Investigation of Tungsten Coatings on Graphite and CFC

R.Neu¹, H.Maier¹, E. Gauthier², H. Greuner¹, T. Hirai³, Ch. Hopf¹, J. Likonen⁴, G. Maddaluno⁵, G.F. Matthews⁶, R. Mitteau², V. Philipps³, G. Piazza⁷, C. Ruset⁸, JET EFDA contributors*

¹ MPI für Plasmaphysik, Euratom Association, Garching, Germany
² Association Euratom-CEA, Cadarache, DSM/DRFC, Saint Paul Lez Durance, France
³ Forschungszentrum Jülich, Euratom Association, Jülich, Germany
⁴ Association Euratom-TEKES, VTT Processes, Finland
⁵ Association Euratom-ENEA, Frascati, Italy
⁶ Association Euratom-UKAEA, Culham Science Centre, Abingdon, UK
⁷ EFDA-Close Support Unit, Culham Science Centre, Abingdon, UK
⁸ NILPRP, Association Euratom-MEdC, Bucharest, Romania

* 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)
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 ($\alpha_W \approx 4.5 \cdot 10^{-6} \text{ K}^{-1}$)

Risk minimisation by test of several coating techniques and thicknesses
Boundery Conditions for W coatings

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

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

W VPS on EK98 after exposure

strike point tiles after campaign
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 $\alpha$:
  SGL R6710: $\alpha \approx 4.7 \cdot 10^{-6} \text{K}^{-1}$
## Test programme for W coatings

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

- Collaboration of 5 Associations:
  - CEA
  - ENEA
  - IPP
  - MEEdC
  - TEKES

- 3 different techniques: PVD, CVD, VPS
- 3 thicknesses: 4, 10, 200 µm
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

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)

EFDA JET
Max-Planck-Institut für Plasmaphysik
Stress state
depends on:
• orientation in respect to fibre plane
• production process
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

beam profiles
(GLADIS)

power density [MW/m²]

beam radius [mm]
HHF tests in GLADIS

- Loading geometry screening
- Cycling

Thermal response of VPS coated CFC and graphite

Beam profiles (GLADIS)

Power density [MW/m²] vs. beam radius [mm]

Surface temperature rise (K) vs. pulse duration (s)

200 µm W VPS (Plansee)
HHF tests in GLADIS

Thermal Screening:
• surface temperatures > 2000°C
• Higher $T_{\text{surf}}$ 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

200 µm W VPS (Plansee)
HHF tests in GLADIS

Thermal Screening:
- surface temperatures > 2000°C
- Higher $T_{\text{surf}}$ of graphite samples consistent with lower therm. cond.
- most of the coatings survived (or failed only at 23.5 MW/m²)
- failure of samples with fibre planes || to surface (‘layout II’) already at 16.5 MW/m²

200 µm W VPS (Plansee)
HHF tests in GLADIS

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

200 µm W VPS (Plansee)
HHF tests in GLADIS

Mounted graphites samples in GLADIS

200 µm W VPS (Plansee) on SGL R6710

Cyclic Loading:

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

\( T_{surf} > 1600^\circ C \)

thermal fatigue expected for CFC samples due to strong mismatch in \( \alpha \)
Cyclic Loading:

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

\( T_{\text{surf}} > 1600^\circ\text{C} \)

thermal fatigue expected for CFC samples due to strong mismatch in \( \alpha \)
**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
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)
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
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/m², 1 ms, 1000 pulses (~0.3 Hz), 8 x 8 mm²
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/m², 1 ms, 1000 pulses (~0.3 Hz), 8 x 8 mm²

**Results:**
- failure mode 2 and 3 for PVD coating
  ⇒ delamination and local melting
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/m², 1 ms, 1000 pulses (~0.3 Hz), 8 x 8 mm²

**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
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
PFCs for the ILW in JET

- Beryllium
- W-coated CFC
- Inconel+8μm
- Bulk W
- Upper Dump Plate
- Poloidal Limiters
- Re-ionisation Protections
- Magnetic covers
- B&C tiles
- Divertor
- Inner Wall Guard Limiters
- Inner Wall Cladding
- Restraint Ring Protections
- Normal NBI IW Cladding
- Normal NBI Inner Wall GL’s
- LH + ICRH Protection
- Saddle Coil Protections
- Saddle Coil protection
- Mushroom s
- Bulk W
- PFMC 11, Greifswald, 11/10/06