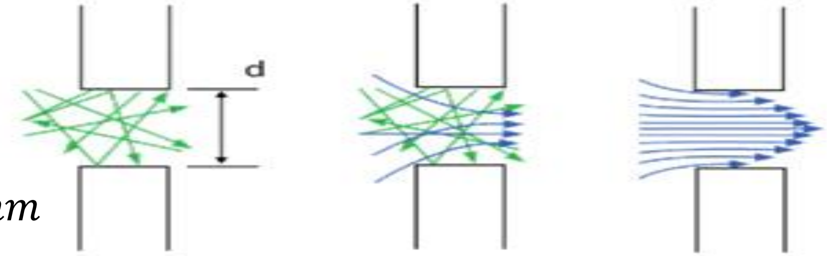
Courtesy V. Haak

Exhaust challenge

- **Reactor perspective – He concentration shrinks operational space**
- The global He particle confinement time $\boldsymbol{\tau_\alpha^*}$ must be small relative to the energy confinement time $\boldsymbol{\tau_E}$

$$\boldsymbol{\rho = \frac{\tau_\alpha^*}{\tau_E} < [10 - 15]}$$

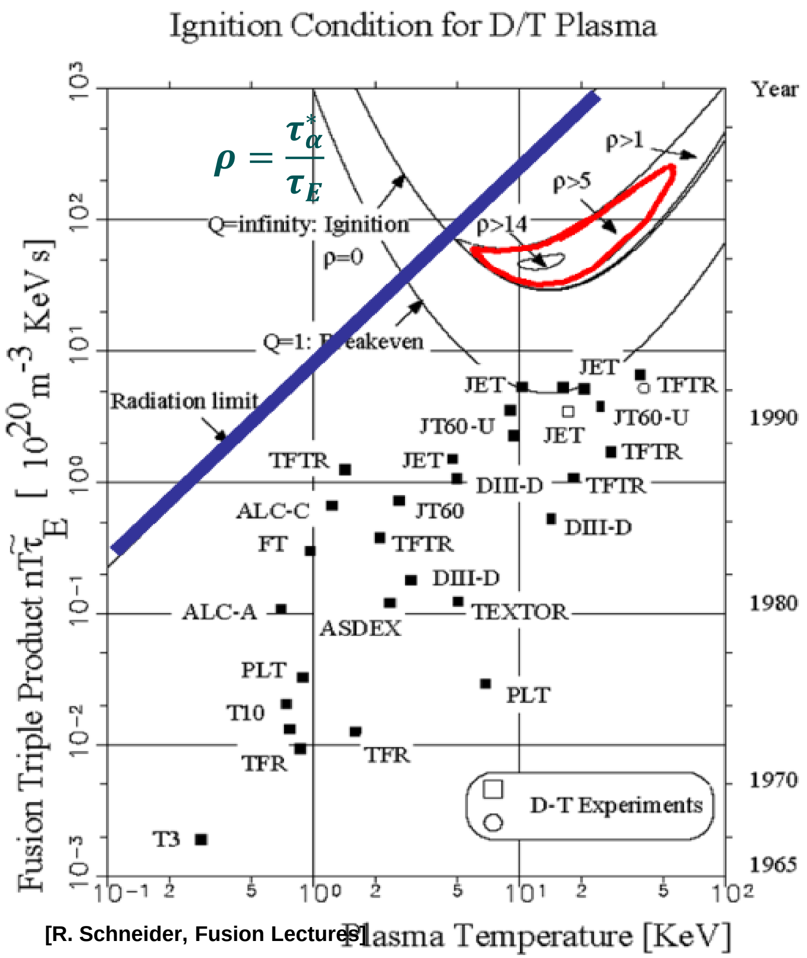
- **Operational perspective – Density control**
  - Only neutrals can be removed
  - Role of target is to intercept, neutralize and exhaust particles
    - Large exhaust relative to wall source/sink improves control



$$Kn = \frac{\bar{l}}{d} \quad d_{PG} = \sim 90\ mm$$

	Molecular flow	Knudsen flow	Continu
Knudsen number Kn	> 0.5	0.01 - 0.5	
	Best of OP1.2		goal
Knudsen number Kn		0.5	0.01
free path leng	2	0.045	0.0009
p_{pg} [Pa]	0.12	0.82	40
$\bar{n}_e$ [10^{19} m^{-3}]	13	135	6569

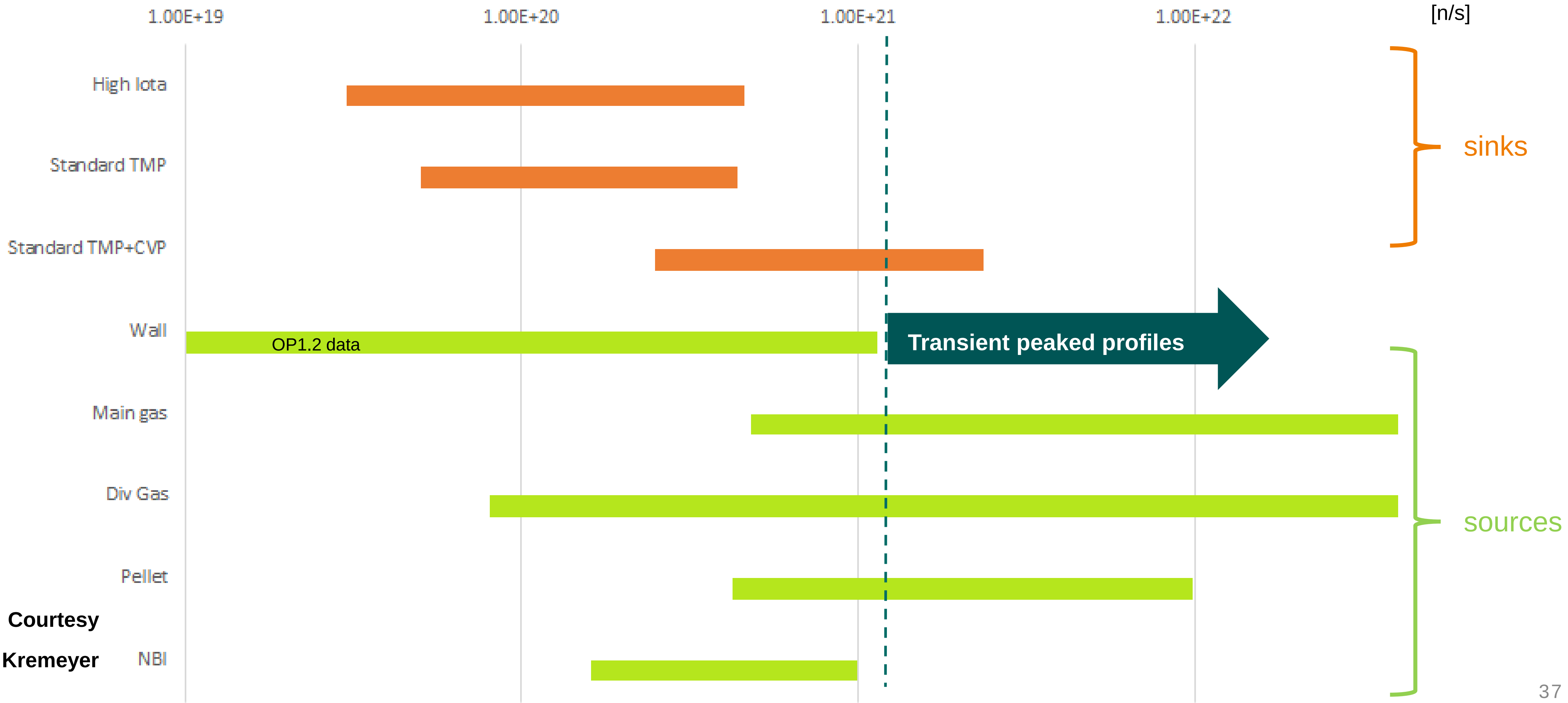
Asdex upgrade 0.5-1.5 Pa
Density must be improved by at least an order of magnitude



[R. Schneider, Fusion Lectures]

Exhausts limits profile shaping

- Flat profiles ➔ Particle exhaust = Wall source
- Peaked profiles ➔ Particle exhaust = Core + Wall source



Courtesy

Th. Kremeyer

Thermal stress at perfect bond W-Cu

Perfect thermal bond implies perfect mechanical bond W-Cu

In steady state @ 10 MW/m²: $\Delta T_{channel}$ = ~150 K, ΔT_{Cu} = ~30 K/mm, ΔT_W = ~100 K/mm

Bending stress in W and Cu

- **Maximum based expansion mismatch $\Delta\varepsilon_T = \varepsilon_{W,int} + \varepsilon_{Cu,int}$**
- **$\Delta\alpha_T$ = 17-5 = 12 µm/mK ➔ $\Delta\varepsilon_T$ = 0.2% @ ΔT_{int} = 170 K**
- **Gradual increase from zero at free end, gradient defined by yielding of soft copper interlayer**

Strain singularity at free end of W-Cu interface

- **FEM results are mesh dependent**
- **All strains are proportional to ΔT**

Delamination stress peak at free end of interface

- **Tensile stress at ΔT < 0 for W-Cu combination**
- **Limited by yielding of soft copper interlayer**

Shear stress along interface

- **Limited by yielding of soft copper interlayer**

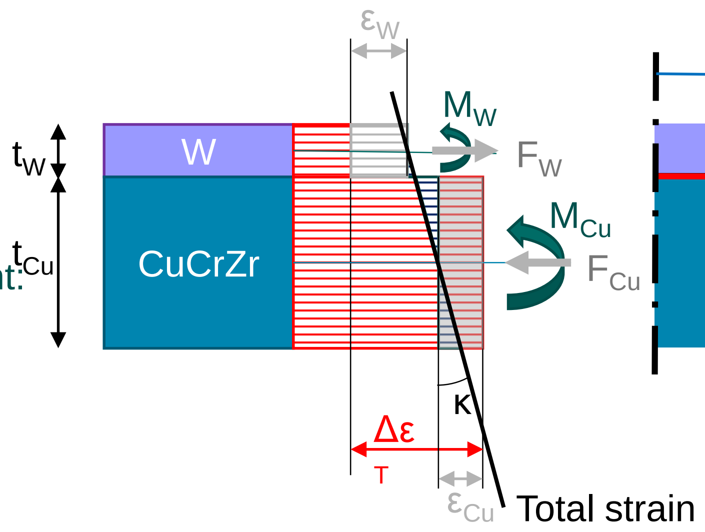
Thermal strain

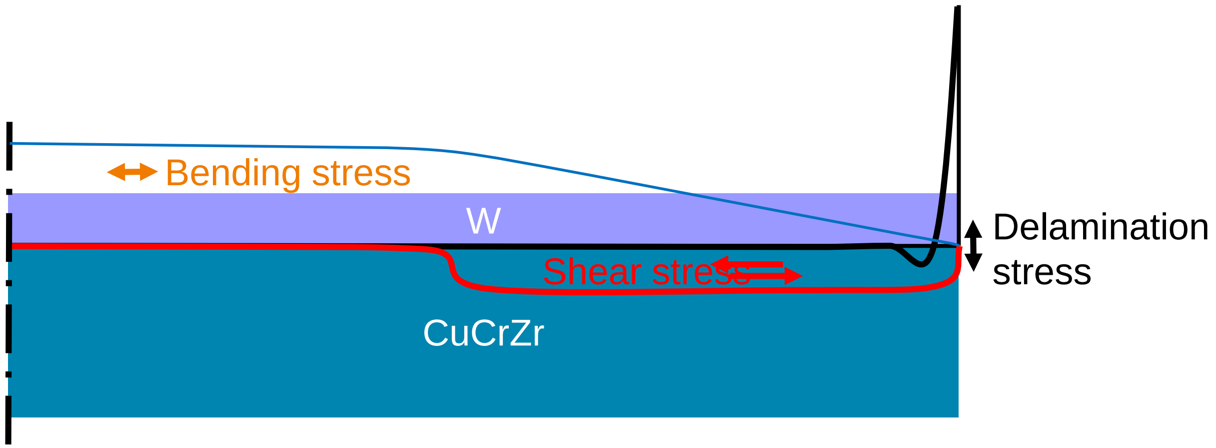
Mechanical strain causing a force:

$F_W + F_{cu} = 0$

Mechanical strain causing a moment:

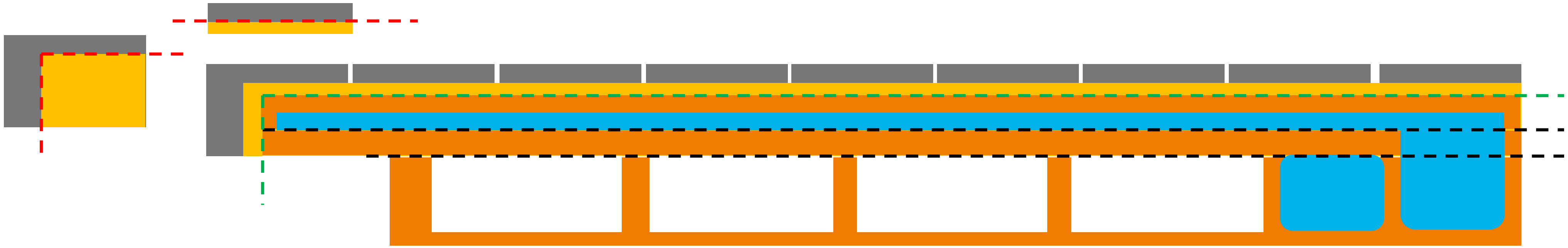
$M_{cu} + M_W + F_W(t_w+t_{Cu})/2 = 0$





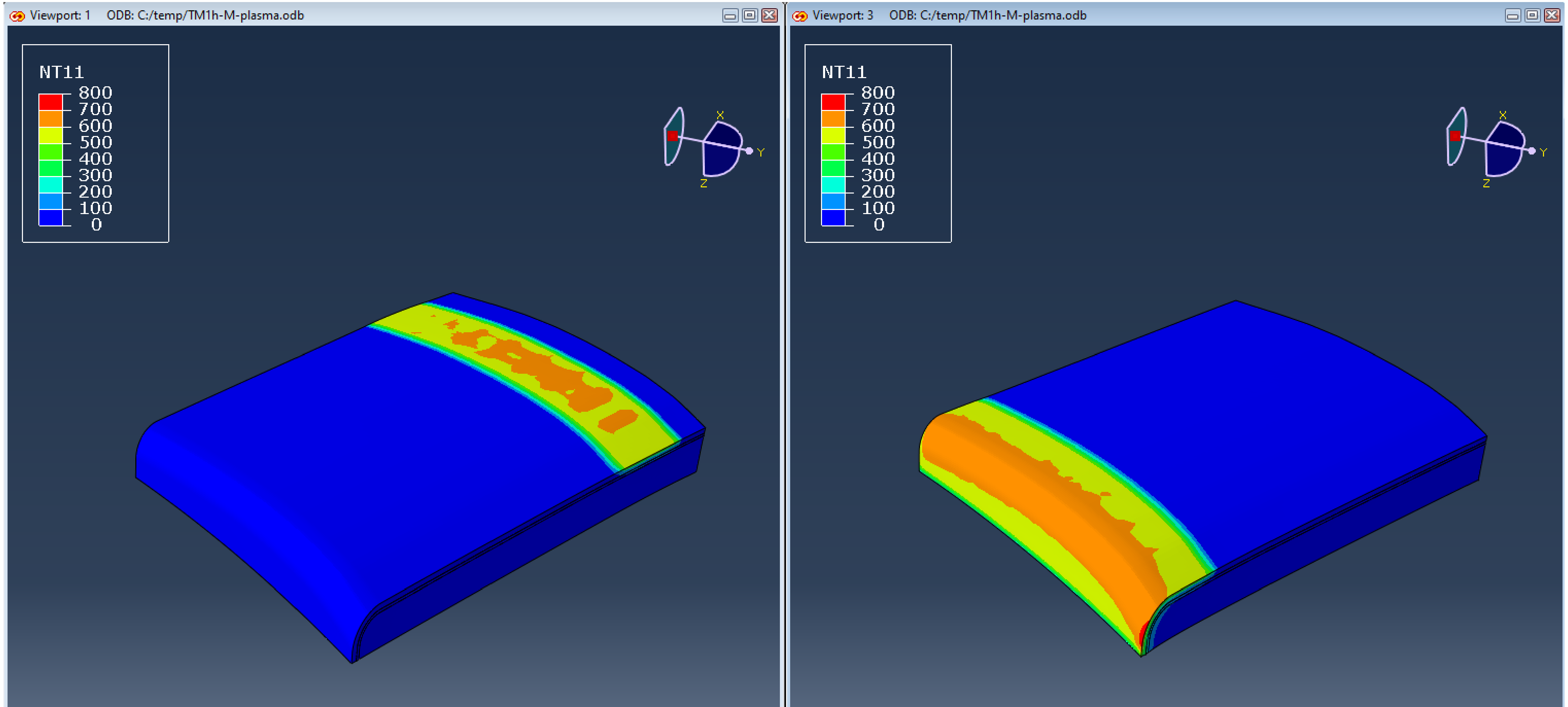
Design approach with HIP

- **Flat tile following curvatures of magnetic field at plasma facing side**
- **CuCrZr heat sink with integrated manifold**
  - Flat plates with machined half sides of water channels
  - Stiffeners at cold side to minimize thermal curvature
  - Threaded channel surface to mimic swirl
  - Diffusion welded with flat weld interface (alternatively brazed)
  - Plasma facing side machined after welding to match optimized plasma facing geometry
  - Alternatively 3D SLM printed heat sink
- **3 mm W or W alloy tiles with 1 mm soft copper interlayer**
  - Galvanized copper (stress free at room temperature, delamination stress is compressive in heating up)
  - Cast copper (stress free at molten copper temperature of 1080°C, delamination stress is tensile in cooling down)
- **HIP process to join heat sink to copper interlayer**
  - Allowing for wavy plasma facing surface shape and L-shaped edge tile L-shaped edge tile
    - L-tile avoids strain singularity at free end of interface where peak temperature occurs
  - Alternatively no HIP with modified plasma facing surface to avoid need for edge tile
  - Alternatively no HIP with separate edge tile (e-beam welding) but lower design load
- **Final W machining after HIP**



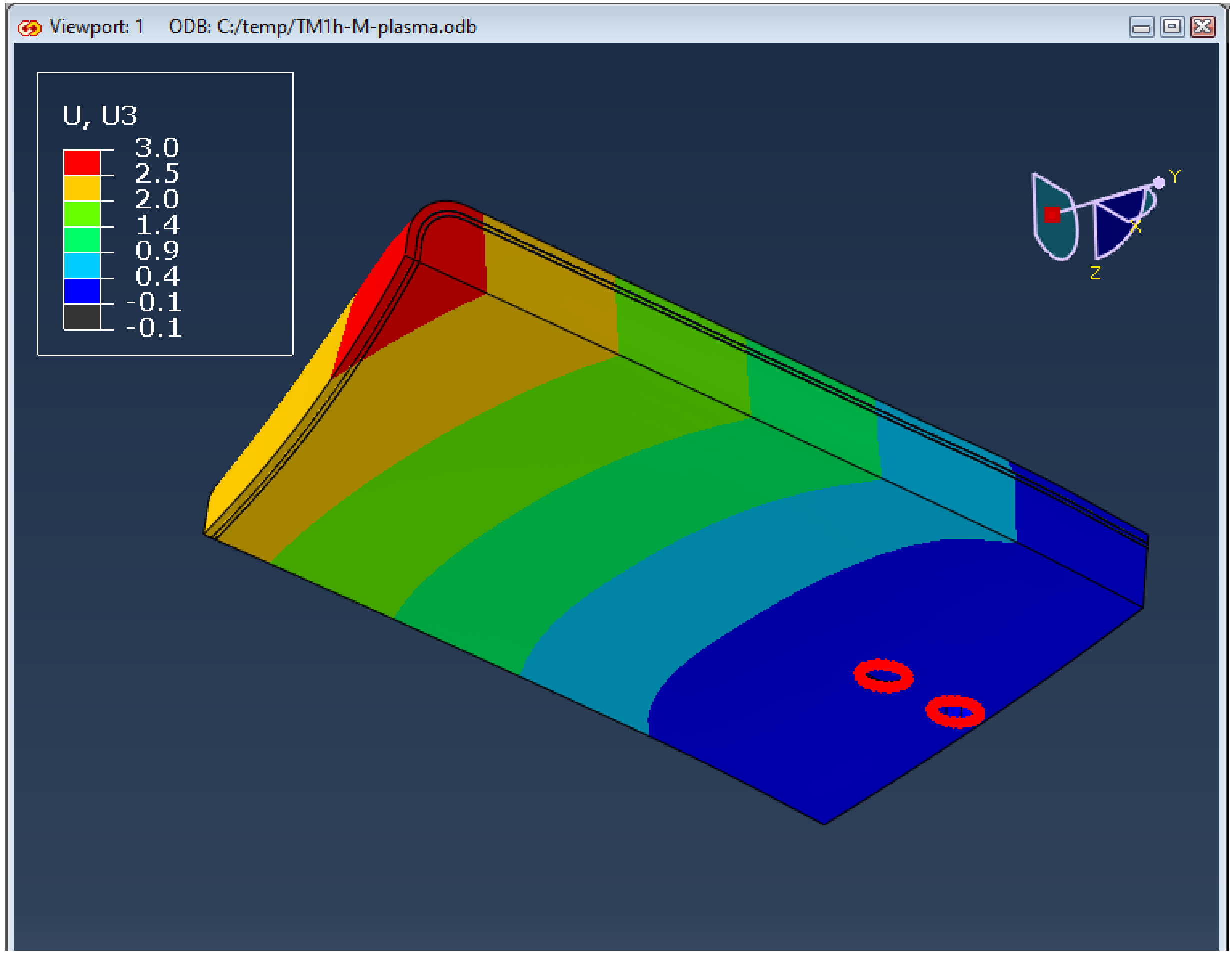
Temperature during plasma operation

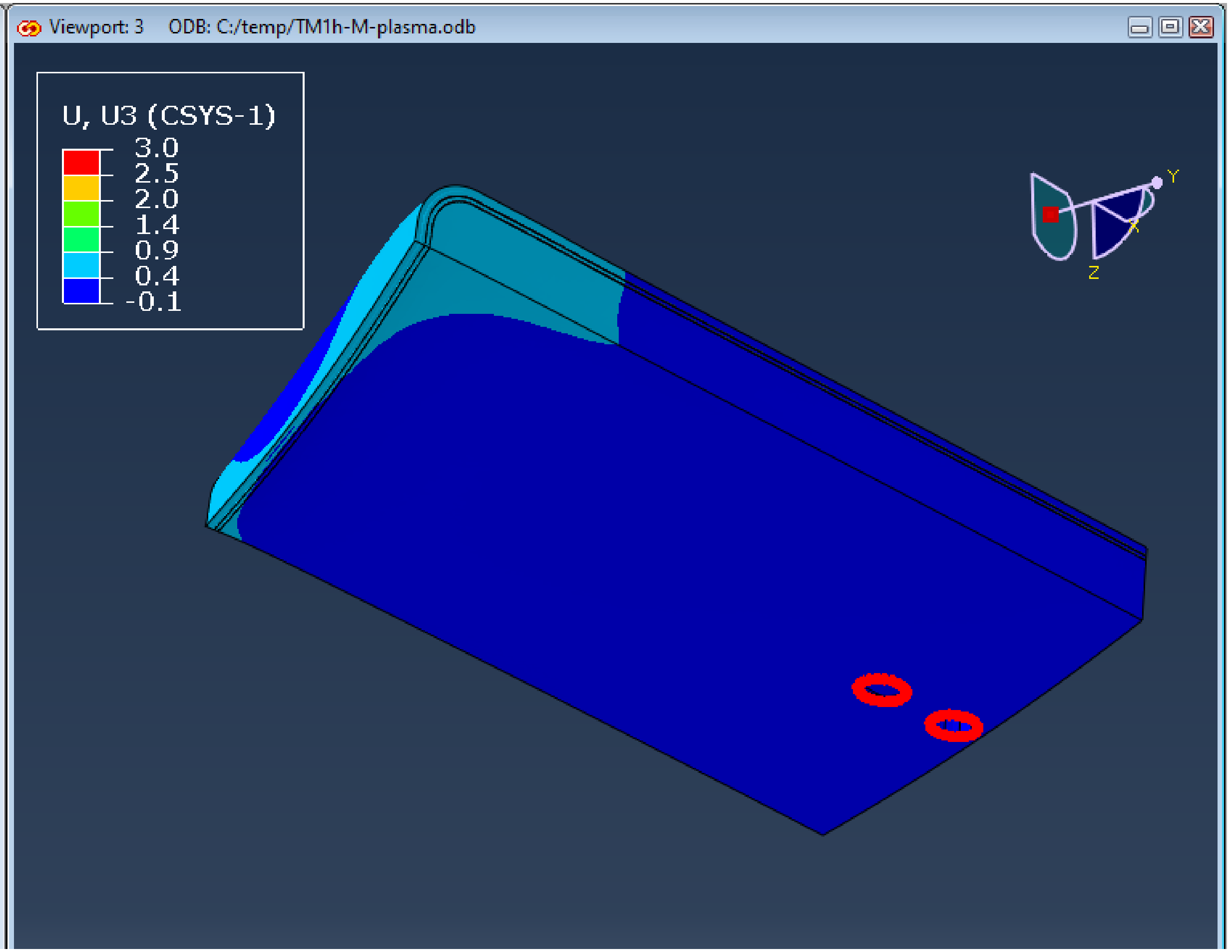
- 10 MW/m² @ 2 toroidal strike lines of 100 mm + 500 kW/m² radiation
- Conductance of 50 kW/m²K along cooling channels (no swirl tape assumed)
- Peak temperature < 800°C at curved edge tile despite 10 MW/m² load



Displacements during plasma operation

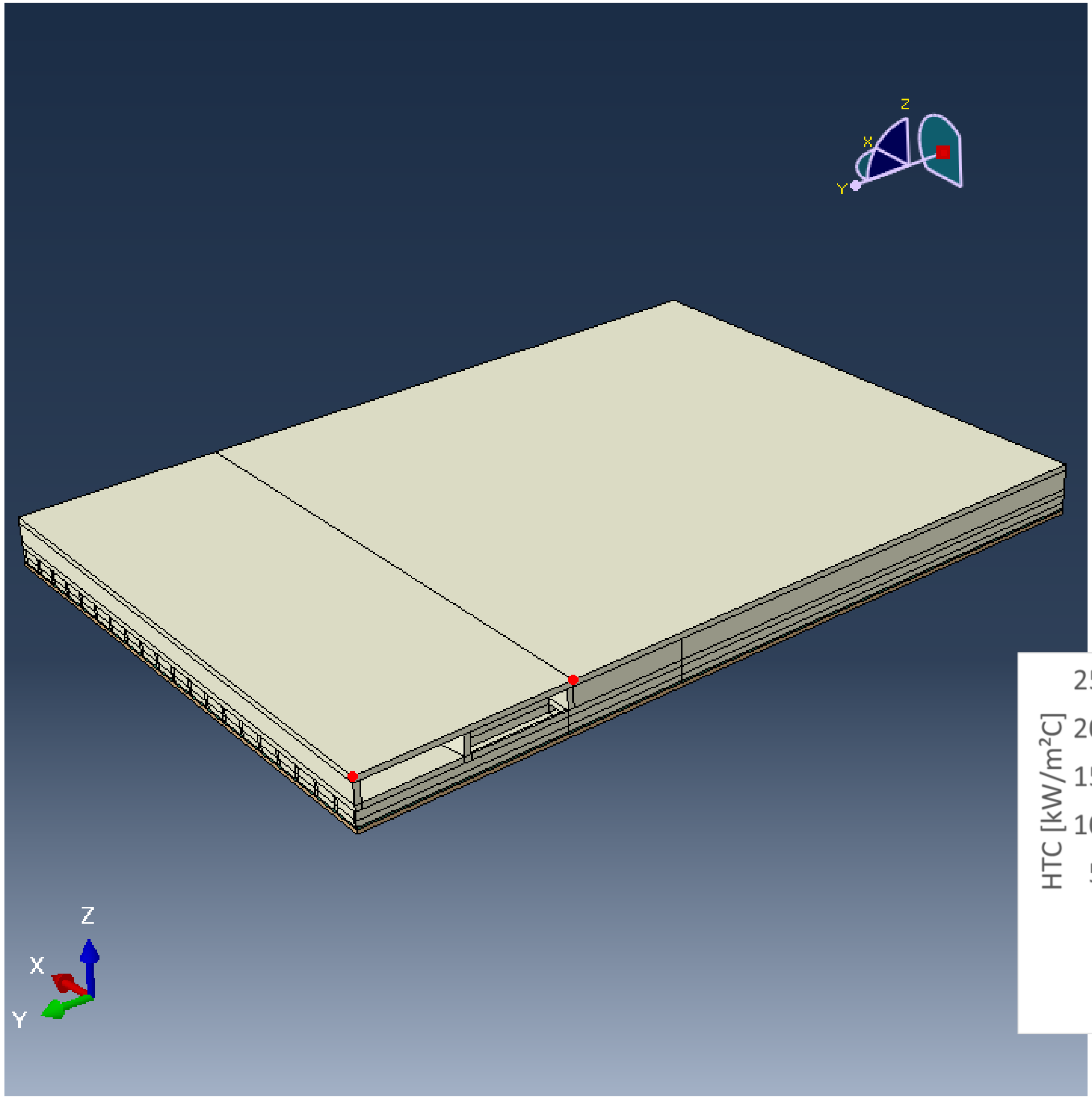
- **Only cantilever support at inlet/outlet tube**
- **Normal displacement < 3 mm, compare to 5 mm for current CFC divertor**
  - Sliding supports at pumping gap could further reduce normal displacement



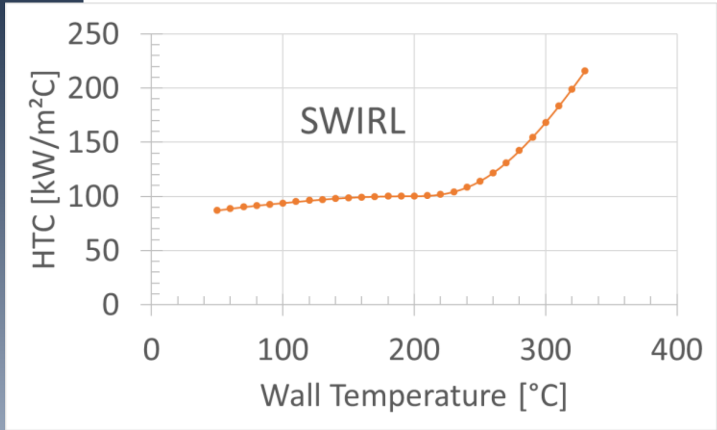


FE model including water channels

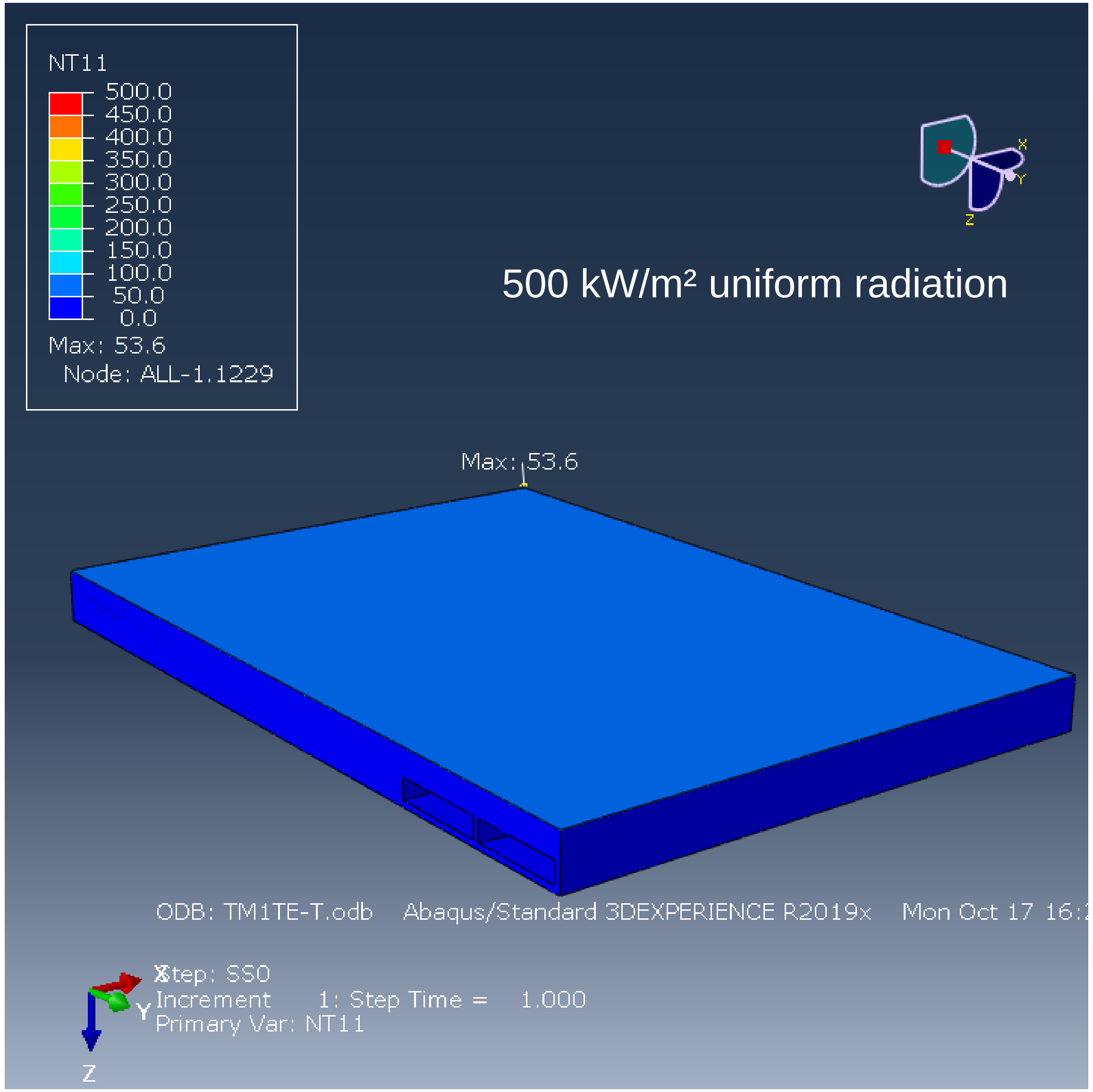
- W95NiFe
- OFE Cu Interlayer
- CUCrZr top plate
- CuCrZr bottom plate
- CuCrZr manifold
- CuCrZr Stiffener
- symmetry fixed in X
- Fixation in Y
- Fixation in Z
- HTC with swirl tape

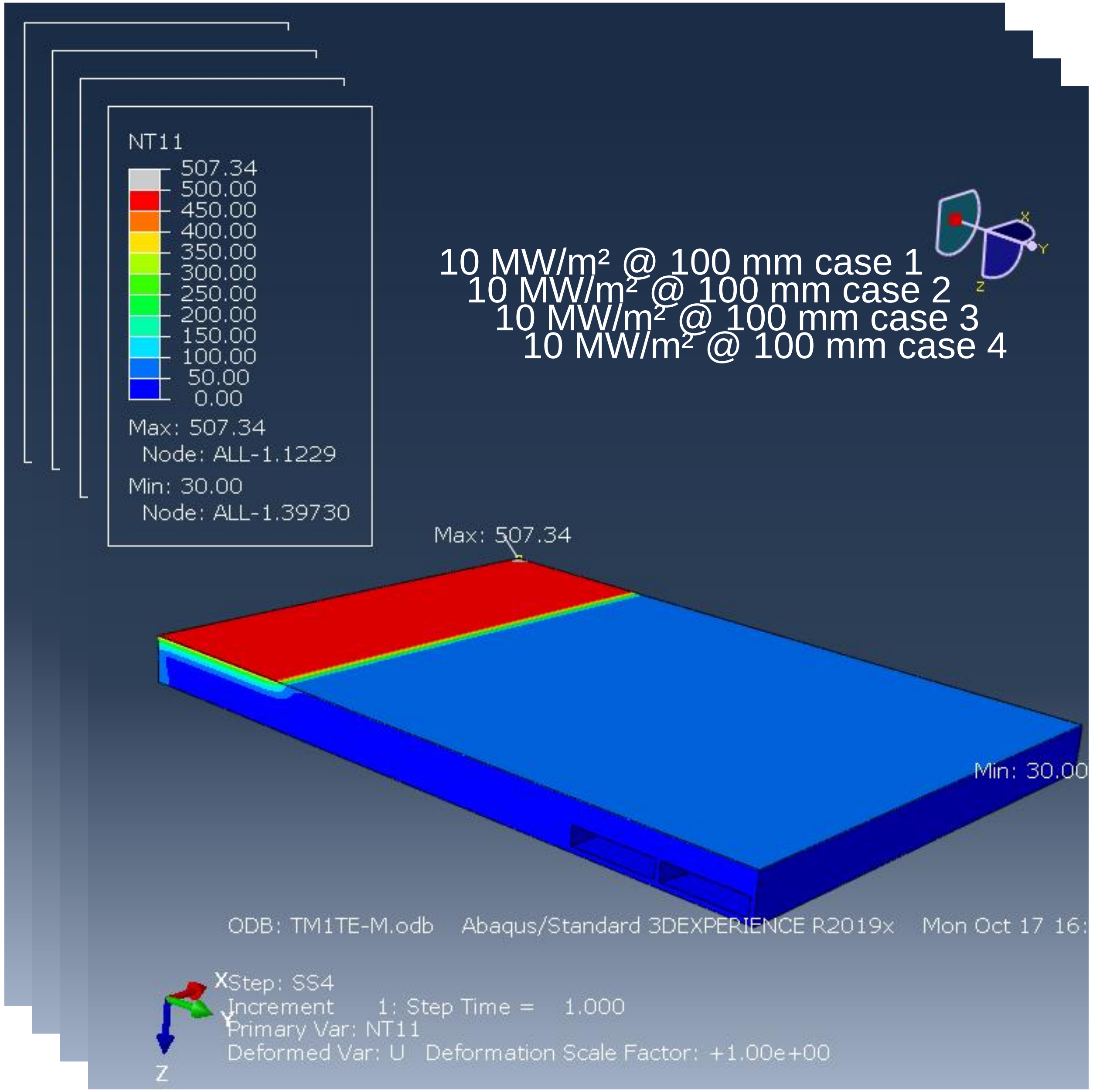


W95NiFe: 2 mm
OFE Cu: 1 mm
CuCrZr: 23 mm
3 mm plate
4 mm water channel
3 mm plate
10 mm manifold/stiffener
3 mm plate

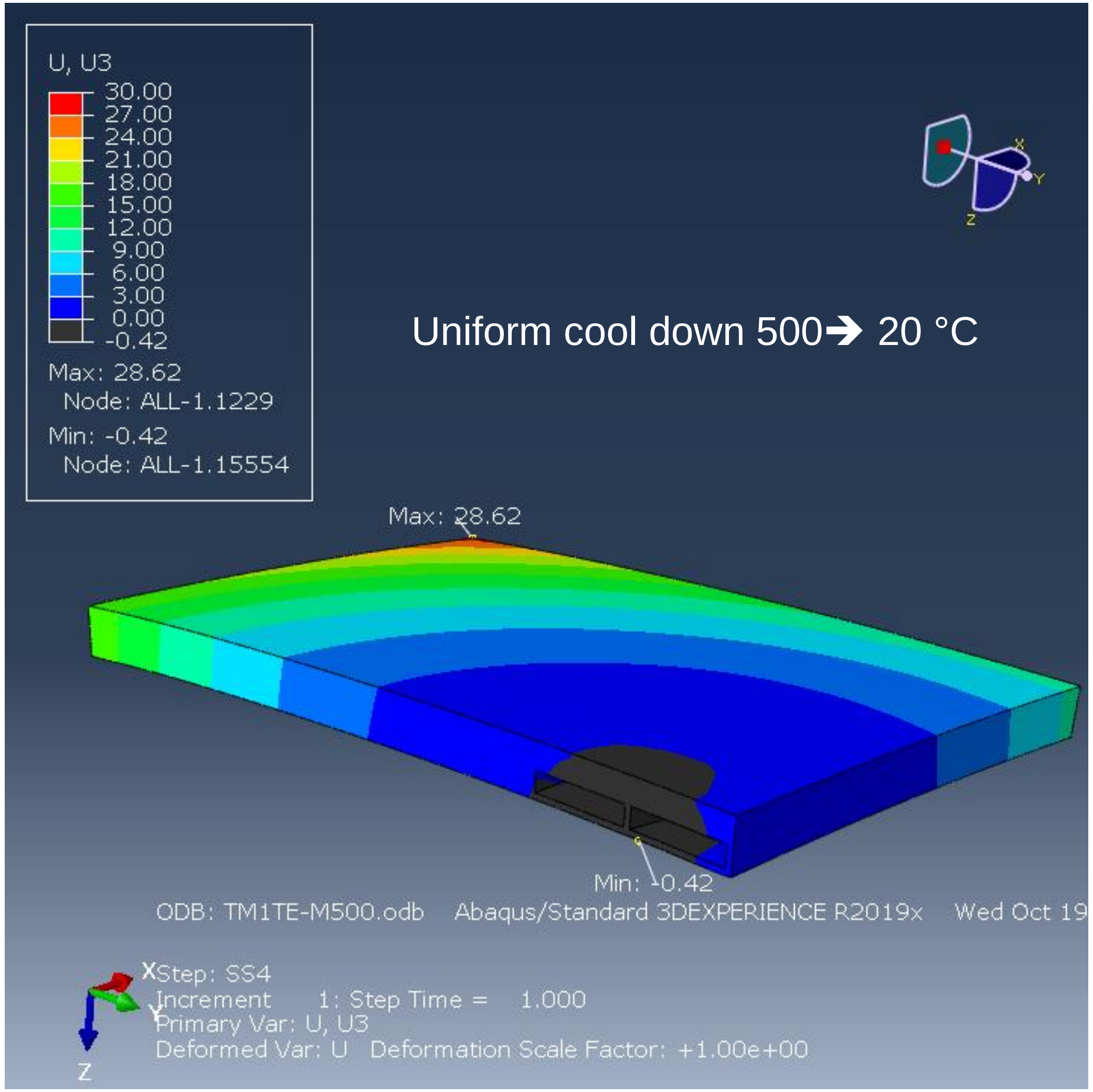


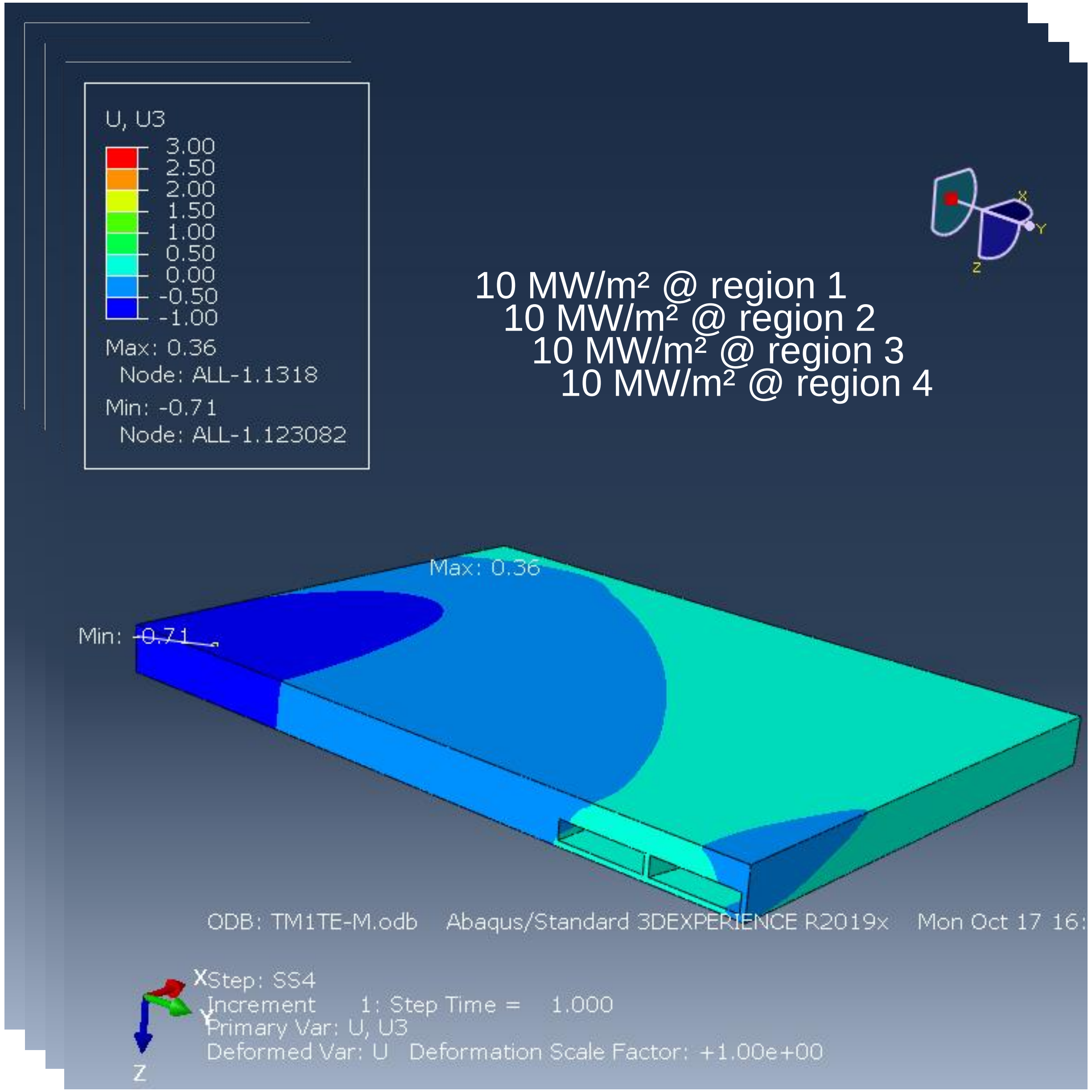
Thermal results





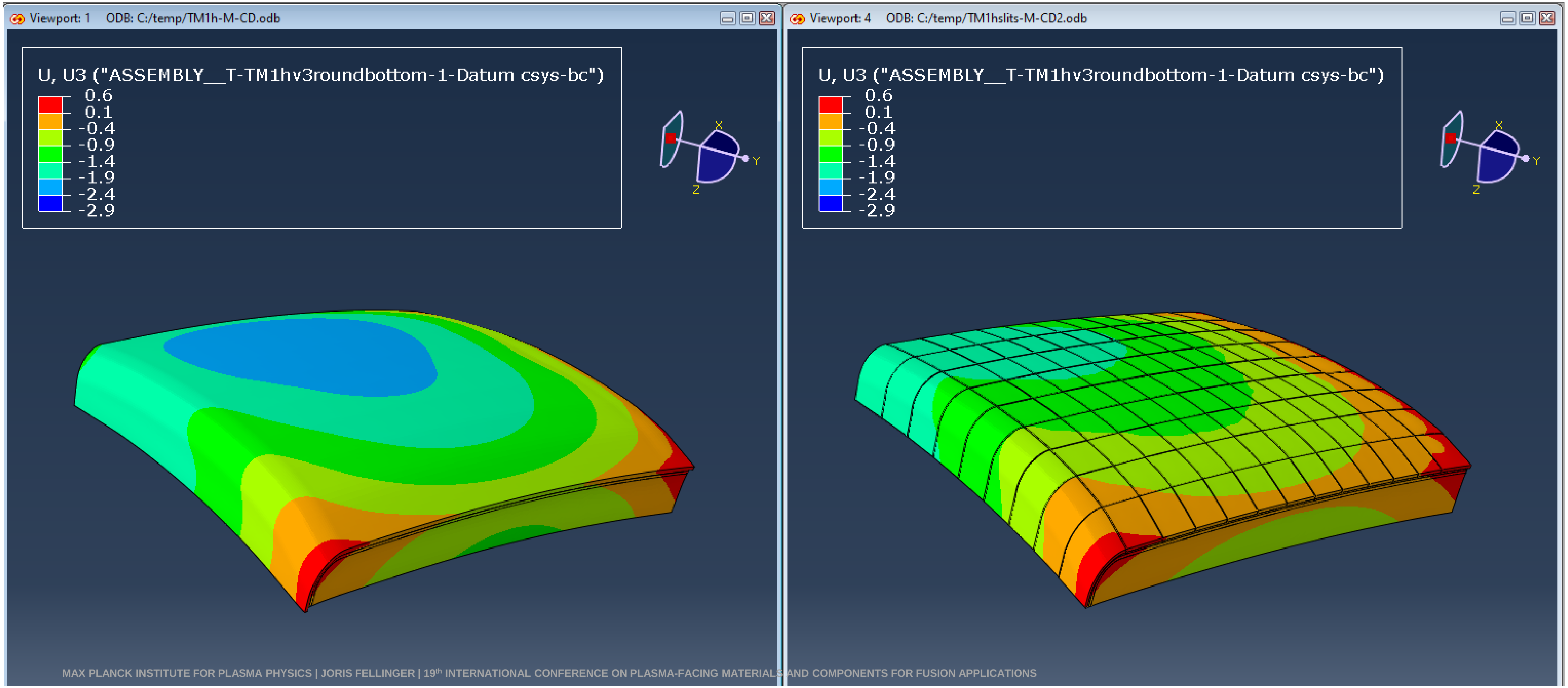
Plasma exposure ⇔ HIP process





Need to use castellated W surface

- Normal displacement during manufacturing cool down from 500 ➔ 20°C
- Castellation strongly reduces normal displacement, allowing for final machining HIP process



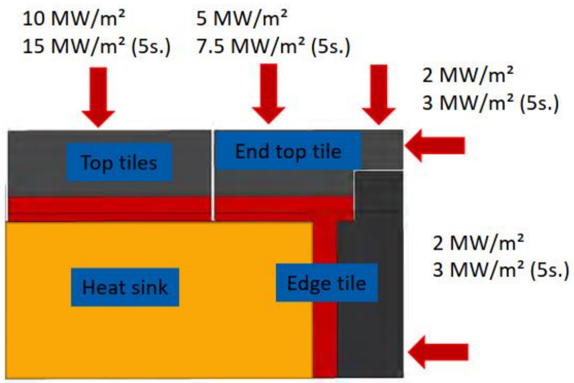
Summary of FEM results

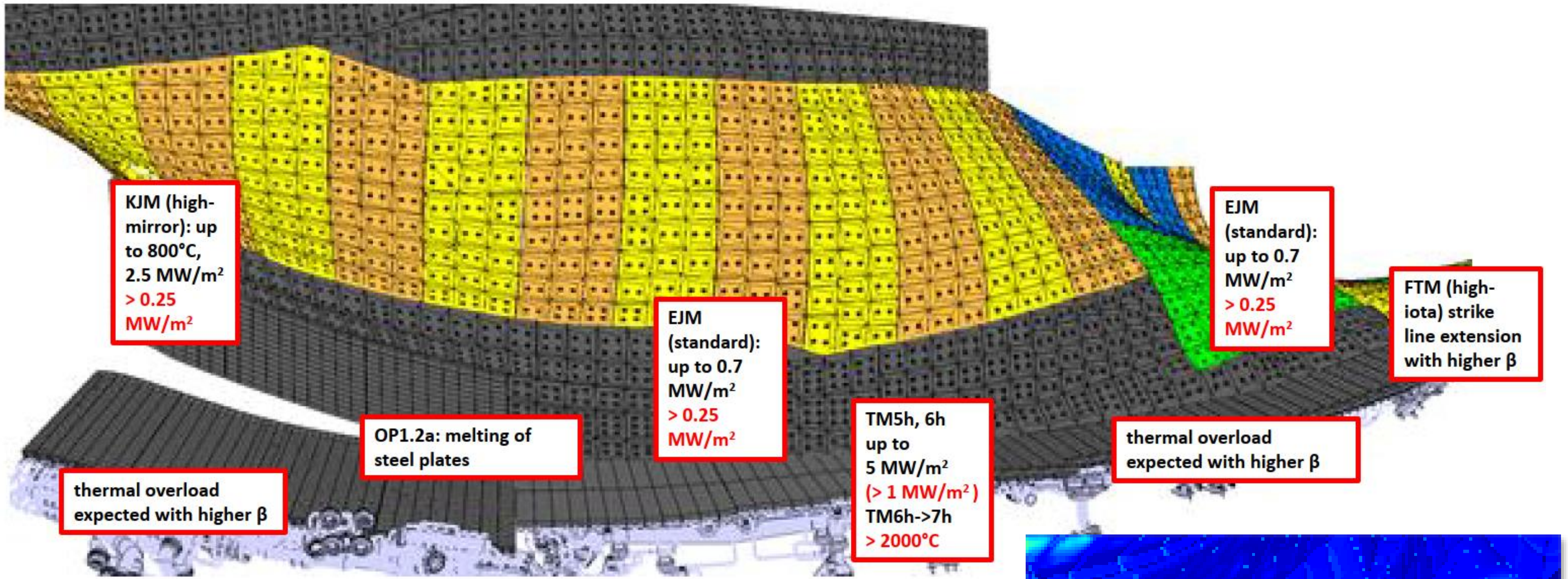
- **Deformation during cool down of HIP process far too large**
- **Possible counter measures**
  - Softer copper interlayer ➔ material will harden over time
  - Thicker copper interlayer
  - Stiffer cold side compared to W based side
  - Castellation of W based surface ➔ only realistic option: Normal deformation < 1 mm

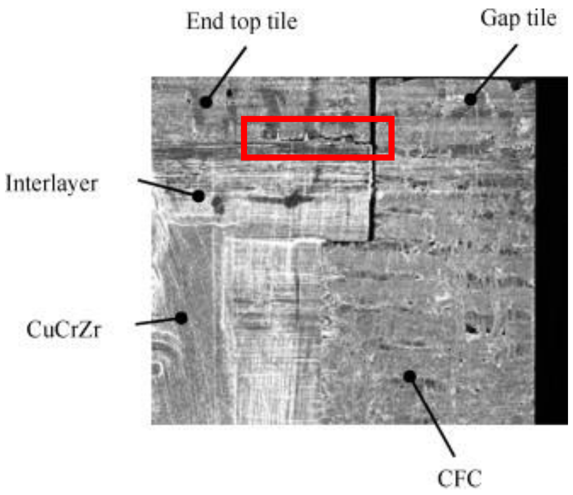
Heat sink	Interlayer	OFE Cu	Slits	u_z	σ WNiFe	σ OFECu
25 mm	1 mm	ITER SDC-IC	no	14.1	-1491	154
25 mm	1 mm	$R_{0.2}$ = 3 MPa	no	2.5	-393	3
50 mm	1 mm	ITER SDC-IC	no	4.5	-2301**	160
48 mm	3 mm	ITER SDC-IC	no	4.3	-1939**	158
80 mm	1 mm	ITER SDC-IC	no	3.2	-2297**	162
50 mm	1 mm	ITER SDC-IC	40x40 mm	0.8	-659	151

** in case of yielding: plastic strain < 0.3%

Divertor / baffle overload issues

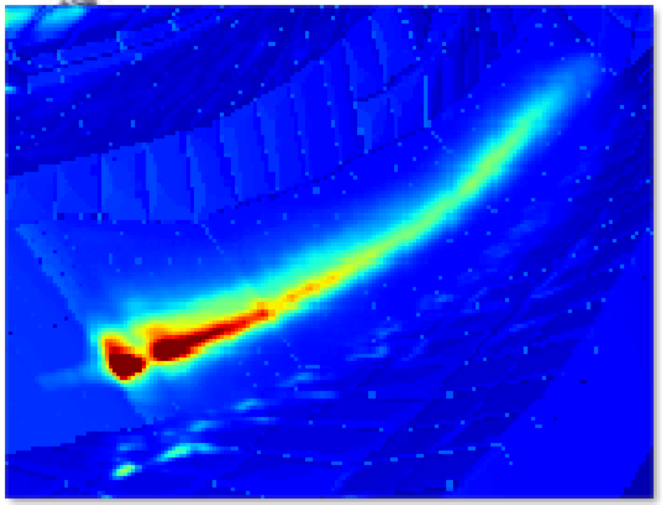






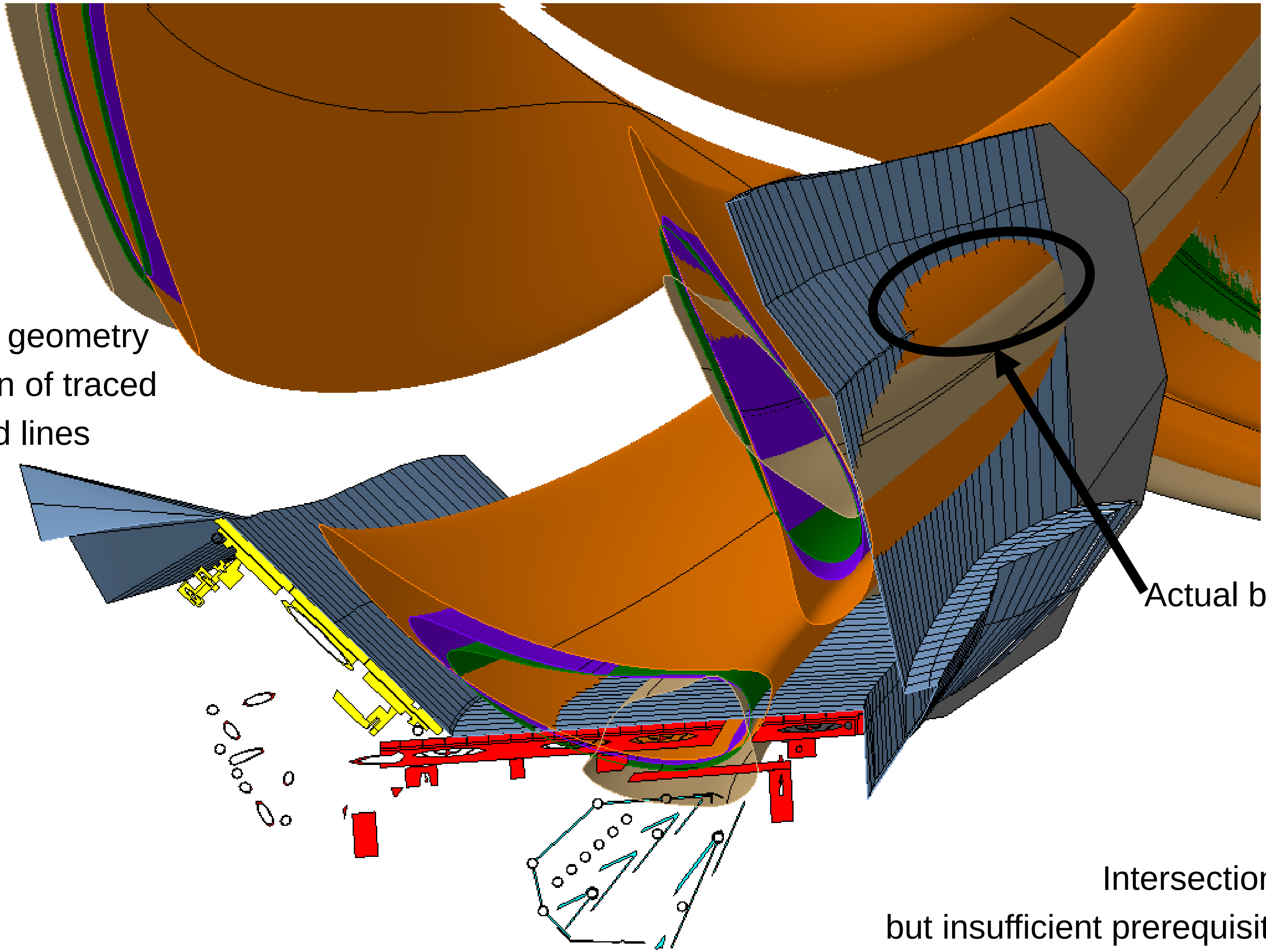
Source: M. Krause (1-QRH80-T0001)

Delamination at CFC-Cu interface limiting allowed load onto edge tiles



Local peak loads due to leading edges

Tools for plasma facing surface shaping



Smooth magnetic island geometry by Fourier transformation of traced particles along edge field lines

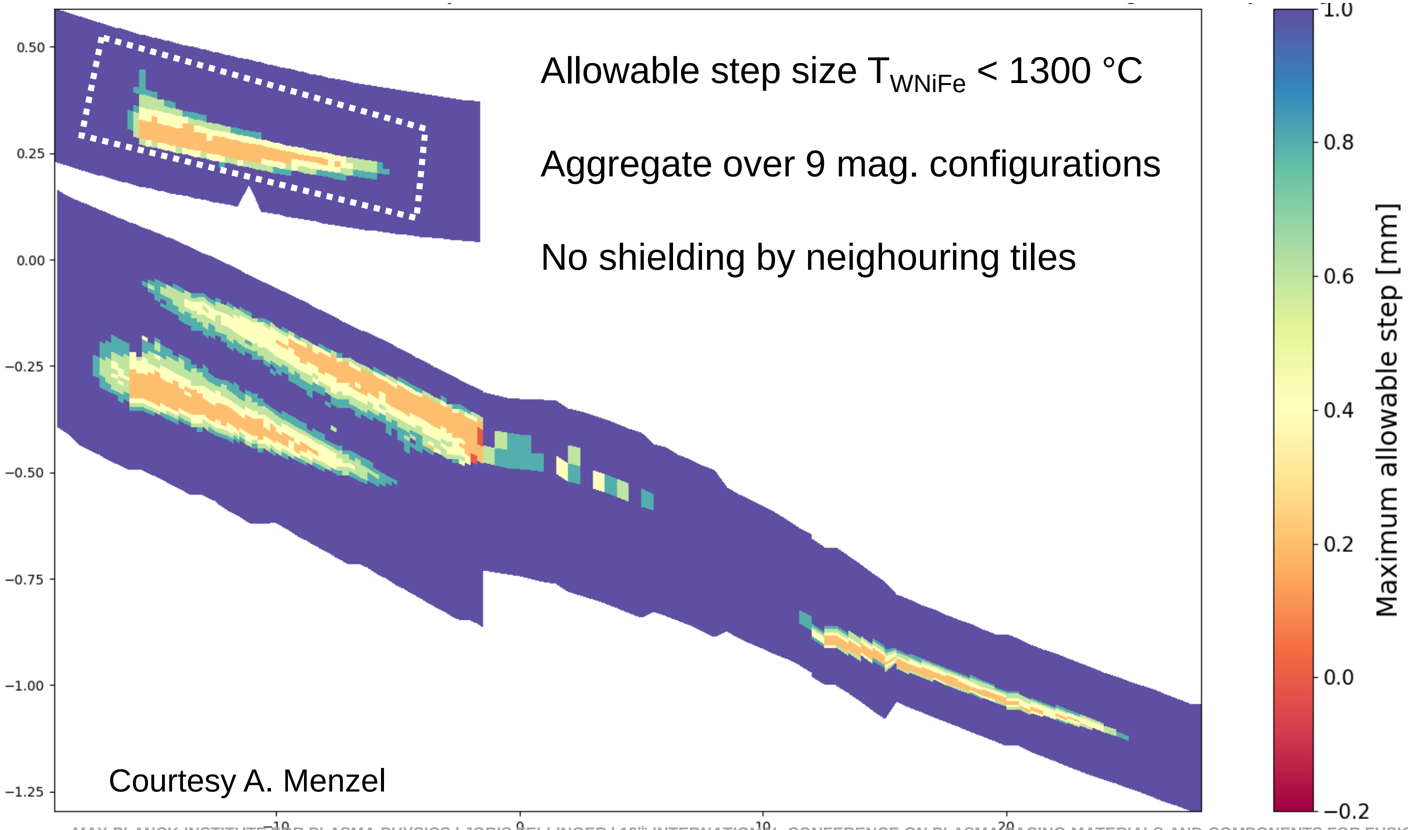
- β = 0 %
- β = 1 %
- β = 2 %
- β = 5.6 %

Actual baffle overloads

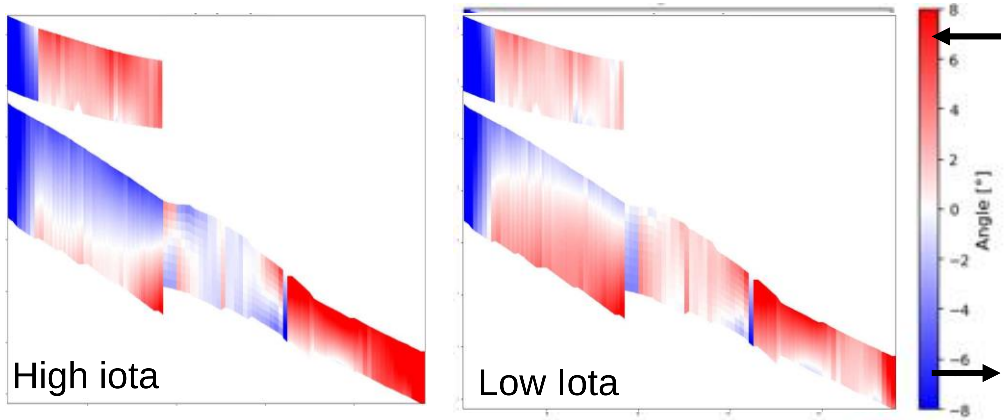
Intersection is a necessary but insufficient prerequisite for heat loads

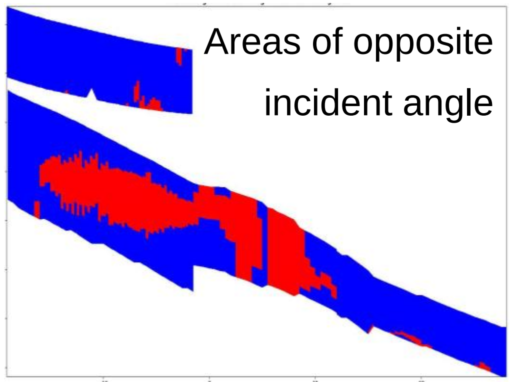
Tools to optimize plasma facing geometry

- **Plasma modeling**
  - EMC3-lite (heat loads)
  - EMC3-Eirene (heat loads + particle balance in the edge)
- **Modelling of neutral gas transport from strike line to pump in sub-divertor space**
- **Leading edge tool to determine allowable steps between tiles and modules**



Incident angles

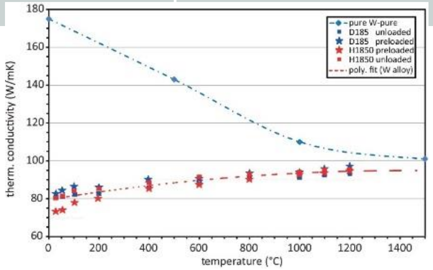




Pure W versus W based mixed metals

	W	$W_{95}N_{3.5}Fe_{1.5}$	$W_{95}Ni_{3.5}Cu_{1.5}$	WCu
Limit temperature[1)]	1300°C: recrystallization	1100°C: crack network 1300°C: recrystallisation? 1455°C: melting Ni	900°C: crack network observed 1050°C: increased vapor pressure Cu 1085°C: melting of copper	
Ductile brittle transition temperature[2)]	200 to 375°C[4)]	-150 to -25°C	-150 to -25°C	
Thermal conductivity [W/mK]	170-110 @20-1000°C[4)]	80-95 @ 20-1000°C[1)]	89-86 @20-850°C[6)]	240 $W_{50}Cu_{50}$ 147 $W_{90}Cu_{10}$
Thermal expansion 10^{-6}/K	4.4-5.0 @20°C-1200°C[4)]	5.2-5.7 @20-600°C[5)]	5.2-5.5 @20-600°C[5)]	13 $W_{50}Cu_{50}$ 7.5 $W_{90}Cu_{10}$
Fracture toughness[3)]	5-8 MPa√m @T < DBTT >100 Mpa√m @T > DBTT	75-110 MPa√m @20°C	45-50 MPa√m @20°C	
Elongation at fracture	0%[4)]	16% @ 20°C[5)]	4% @ 20°C[5)]	8% $W_{50}CuCrZr_{50}$ 5% $W_{70}CuCrZr_{30}$ <1% $W_{85}CuCrZr_{15}$
Magnetic permeability	<1.01	1.05 @ 1.4 T & 20°C	1.03 @ 1.4 T & 20°C	<1.01

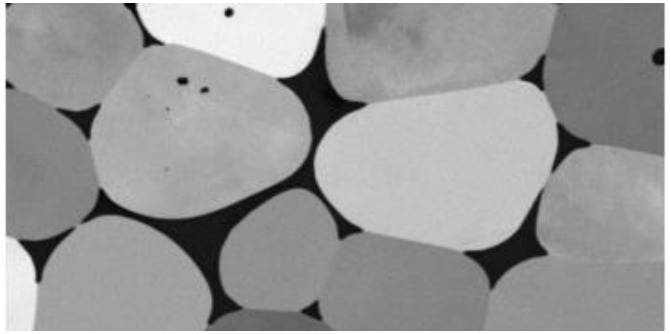
1) https://doi.org/10.1016/j.fusengdes.2017.01.043
2) https://fmp.ornl.gov/semiannual-progress-reports/fusion-materials-semiannual-progress-report-65.pdf
3) https://doi.org/10.2172/1562913
4) ITER Material Properties Handbook
5) https://www.plansee.com/download/?DOKNR=HPM-070-TD-024&DOKAR=QM1&DOKTL=100
6) 1-ACE-Y0027, p.36

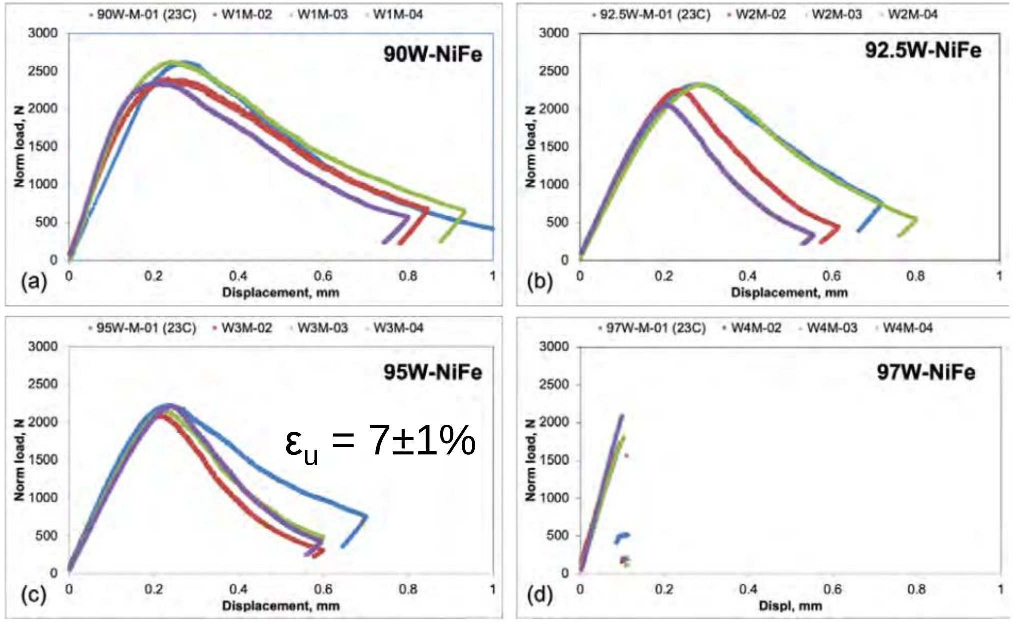


Assessment of W and $W_{95}NiFe$

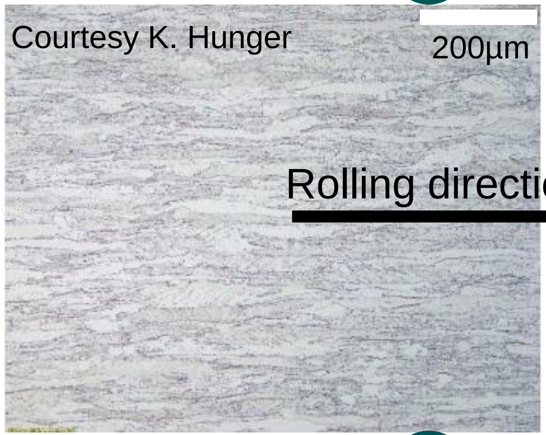
- **Comparison of 2 suppliers**
- **Rolling direction visible in W but not in $W_{95}NiFe$**

W95NiFe

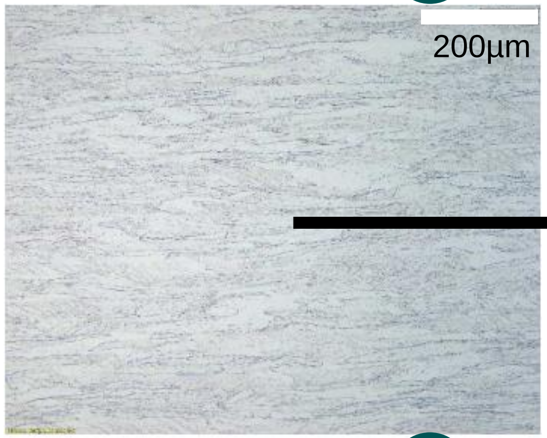


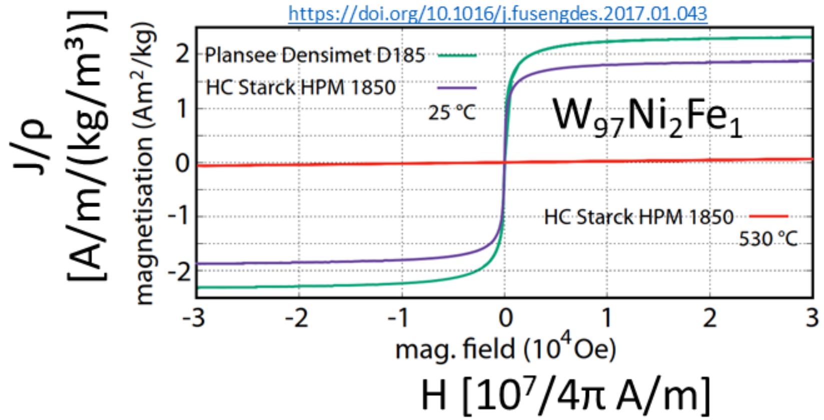


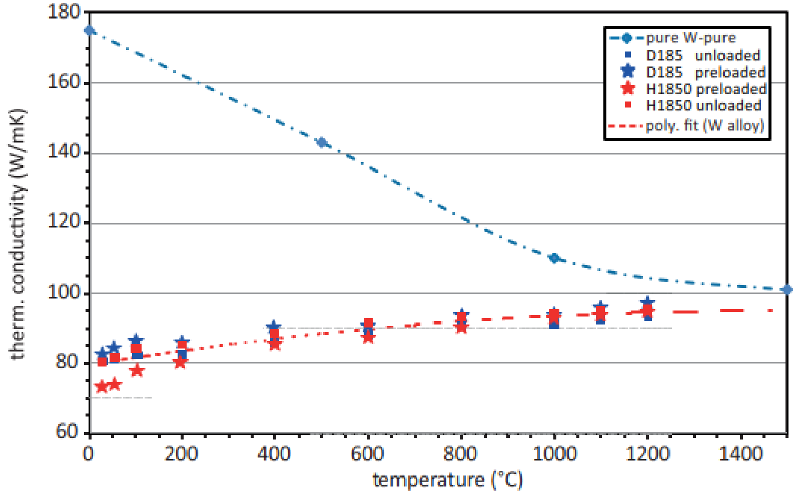
W



Rolling direction







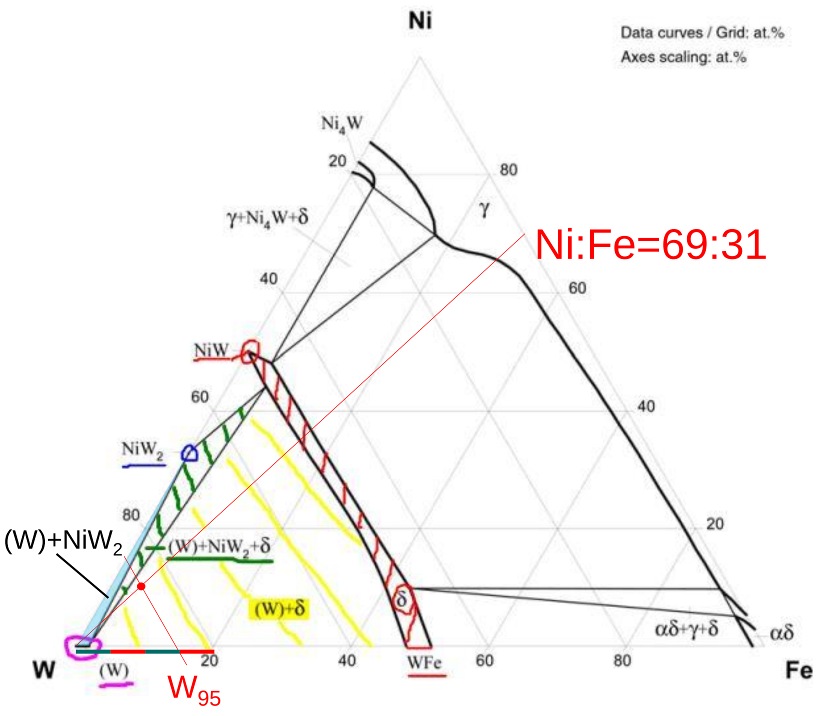
Phase diagram WNiFe

$W_{95}Ni_{3.5}Fe_{1.5}$ by weight% ➔ $W_{85.7}Ni_{9.9}Fe_{4.5}$ by atom% ➔ Ni:Fe = 69:31 at%

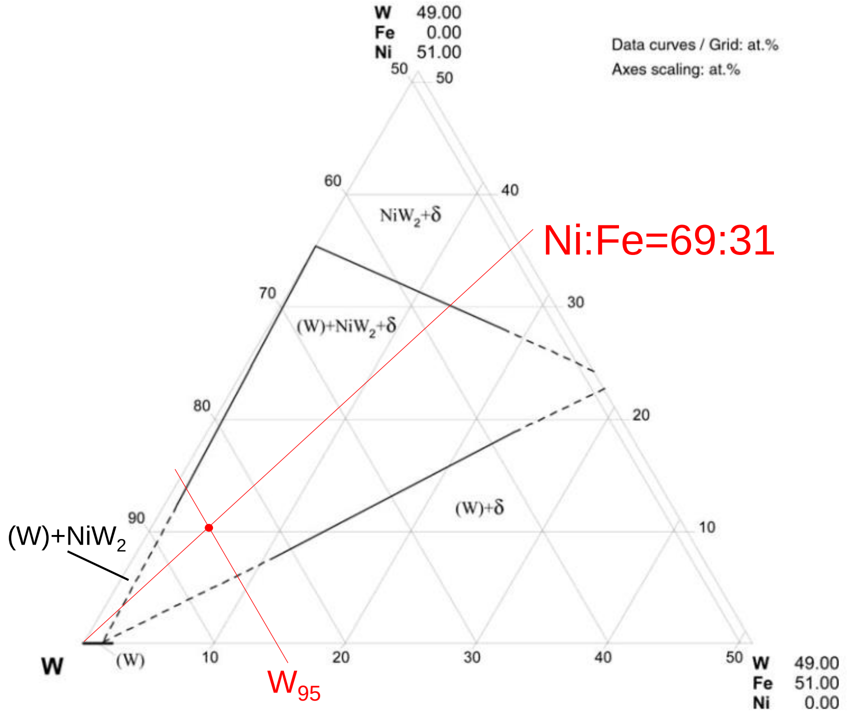
$\delta = Fe_xNi_{1-x}W$

$\gamma = Fe_{1-x-y}Ni_xW_y$

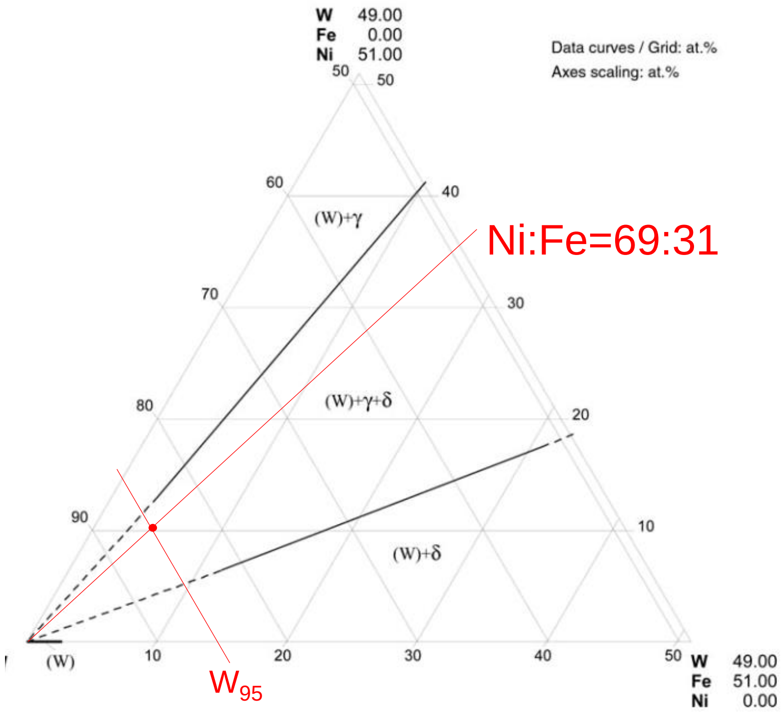
Fig. 7
Fe-Ni-W. Isothermal section at 800˚C



Fe-Ni-W. Fragment of the isothermal section at 950˚C

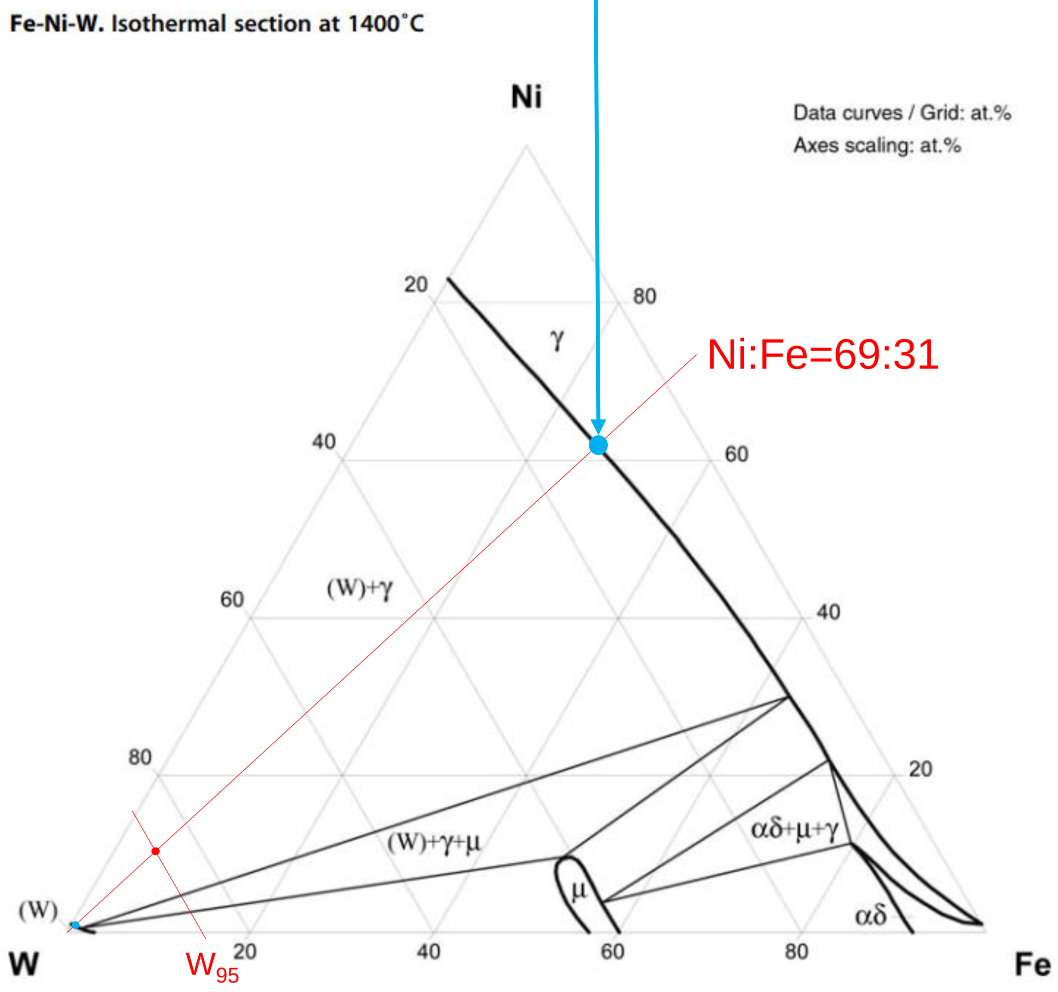


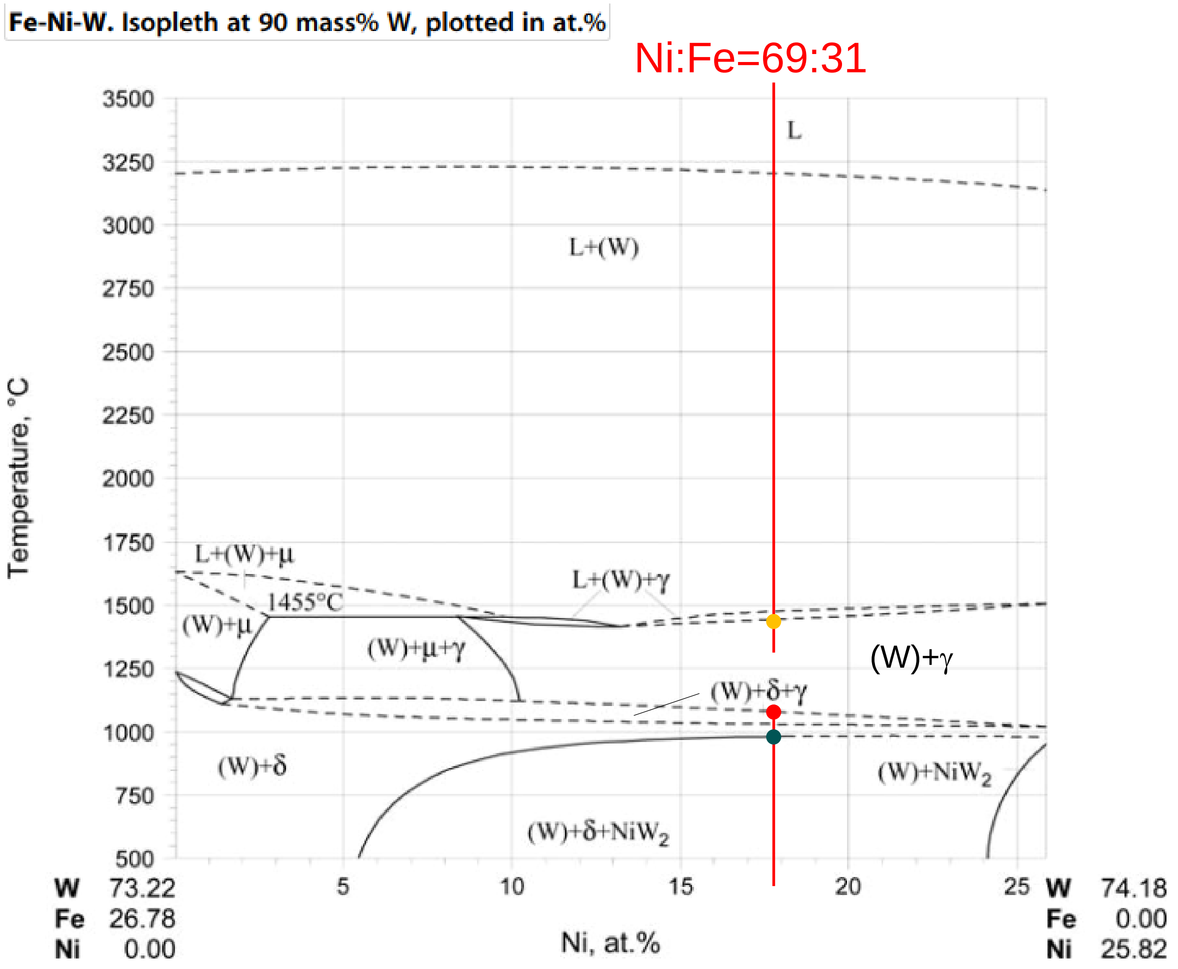
-Ni-W. Fragment of the isothermal section at 1050˚C



Phase diagram at annealing temperature

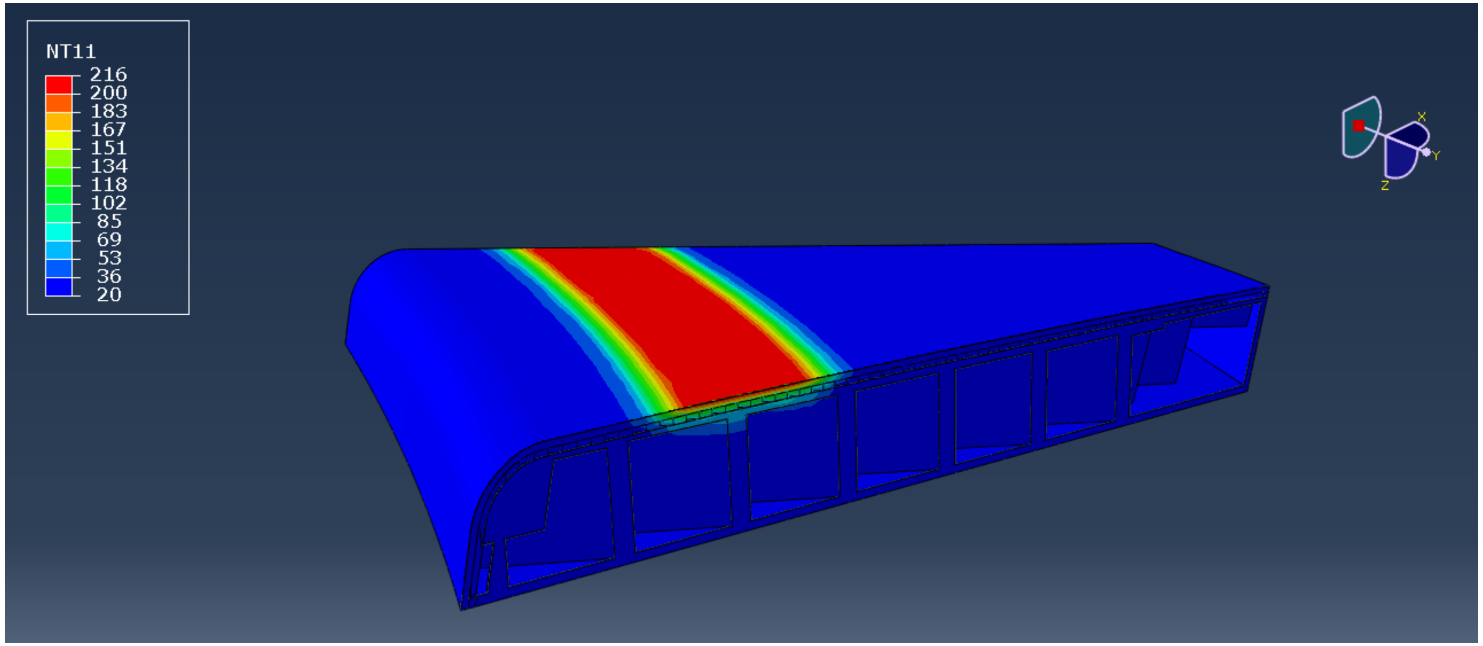
11.4 at% (29 wt%) W in γ phase dissolved at 1400 °C





Alternative approach: galvanize heat sink

- **Alternatively starting from W based tiles, a complete heat sink can be galvanized in 2 steps**
  - Soft copper directly onto W-tiles with heat treatment to anneal it further
  - Hard copper galvanized onto soft copper after heat treatment
  - Drawback: Limit temperature < 250 °C instead of 450°C for CuCrZr

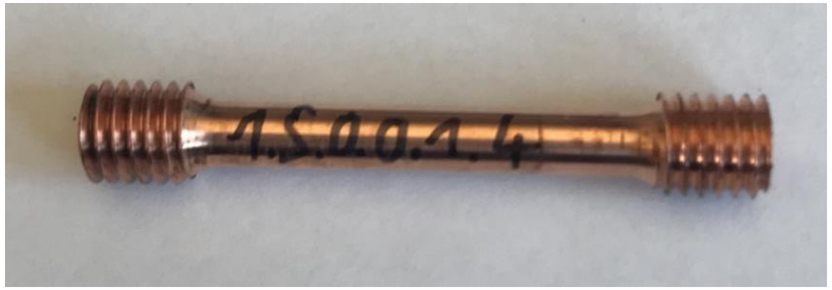


Material properties OFE Cu

- **Tensile tests at RISE at room temperature**
  - without heat treatment

OFE Cu (RISE)	$R_{0.2}$ MPa	R_m MPa	ε_u %
Plate	308	311	15-19
Cast	30-42	120-138	48
Galvanic Zeta	221-236	310	46
Galvanic LP1	234-268	356	7-25

  - With heat treatment pending
    - Plate: 1000°C (DW to W) + 550°C (braze to CuCrZr)
    - Cast: 550°C (braze to CuCrZr)
    - Galvanic: 550°C (braze to CuCrZr)

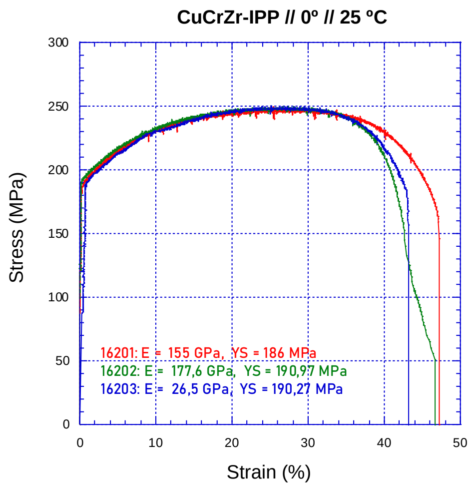


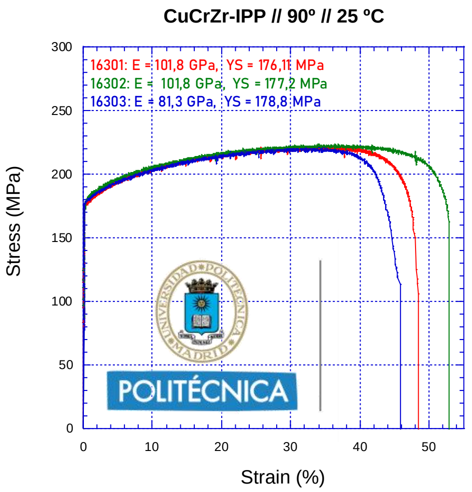
Normal failure

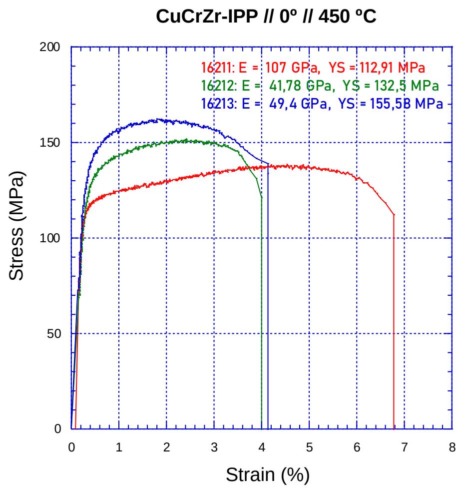
Abnormal failure due to extreme ductility cast copper

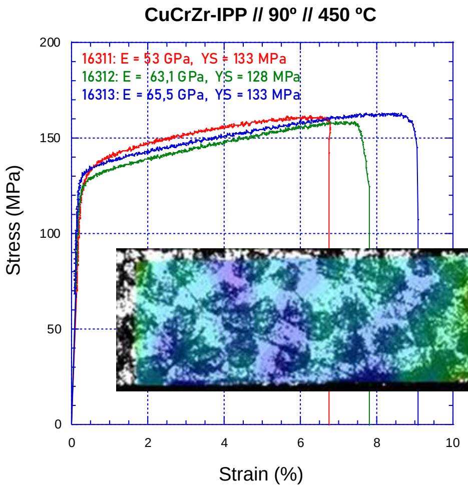
Material properties CuCrZr

- **Additive manufactured CuCrZr in loaded in horizontal and vertical direction at 20 and 450°C**
  - No heat treatment, tensile tested by UPM and RISE
    - loss of ductility at 450°C (also observed for cold worked CuCrZr plate, see DEMO MPH)
  - sol. ann. (950°C) + quench + aging (450°C), direct age hardening (580°C) 10 or 60 min: tests pending

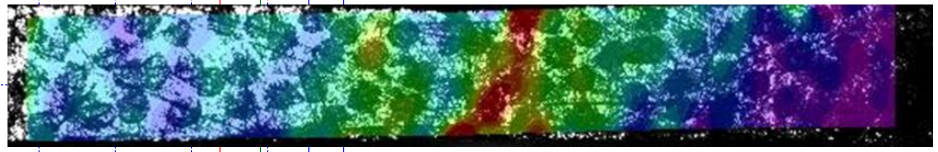






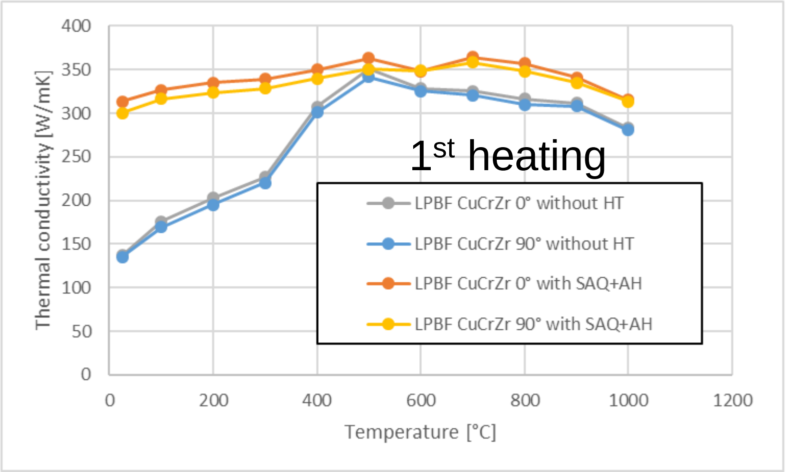


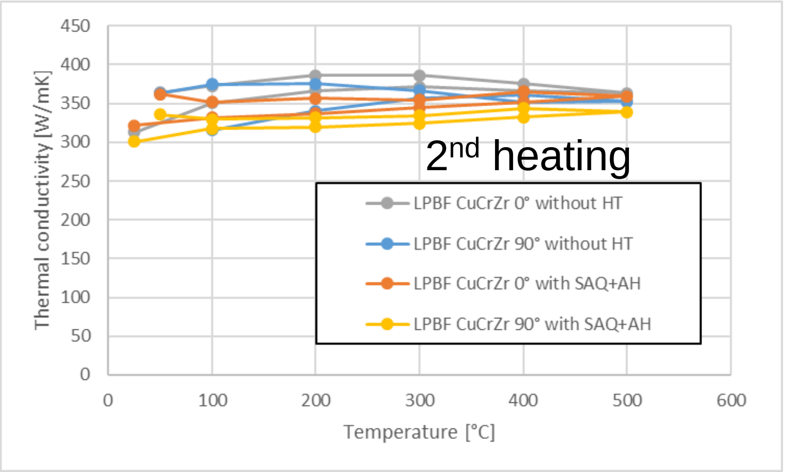
Strain measurement by Digital image correlation



CuCrZr (RISE)	$R_{0.2}$ MPa	R_m MPa	ε_u %
Plate	405	445	25
Plate after DW	90	242	45
LPBF 0° no HT	186	258	43
LPBF 90° no HT	173	233	45

- Thermal conductivity (LFA)
  - >300 W/mK after 1st cycle



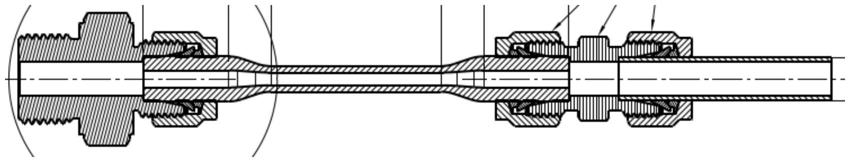


He leak test program AM CuCrZr

Sample Ø	Wall thickness	Vertical manufacturing		Horizontal manufacturing	
[mm]	[mm]	No heat treatment	Solution annealing & quenching + aging	No heat treatment	Solution annealing & quenching + aging
10	1	OK	OK	OK	OK
	1.5	OK	OK	OK	OK
	2	OK	OK	OK	OK
	2.5	OK	OK	OK	OK
	3	OK	OK	OK	OK
6	1	OK	Not OK	OK	OK
	1.5	OK	OK	Not OK	OK

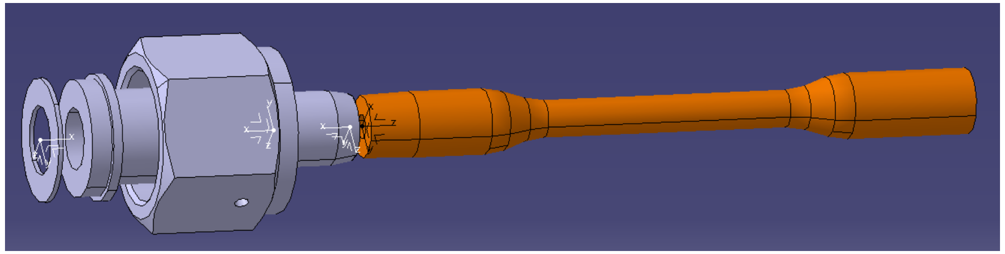
Solution annealing (SA): 15 minutes @ 950 °C, Quenching in water (Q)

Aging (A): 120 minutes @ 450 °C



Improvements:

- galvanic connection to VCR instead of clamping ring
- Direct age hardening (DAH): 10 or 60 minutes at 580 °C i.o. SA+Q+A
  - Prepared, to be tested



Cooling constraints divertor/baffle

	Req. flow speed in TE [m/s]	Flow rate [l/s]	Total flow rate all modules Required / available [m³/h]		Pressure drop in module [bar]		temperature rise [K]	
		At 9 m/s	Required at 9 m/s	Available	at required flow speed	Available	Expected per TE	Allowed
divertor	9	0.5 pro TE TM7-9h: 6x: 3 TM1-4h: 8x: 4 TM1-3v: 10x: 5	1535	2000 m³/h ➔ 0.5K/MW	TM7h: 9[1] TM9h: 15[1]	14	24[2] 48 (TM8-9 h)	60[4]
baffle	6	0.5 pro Baffle	320		B2: 10.5 B5: 4.9		48[3]	
PSP	2	0.29			6			
Pol. Clos.	2	0.21			6			

[1])Pressure drop of plug-in not included. Based on simple calculation with Moody diagram:

5 l/s in D = Ø32 mm pipe ➔ v = 6.2 m/s ➔ $Re = Dv/\mu = 2e5$ ($\mu_{water} = 0.894$ mm²/s)

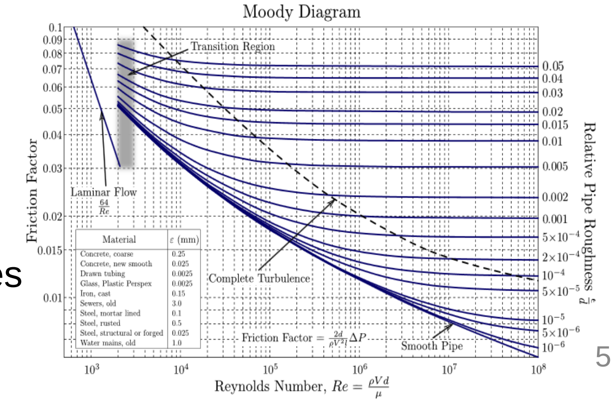
relative roughness = 0.05/D = 0.0015 ➔ friction from Moody diagram: f = 0.016

$\Delta P/m = f\rho v^2/2D$ = 0.04 to 0.1 bar/m between 3 and 5 l/s flow rate

[2])Based on 100x50 mm² @ 10 MW/m² = 50 kW/TE ➔ 50/(0.5*4.2 kJ/kgK) = 24 K

[3])Based on 0.2 m² @ 0.5 MW/m² = 100 kW/ baffle ➔ 100/(0.5*4.2) = 48 K➔ higher flow rate or smaller baffles required for 1 MW/m²

[4]) 60 K temperature rise corresponds to TM7-9h: 0.75 MW, TM1-4h: 1.00 MW, TM1-3v: 1.25 MW



Separatrix for any config with beta and I_{tor}

- Standard – beta variation – toroidal current = 0 kA
- Standard – beta = 0 % – toroidal current variation -30 kA to +18 kA
- Standard – beta = 3.4% – toroidal current variation -24 kA to +24 kA

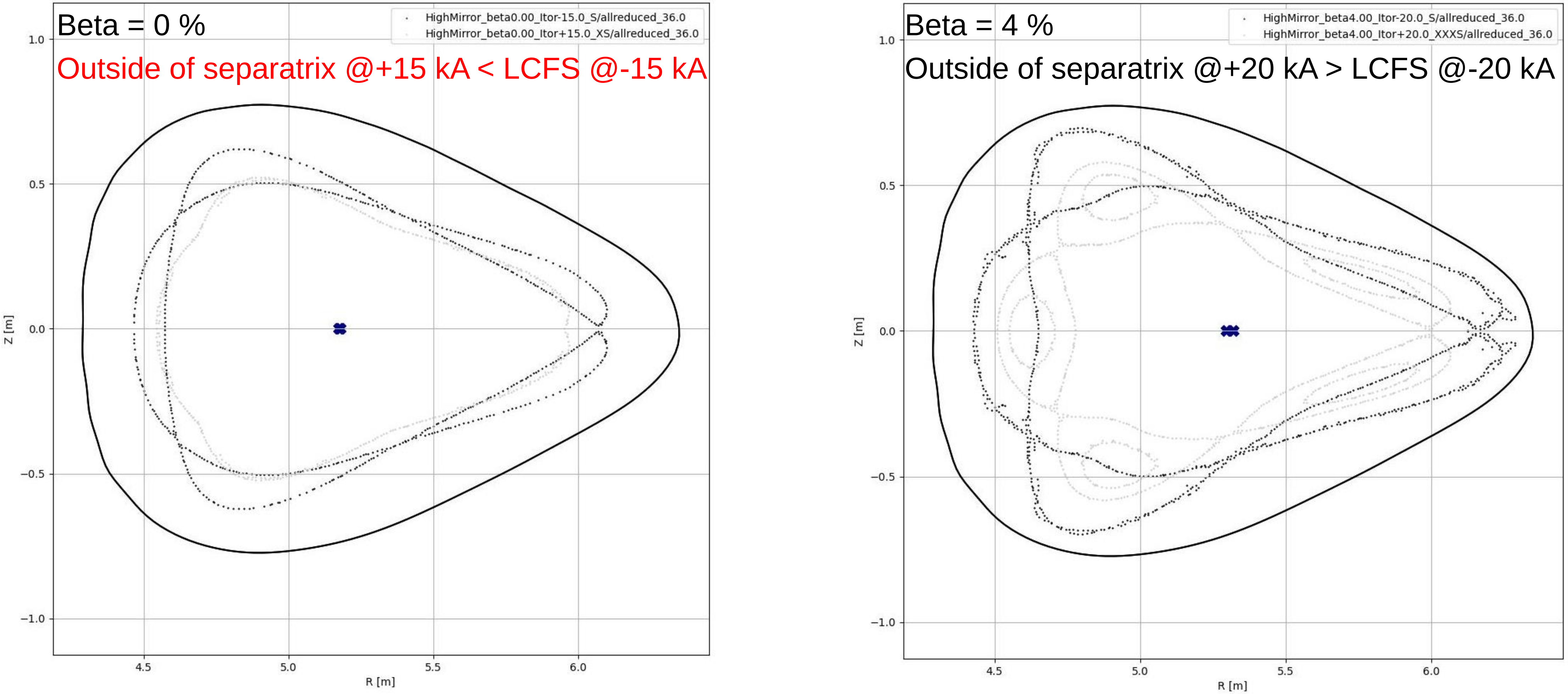
- High mirror – beta variation – toroidal current = 0 kA
- High mirror – beta = 0 % – toroidal current variation -20 kA to +20 kA
- High mirror – beta = 4 % – toroidal current variation -20 kA to +20 kA

- High iota – beta variation – toroidal current = 0 kA
- High iota – beta = 0 % – toroidal current variation -20 kA to +20 kA
- High iota – beta = 2.8 % – toroidal current variation -20 kA to +20 kA

- Standard / high mirror / high iota – beta = 0 % – toroidal current = 0 kA
- Standard / high mirror / high iota – beta = 2.7 / 3.0 / 2.8 % – toroidal current = 0 kA

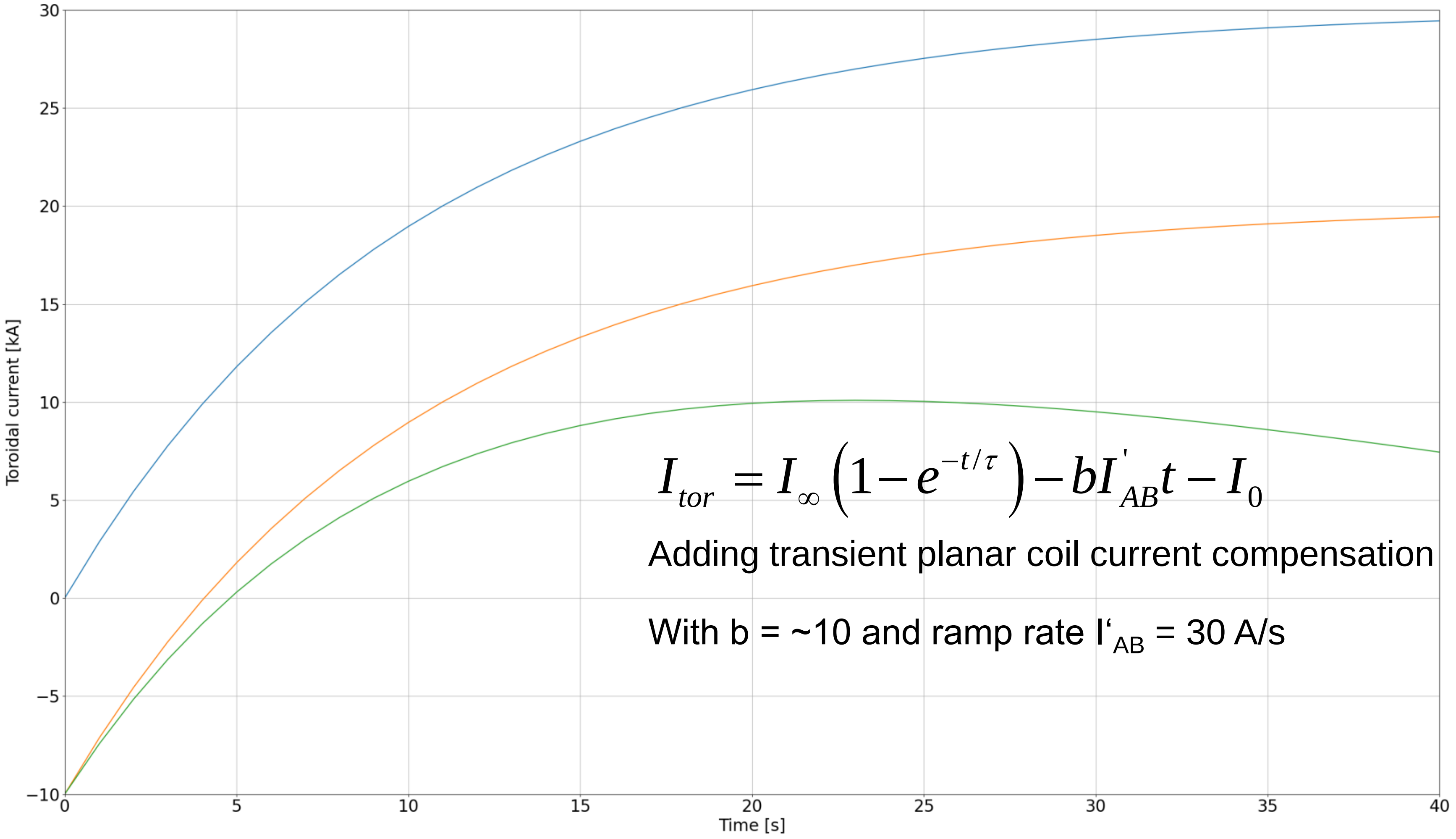
Design limitations

- **Provided the divertor intersects the outer contour of the separatrix but does not intersect the LCFS poses a limit on the toroidal current that can be tolerated, especially at low beta**
  - Power shell at beta = 0 % is best suited for first design iteration of plasma facing geometry



Toroidal current compensation by planar coils

Using transient planar coil currents compensation
the power shell geometry variations can be limited ±10 kA for $|I_\infty|$ < 30 kA



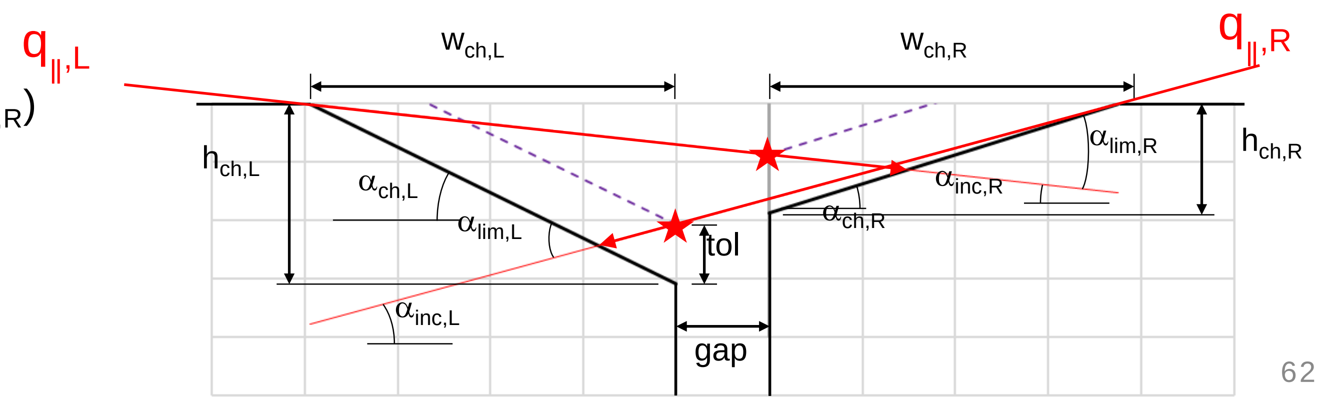
$$I_{tor} = I_\infty\left(1-e^{-t/\tau}\right)-bI'_{AB}t-I_0$$

Adding transient planar coil current compensation

With b = ~10 and ramp rate I'_{AB} = 30 A/s

Aovid leading edges by chamfering

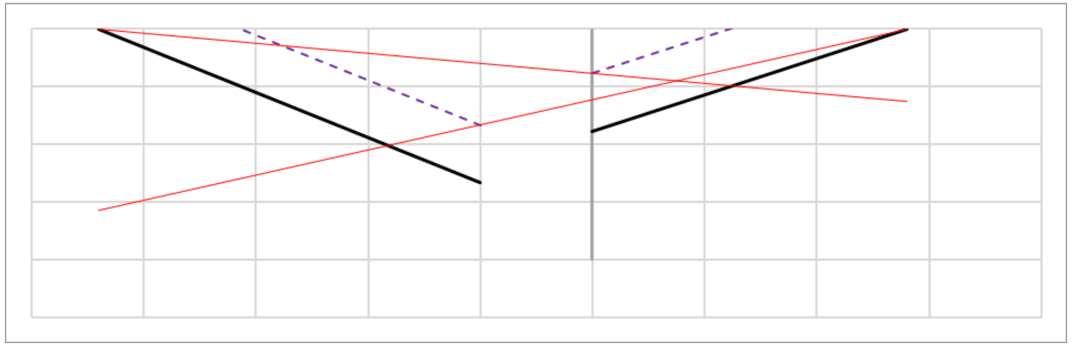
- **Normal heat load limit q_{lim} is determined by FEM from temperature limits of channel surface, CuCrZr, OFE Cu, W or WHA**
  - **Only temperature over heat load variation needs to be assessed in FEM**
- **Allowed incident angle is limited by parallel heat flux $q_{\parallel}$ and q_{lim} as**
  - **$q_{\parallel} \cdot \sin(\alpha_{inc}) < q_{lim} \Rightarrow \alpha_{lim} = \sin^{-1}(q_{lim} / q_{\parallel})$**
    - No overload on chamfer if chamfer angle is limited: $\alpha_{ch,max} = \alpha_{lim} - \alpha_{inc}$
    - $h_{ch} / w_{ch} < \tan(\alpha_{lim} - \alpha_{inc})$
- **Required left chamfer height $h_{ch,L}$ to avoid leading edge on left target**
  - **$\alpha_{ch,max,R} > \alpha_{inc,L}$: $h_{ch,L} >$ tol + (gap + $w_{ch,R}$)·$\tan(\alpha_{inc,L})$**
  - **$\alpha_{ch,max,R} \leq \alpha_{inc,L}$: $h_{ch,L} > h_{ch,R}$ + tol + (gap)·$\tan(\alpha_{inc,L})$**
    - Only possible if
    - $\alpha_{ch,max,L} > \alpha_{inc,R} \Rightarrow h_{ch,R} >$ tol + (gap + $w_{ch,L}$)·$\tan(\alpha_{inc,R})$



Avoid leading edges: 4 cases – 3 solutions

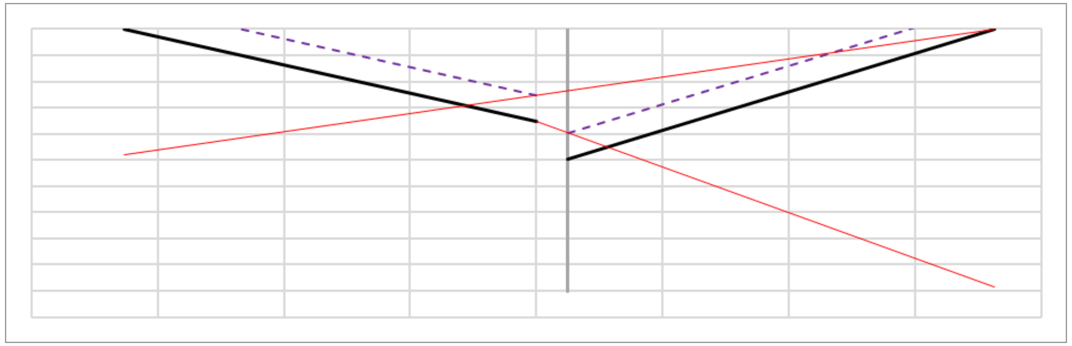
$\alpha_{ch,L,max} > \alpha_{inc,R}$

$\alpha_{ch,R,max} > \alpha_{inc,L}$



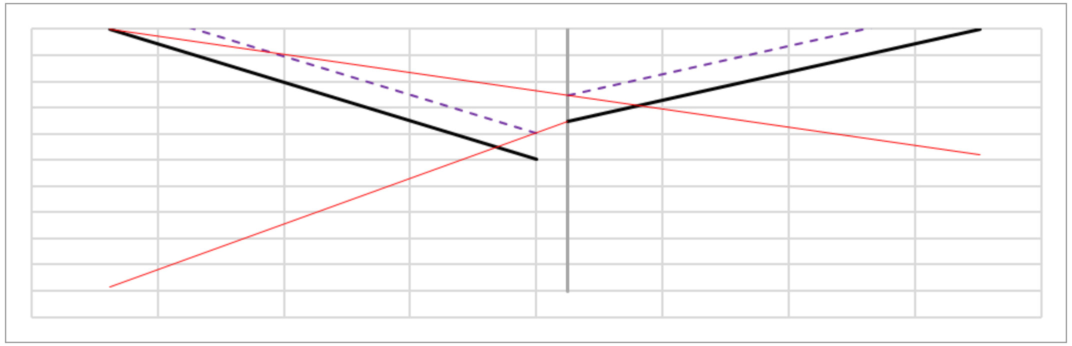
$\alpha_{ch,L,max} < \alpha_{inc,R}$

$\alpha_{ch,R,max} > \alpha_{inc,L}$



$\alpha_{ch,L,max} > \alpha_{inc,R}$

$\alpha_{ch,R,max} < \alpha_{inc,L}$



$\alpha_{ch,L,max} < \alpha_{inc,R}$

$\alpha_{ch,R,max} < \alpha_{inc,L}$

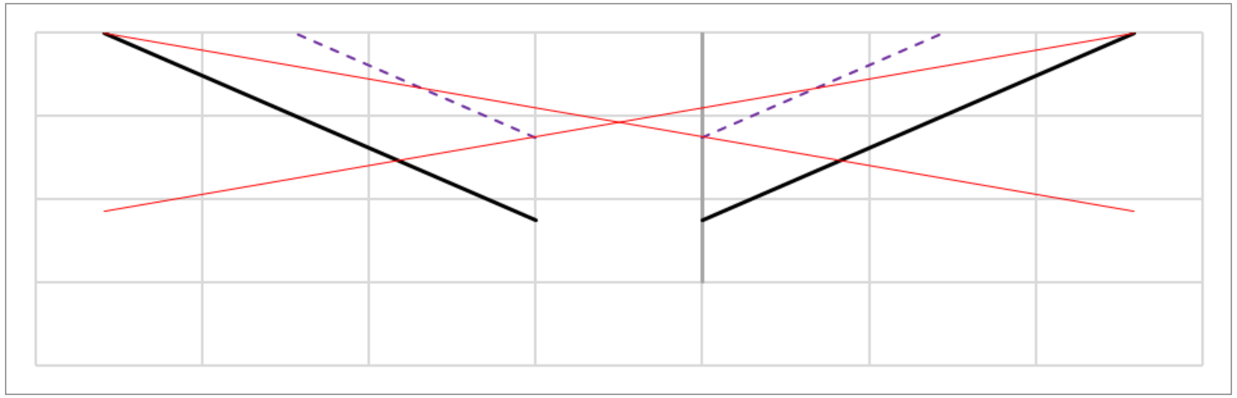
No solution possible

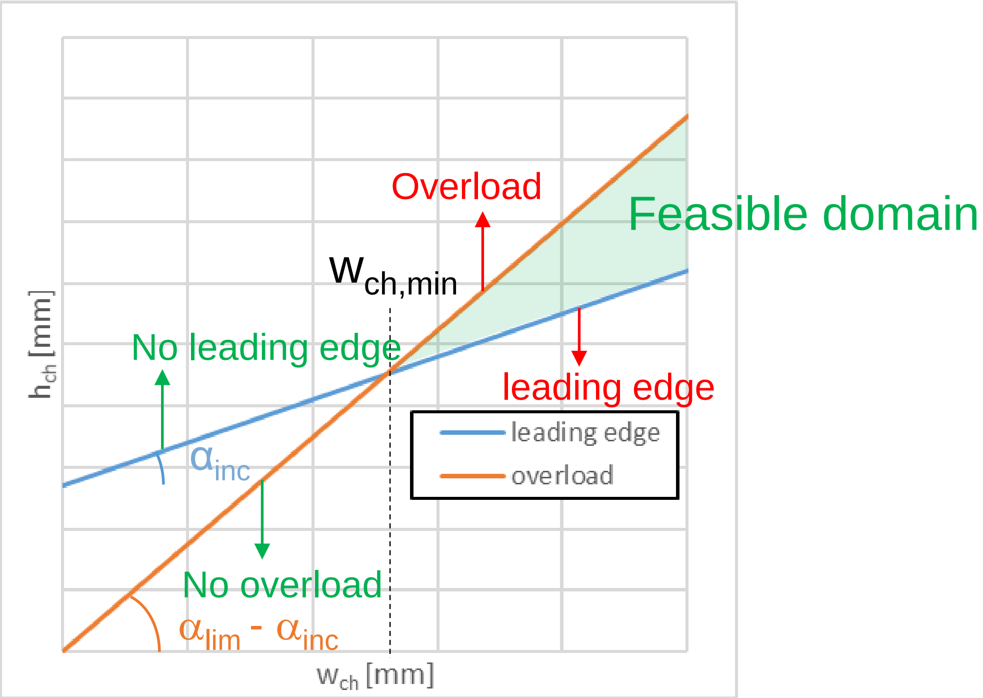
symmetric case

No overload: $\alpha_{ch} < \alpha_{lim} - \alpha_{inc} \rightarrow h_{ch} < w_{ch} \cdot \tan(\alpha_{lim} - \alpha_{inc})$

No leading edge: $h_{ch} > tol + (gap + w_{ch}) \cdot \tan(\alpha_{inc})$

$\rightarrow w_{ch,min} = (tol + gap \cdot \tan(\alpha_{inc}))/(\tan(\alpha_{lim} - \alpha_{inc}) - \tan(\alpha_{inc}))$





Asymmetric case

- **Constraints**
  - $h_{ch,L} > \text{tol} + (\text{gap} + w_{ch,R})\cdot\tan(\alpha_{inc,L})$
  - $h_{ch,L} < w_{ch,L}\cdot\tan(\alpha_{lim,L} - \alpha_{inc,L})$
  - $h_{ch,R} > \text{tol} + (\text{gap} + w_{ch,L})\cdot\tan(\alpha_{inc,R})$
  - $h_{ch,R} < w_{ch,R}\cdot\tan(\alpha_{lim,R} - \alpha_{inc,R})$
- **Iterate until leading edge at both sides is zero**
  - $w_{ch,R} = 0$
  - $h_{ch,L}$
    - $\alpha_{ch,R} > \alpha_{inc,L}$: $h_{ch,L} = \text{tol} + (\text{gap} + w_{ch,R})\cdot\tan(\alpha_{inc,L})$
    - $\alpha_{ch,R} < \alpha_{inc,L}$: $h_{ch,L} = h_{ch,R} + \text{tol} + (\text{gap})\cdot\tan(\alpha_{inc,L})$
  - $w_{ch,L} = h_{ch,L}/\tan(\alpha_{lim,L} - \alpha_{inc,L})$ (set chamfer angle to limit angle)
  - $h_{ch,R}$
    - $\alpha_{ch,L} > \alpha_{inc,R}$: $h_{ch,R} = \text{tol} + (\text{gap} + w_{ch,L})\cdot\tan(\alpha_{inc,R})$
    - $\alpha_{ch,L} > \alpha_{inc,R}$: $h_{ch,R} = h_{ch,L} + \text{tol} + (\text{gap})\cdot\tan(\alpha_{inc,R})$
  - $w_{ch,R} = h_{ch,R}/\tan(\alpha_{lim,R} - \alpha_{inc,R})$ (set chamfer angle to limit angle)