Investigation of Tungsten Coatings on Graphite and CFC

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[*] see Appendix of M.L. Watkins et al., Fusion Energy 2006 (Proc. 21st Int. Conf. Chengdu, 2006)

Objectives for use of W coatings

JET ‚ITER-like Wall' project:

Test of ITER material mix of PFCs: Be/W/(CFC)

However:

present-day devices are optimized

for C based components:

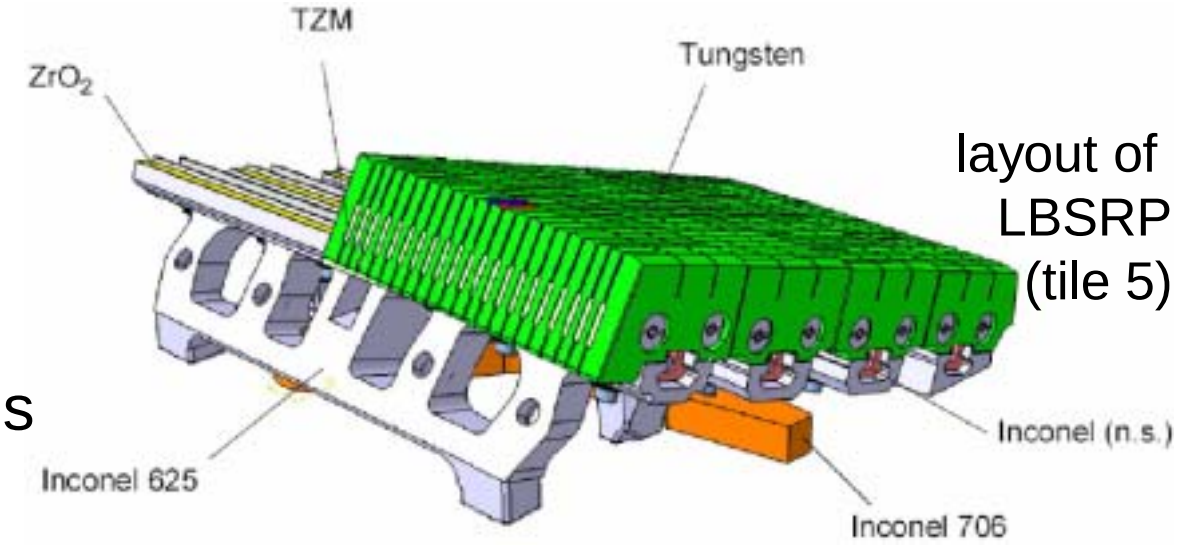
- low weight,
- low conductivity,
- no melting

⇒ design of metal PFCs has to be adapted to metal-specific solutions

or

⇒ use of coated CFC/graphite tiles

T. Hirai et al.
(this conference)



layout of LBSRP (tile 5)

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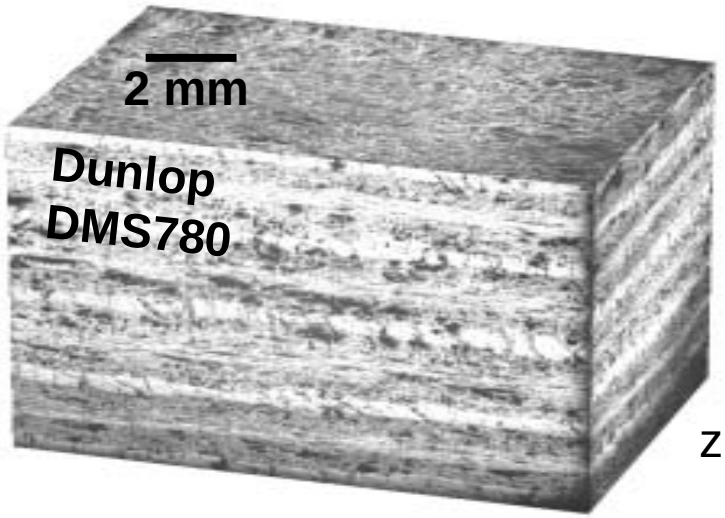
Boundery Conditions for W coatings

Decision driven by technical considerations

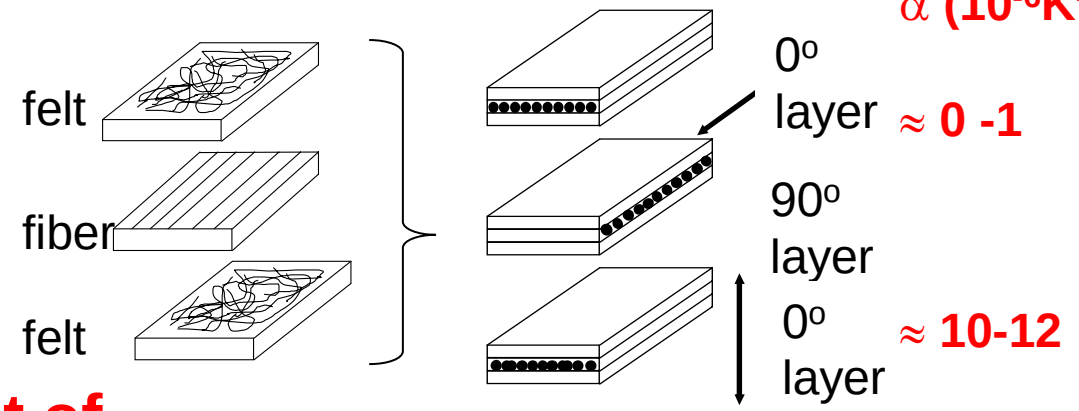
& very tight schedule

CFC grade to be used:

- Dunlop DMS780
- 2d, strongly anisotropic depending on ‚layout'
- strong mismatch of thermal expansion compared to W ($\alpha_W \approx 4.5 \cdot 10^{-6}$ K^{-1})



α (10^{-6}K^{-1})



Risk minimisation by test of several coating techniques and thicknesses

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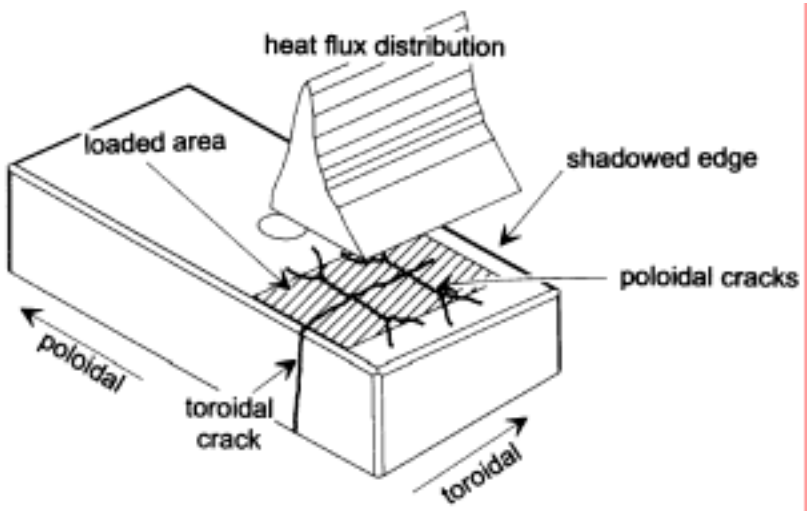
Boundery Conditions for W coatings

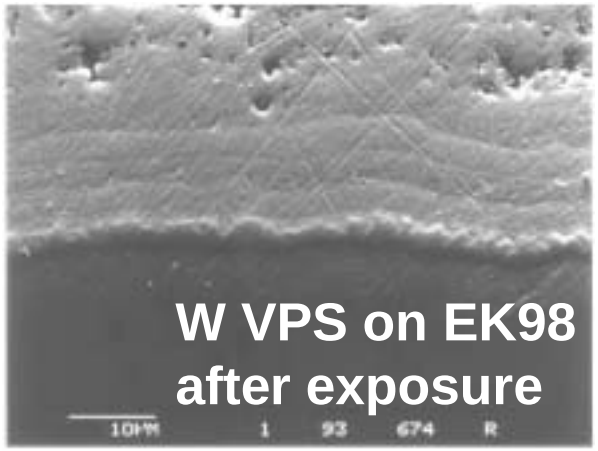
W program in ASDEX Upgrade:

- W divertor in 1995/1996:
  VPS coatings successfully
  applied on EK98



strike point tiles after campaign

H. Maier et al. JNM 258-263 (1998) 921



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Boundery Conditions for W coatings

W program in ASDEX Upgrade:

- W divertor in 1995/1996: VPS coatings successfully applied on EK98
- steady increase of area of W PFCs since 1999
- W coatings on graphite
- only divertor strike point region not yet coated
- main chamber: 3-4 µm PVD strike point: 200 µm VPS

⇒ use of graphite with adapted α: SGL R6710: $\alpha \approx 4.7 \cdot 10^{-6} K^{-1}$

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Test programme for W coatings

Provider	Nominal Thickness	Measured Thickness	Coat. Techn. (Interlayer)	
Plansee	4	2-6	PVD	DMS780
Plansee	10	11-13	PVD	
Plansee	200	220-240	VPS (Re SW)	
Archer Techn.	4	7-8	CVD	
Archer Techn.	10	12-14	CVD	
Archer Techn.	200	240-250	CVD (Re)	
WTCM	4	4	CVD	
WTCM	10	4-10	CVD	
Saint Gobain	200	190-260	VPS (Re)	
DIARC	4	3-5	PVD	
DIARC	4	5-7	PVD (Re)	
DIARC	10	8-14	PVD	
MEdC	10	10-13	PVD/II (Mo)	
C.S.Materiali	200	230-250	VPS (TiC)	
Plansee	200	220-240	VPS (Re SW)	R6710
Sulzer Metco	200	160	VPS (Re)	

- Collaboration of 5 Associations:
  CEA
  ENEA
  IPP
  MEdC
  TEKES
- 3 different techniques:
  PVD, CVD,VPS
- 3 thicknesses:
  4, 10, 200 µm

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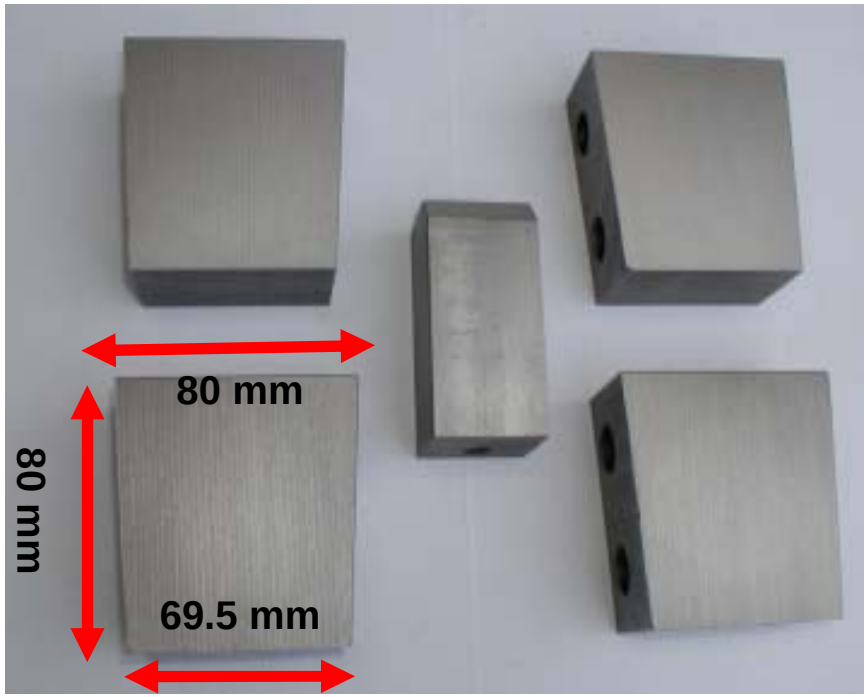
Test programme for W coatings

Three-stage high heat flux test program

- thermal screening 5 steps (GLADIS)
  6.6 – 23.5 MW/m²
- cyclic loading (GLADIS)
  200 pulses, 10.5 MW/m²
- thermal shocks (JUDITH)
  1000 pulses, 0.35 GW/m²

layout of CFC test tiles



Further investigations

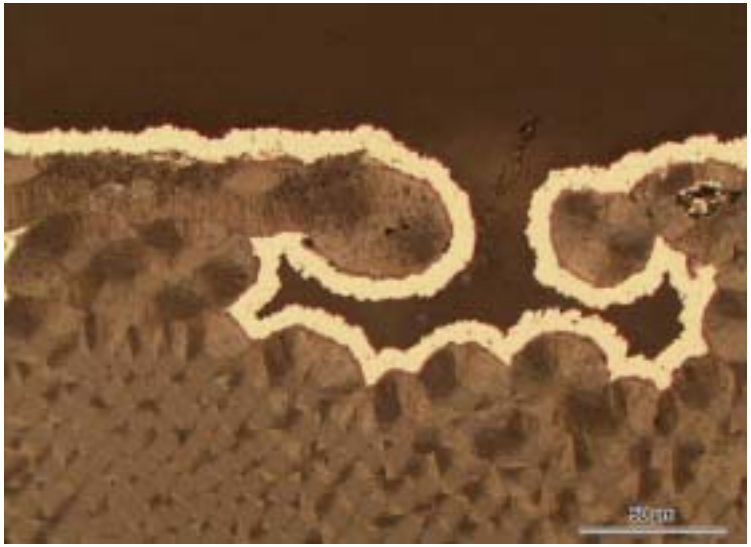
- stress analyses
- metallographic analyses
- adhesion tests (generally high)
- impurity content (generally low)

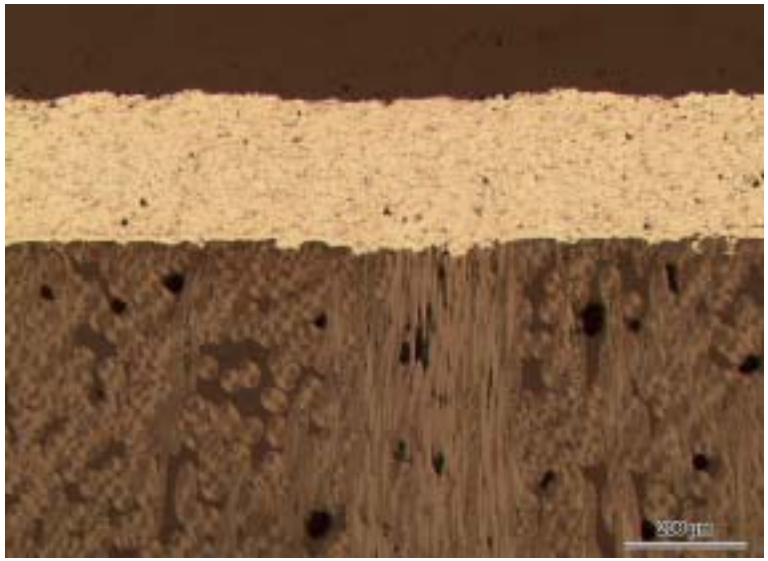
Metallographic Analyses

10 µm

PVD (DIARC)

CVD (ATL)

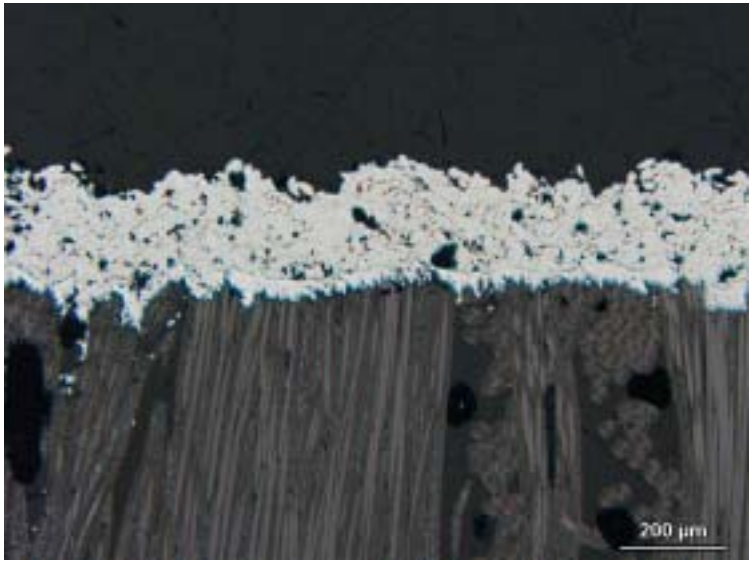




200 µm

VPS (CSM)

VPS (StG)



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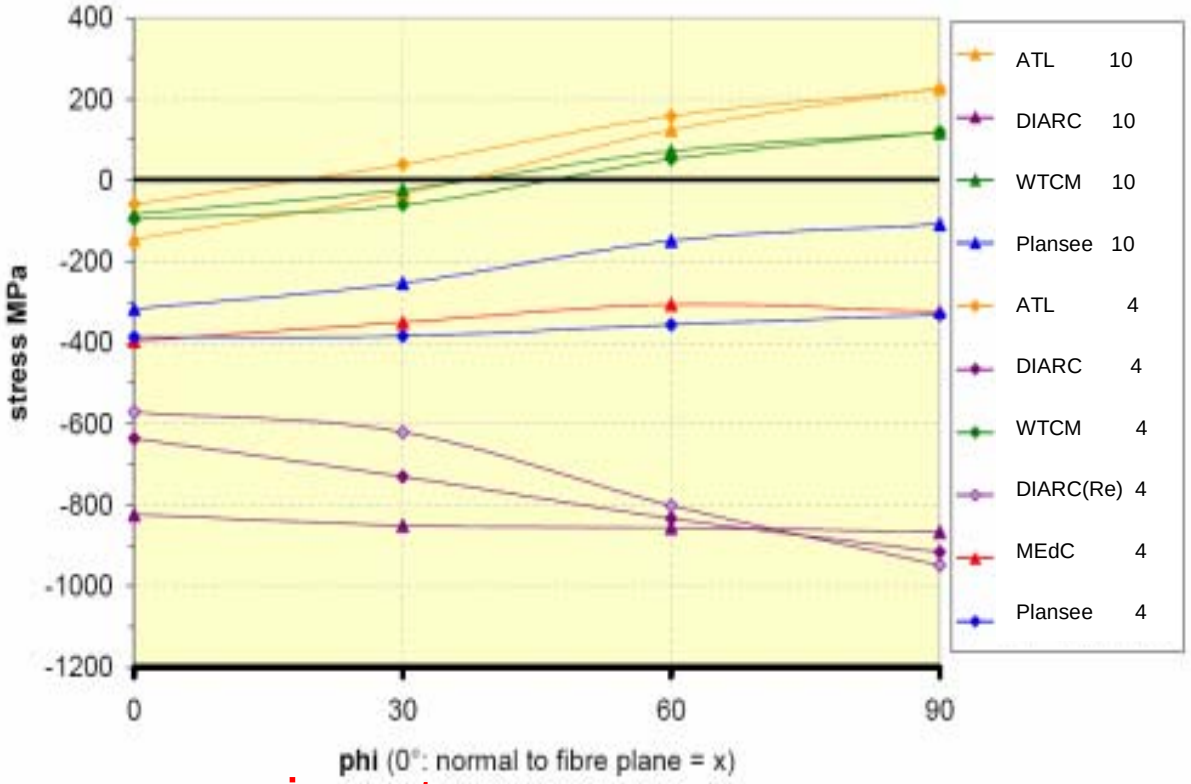
Stress Analyses

Stress state

depends on:

- orientation in respect to fibre plane
- production process

stress states of thin coatings @ r.t. by X-ray diffraction



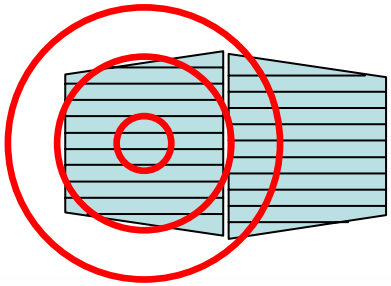
generally:

- CVD coatings almost stress free
- rest of coatings show compressive stress
- stresses in coating provided by MEdC (CMSII) rather low
- surface of VPS coatings show only low orientation independent stresses

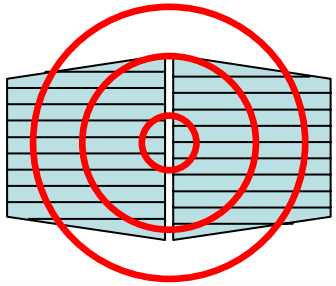
HHF tests in GLADIS

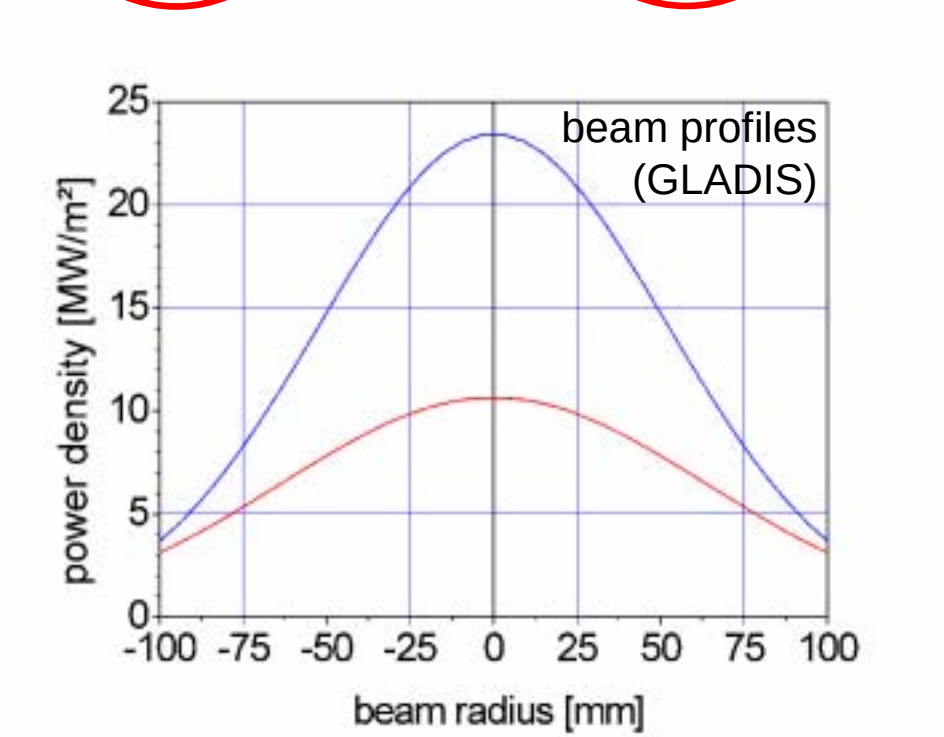
loading geometry

screening



cycling





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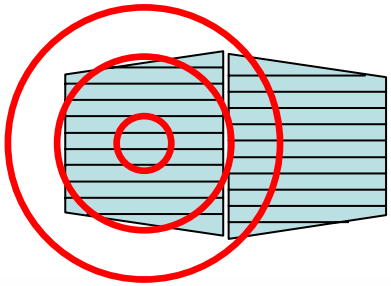
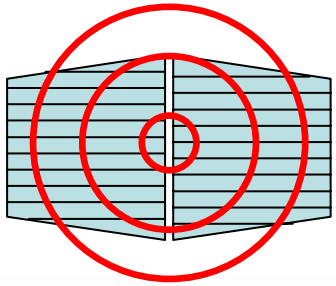
HHF tests in GLADIS

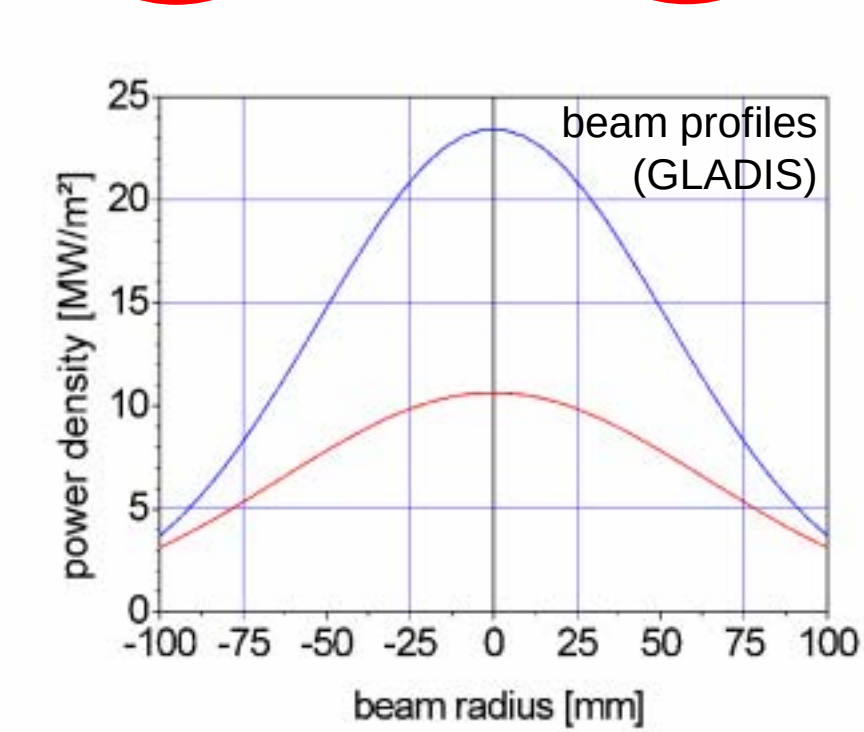
loading geometry

screening

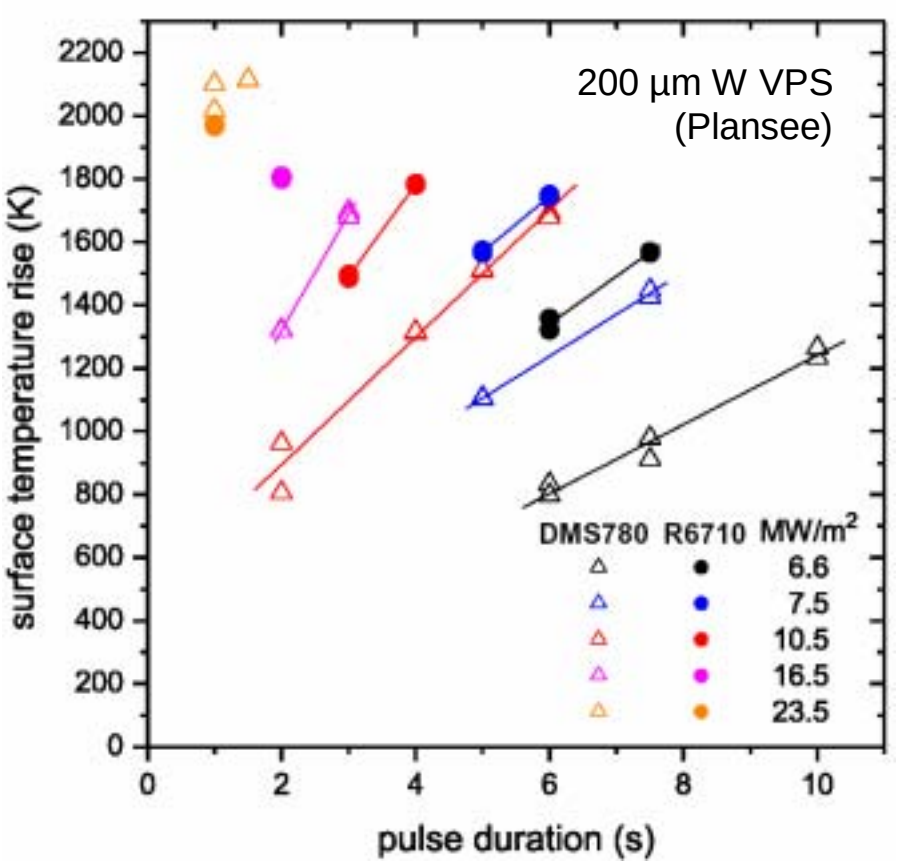


cycling





thermal response of VPS coated CFC and graphite



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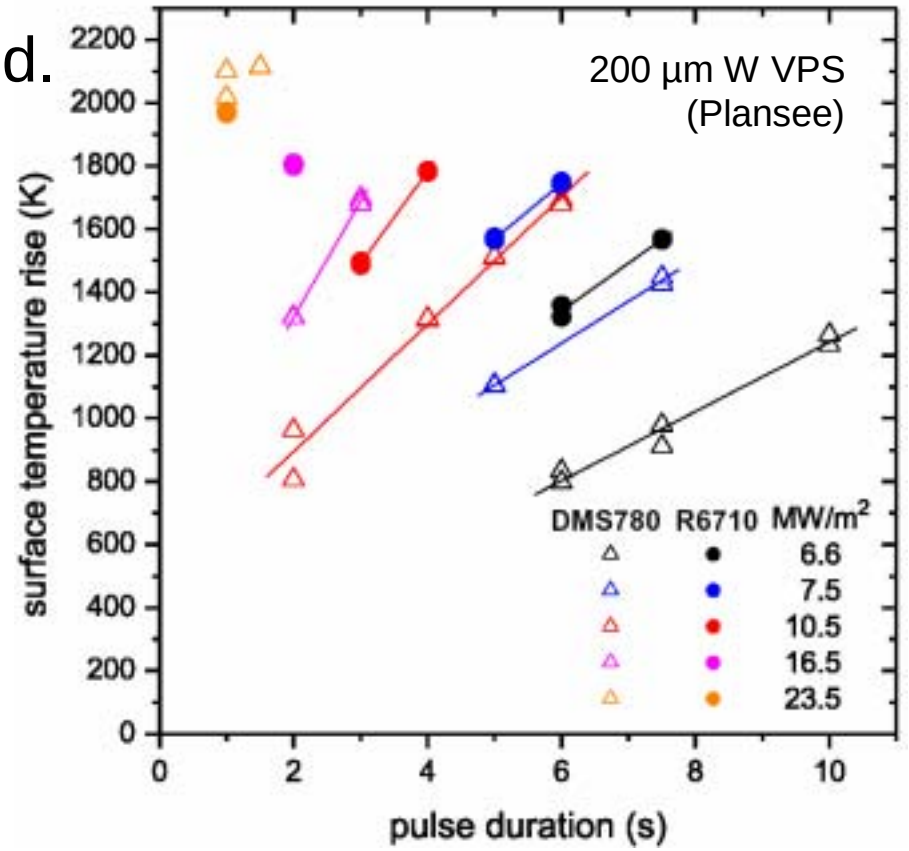
HHF tests in GLADIS

Thermal Screening:

- surface temperatures > 2000°C
- Higher T_{surf} of graphite samples consistent with lower therm. cond.
- most of the coatings survived (or failed only at 23.5 MW/m²)

thermal response of VPS coated CFC and graphite



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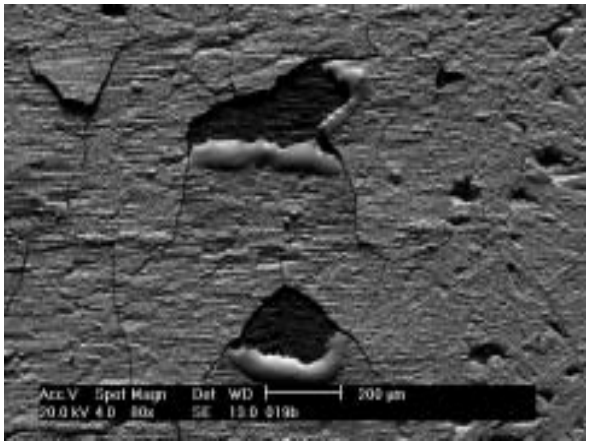
- failure of samples with fibre planes || to surface (’layout II’) already at 16.5 MW/m²



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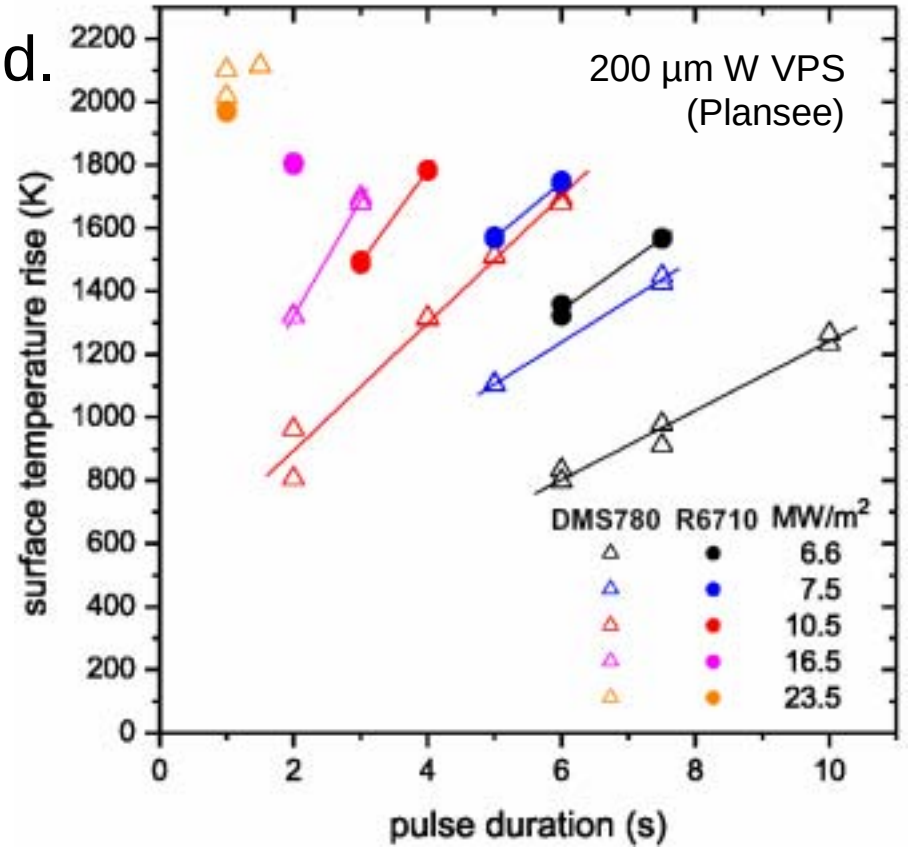

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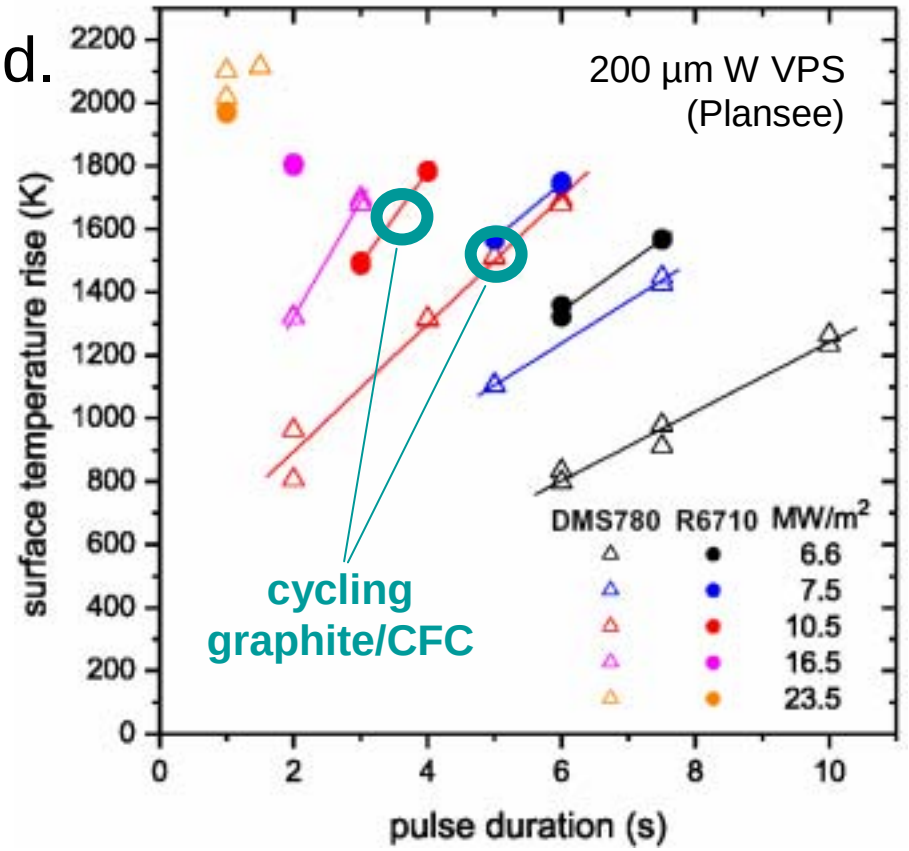
- failure of samples with fibre planes || to surface (’layout II’) already at 16.5 MW/m²
- defects not detectable in pre-NDT

thermal response of VPS coated CFC and graphite



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HHF tests in GLADIS

Mounted graphites samples in GLADIS

Cyclic Loading:

200 pulses @
- 10.5 MW/m²
- 5.0 s (DMS780)
- 3.5 s (R6710)

T_{surf} > 1600°C

thermal fatigue expected for CFC samples due to strong mismatch in α

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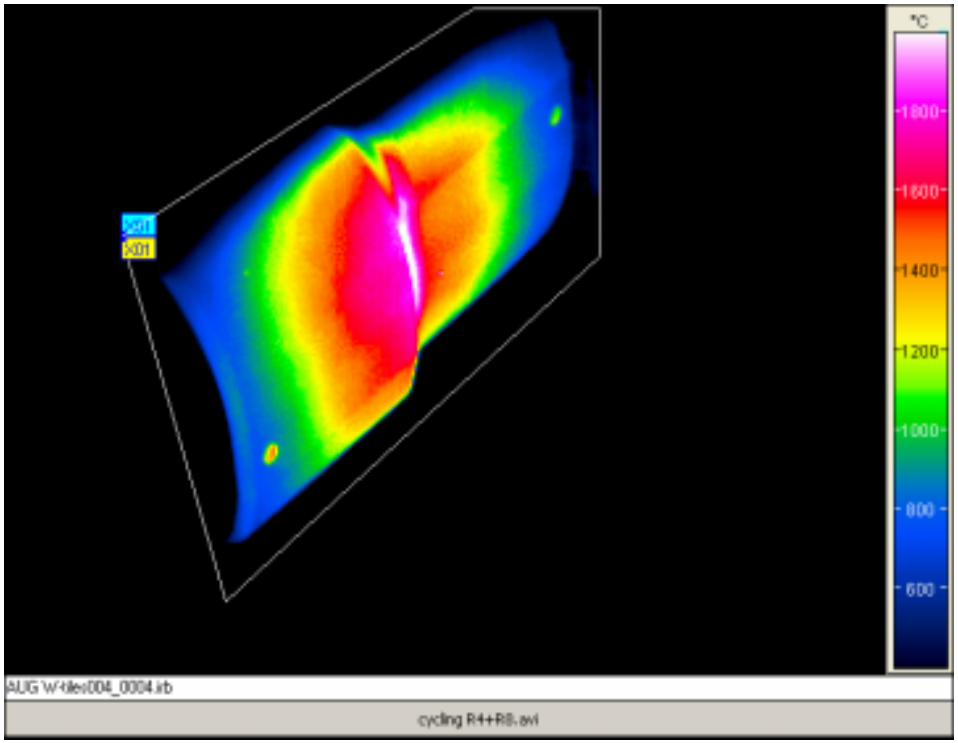
HHF tests in GLADIS

Sequence of thermograpic pictures from 200 pulses



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T_{surf} > 1600°C

thermal fatigue expected for CFC samples due to strong mismatch in α

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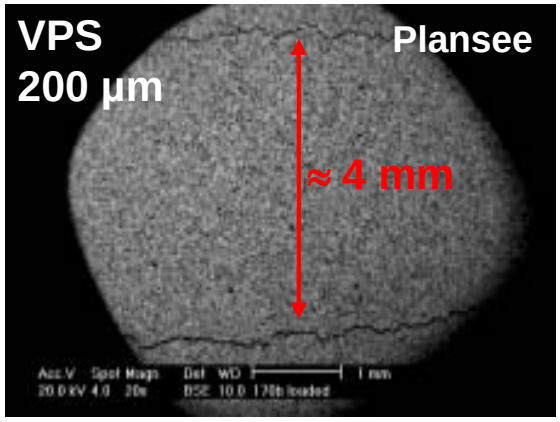
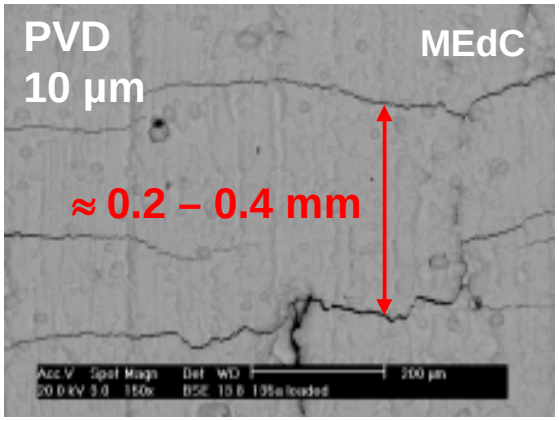
HHF tests in GLADIS

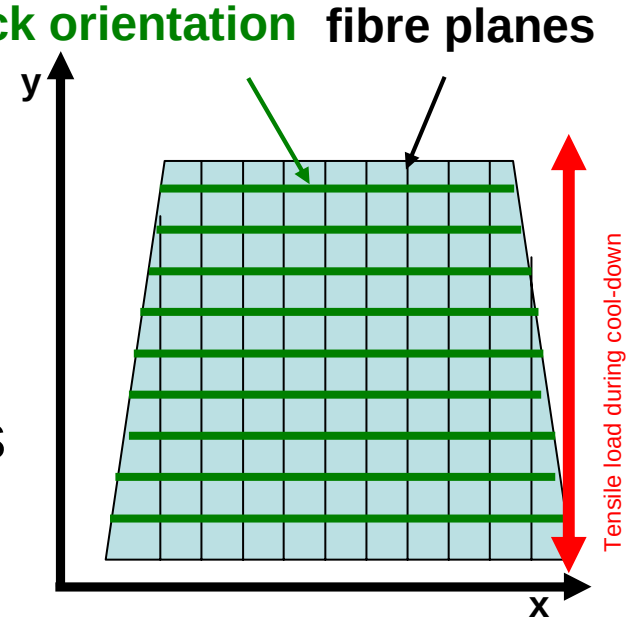
Results of cyclic loading

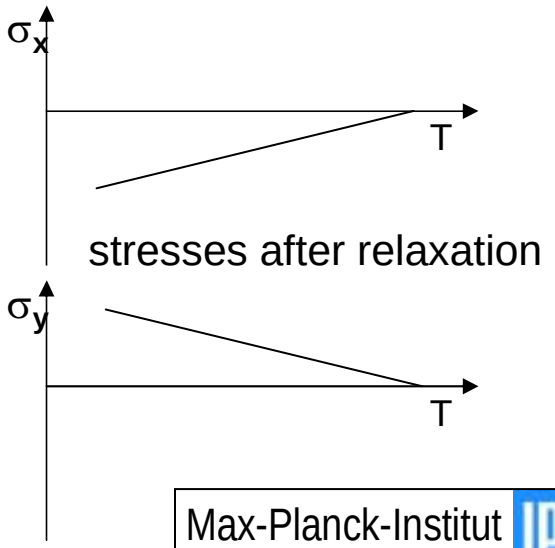
All coatings on CFC show typical pattern:

- regular cracks in x-direction (‚failure mode 1‘, not regarded as problematic)
- distance depending linearly on thickness









VPS Coatings on graphite show only very small (µm) irregular cracks

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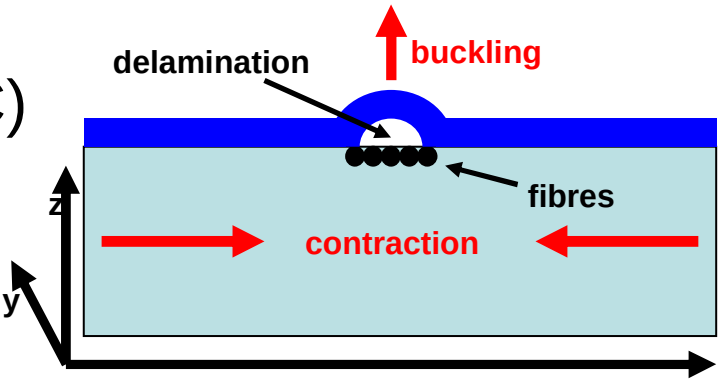
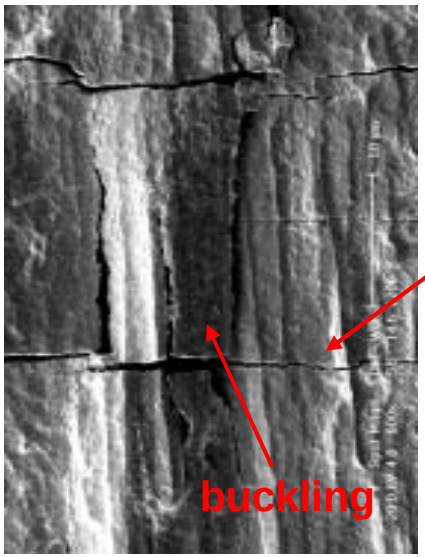
HHF tests in GLADIS

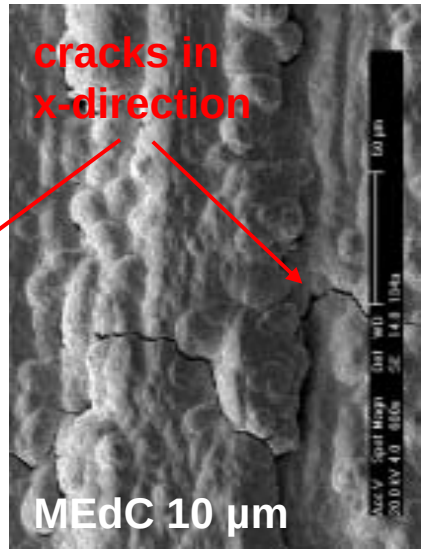
Results of cyclic loading

All ‚thin' coatings on CFC (except MEdC) show two more typical patterns:

- buckling y-direction (‚failure mode 2', loss of thermal contact, melting)





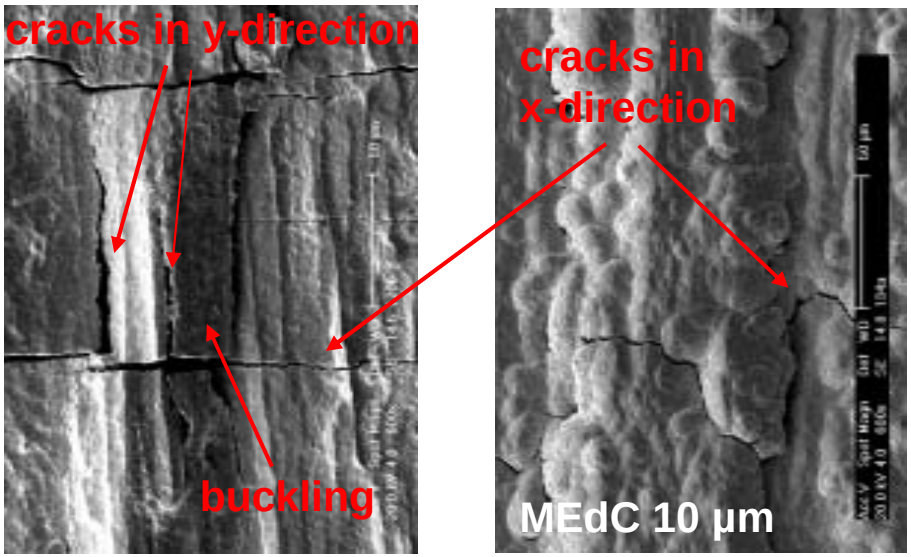


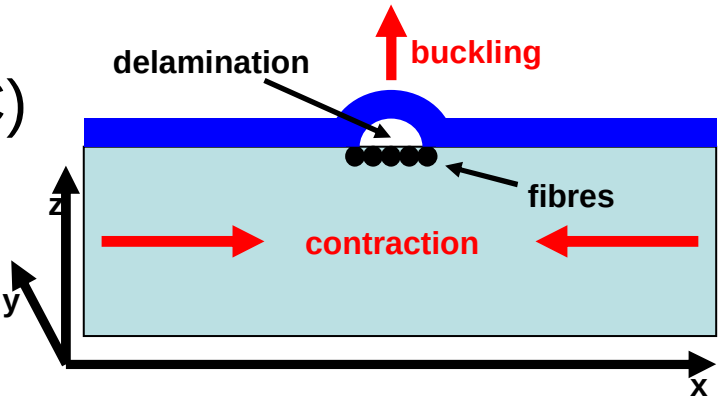
HHF tests in GLADIS

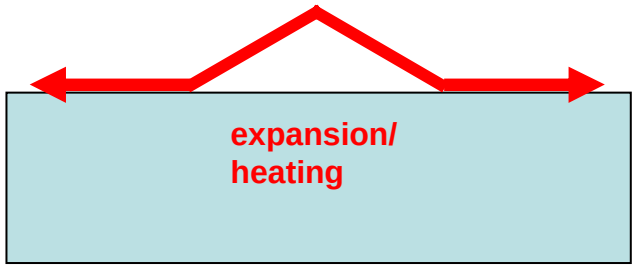
Results of cyclic loading

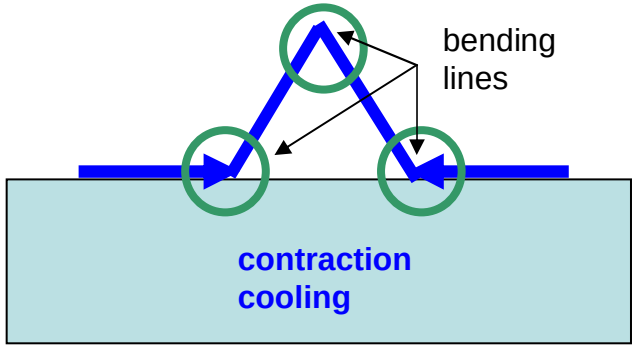
All ‚thin' coatings on CFC (except MEdC) show two more typical patterns:

- buckling y-direction (‚failure mode 2', loss of thermal contact, melting)
- cracking in y-direction (‚failure mode 3', delamination) due to fatigue









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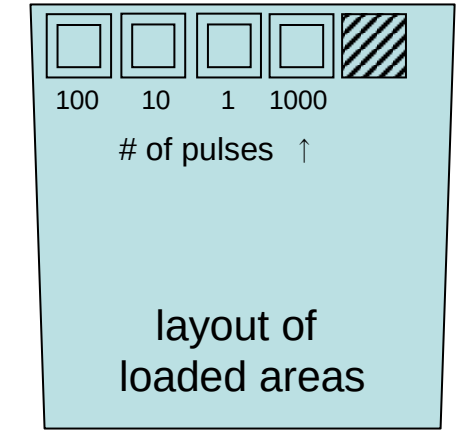
Thermal shock tests in JUDITH

Three most successful coatings on CFC (VPS: Plansee, St. Gobain, PVD: MEdC) were exposed to thermal shocks in the electron beam test facility JUDITH to simulate ELMS



Loading conditions:

0.35 GW/m^2, 1 ms, 1000 pulses (~0.3 Hz), 8 x 8 mm^2

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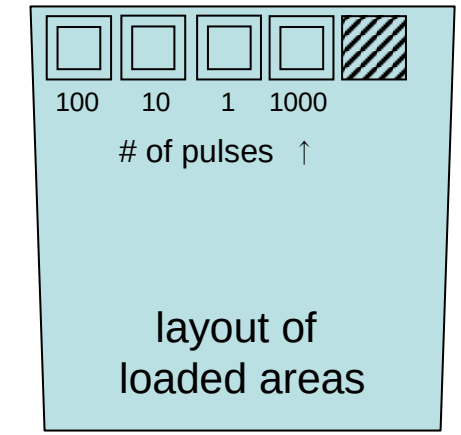

Loading conditions:

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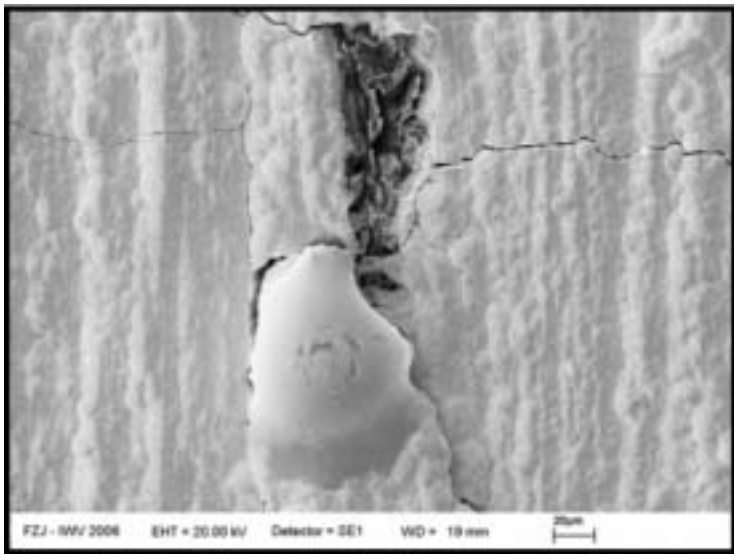
Results:

- failure mode 2 and 3 for PVD coating

$\Rightarrow$ delamination and local melting



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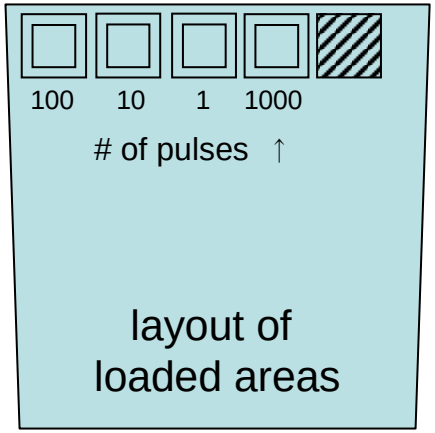


Loading conditions:

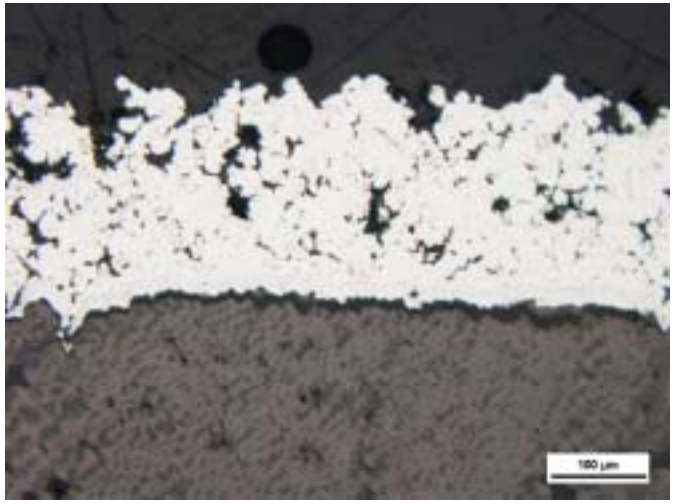
0.35 GW/m^2, 1 ms, 1000 pulses (~0.3 Hz), 8 x 8 mm^2

Results:

- failure mode 2 and 3 for PVD coating

⇒ delamination and local melting

- no visible defect on VPS surfaces
- however, metallographic cross section reveal start of delamination at areas with fibres parallel to surface



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Summary and Conclusions

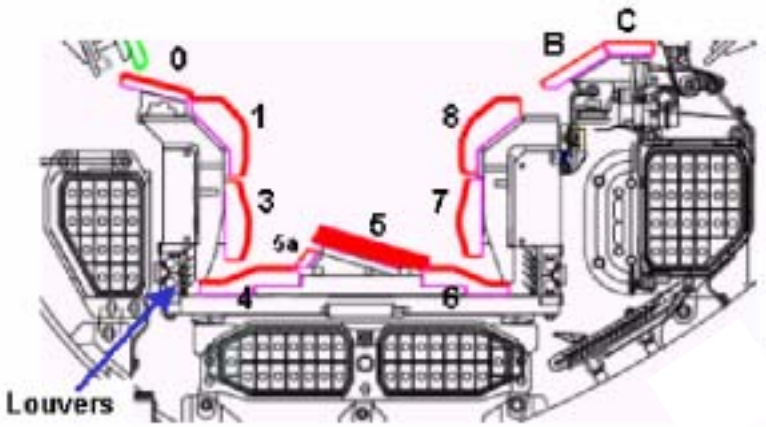
Comprehensive test program on W coatings on CFC and graphite

- 14 different coatings on CFC (Dunlop DMS780)
- 3 different coatings on graphite (SGL R6710)
- anisotropic thermal expansion of CFC leads to cracks and can cause thermal fatigue of thin coatings
- coating of surface || to CFC fibre plane should be restricted to low power load areas
- tile geometry has to be adapted to avoid sharp edges
- coatings on graphite exhibit lower risk of failure
- generally, VPS coatings show best performance under high heat load

Summary and Conclusions

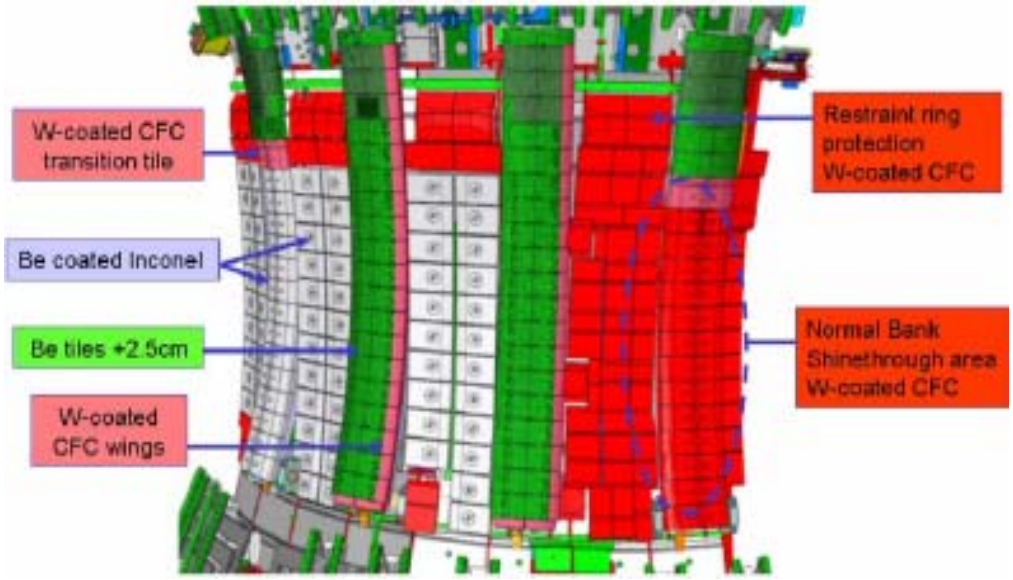
JET ‚ILW' project solution (coatings on CFC)

- divertor (except 5, 5a, B,C):
  200 µm VPS
- main chamber (mainly NBI shinethrough areas):
  10 µm PVD (CMSII)



ASDEX Upgrade (coating on graphite)

- outer strike point area
  200 µm VPS



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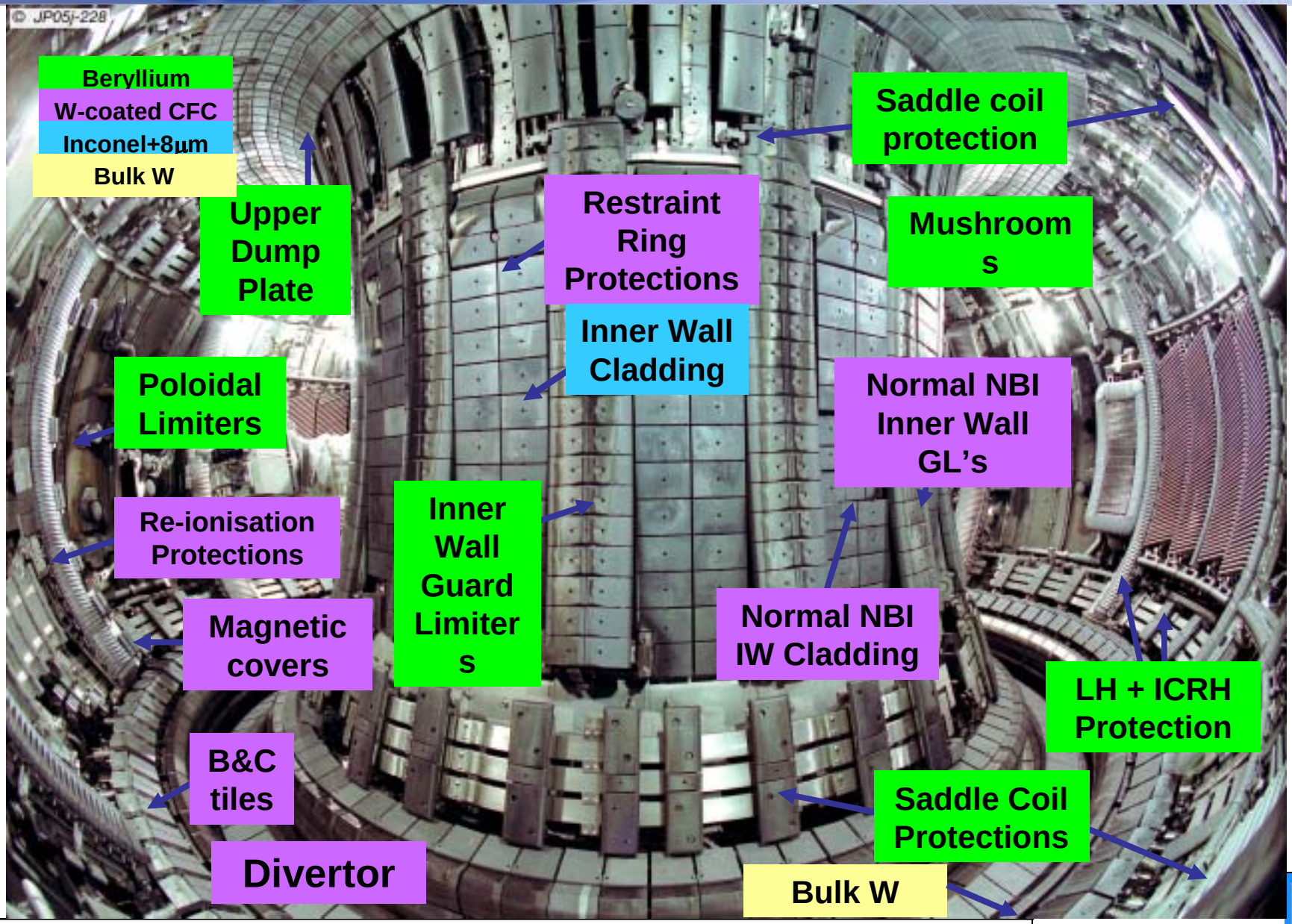
PFCs for the ILW in JET



für Plasmaphysik