W Divertor Technical Development & Materials Research towards DEMO

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W/Cu divertor for EAST
- Engineering and commissioning
History of PFMC for EAST

2008
Full C PFC

2012
Mo-FW + C-Div

2014
W&C-Div+Mo-FW

1st plasma

Full SS

2006

W
Mo
C

2015-05-11
IAEA DPW-3, Hefei, May 11-14, 2015
Motivation of W/Cu divertor on EAST

- ITER-like W monoblocks
  - divertor targets (10 MW/m²)
- Flat type W/Cu PFCs
  - divertor dome and baffles (5 MW/m²)
- Cassette body structure (80)

Better active cooling + feedback controlled radiative divertor scenarios
Structure analyses

ASIPP

$I_x = 0.5I_f \times 2/80$

$I_k = 12500$

50\% Ip

$80/25.0 \times \phi_h$

方案 1

方案 2

方案 3

6mm 销

圆孔

2015-05-11

IAEA DPW-3, Hefei, May 11-14, 2015
Cassette body and cooling

Requirements for cooling

- Surface temperature of W monoblock < 1200 °C
- Maximum temperature of CuCrZr < 500 °C
- Water coolant, inlet temperature 20 °C, and temperature rise < 70 °C, to avoid boiling (total length a set of PFU: 1329mm)
Design of PFCs

ASIPP

- ~15,000 monoblocks
- 720 monoblock-units
- 240 flat-type mockups
- Tolerance of plasma-facing surface: toroidal: 1mm; neighbor: 0.5mm

End-box design

Compact end-boxes for cooling connects

Monoblock-W/Cu targets

End-boxes

Flat type W of ~2mm thick

Monoblock units × 4-5

Coolant from Cassette body
ITER grade tungsten

• Manufacturing process
  – Sintering (~2000°C)
  – Warm rolling (~1100°C), ~70% reduction in thickness
  – Annealing

• Mechanical Properties
  – Tensile strength, ~470 MPa (1000°C)
  – Young’s modulus, $E=390-410$ GPa (room T)
  – Shear modulus, $G=156-177$ Gpa (room T)
  – Poisson's ratio, $v = 0.28-0.30$ (room T)
  – Purity , ~99.95%
Monoblock-W tiles

- ITER grade W has been manufactured in batch scale
- W/Cu monoblocks prepared employing HIP technology
- ITER-like W/Cu mockups via domestic collaboration
• HIP+HIP: W/Cu mockups were manufactured successfully by a double Hot Isostatic Pressing technology

• NDT results: bondings between monoblocks/OFC/CuCrZr tube excellent; HHF testing: 10MW/m²-1000cycles passed
Flat-type W/Cu PFCs

• **Casting + HIP**: The interface of W/Cu were joined by casting, and then the interface of Cu/CuCrZr was bonded by HIP at lower temperature of 500~600℃.

• **NDT results**: bondings between W tiles/OFC/CuCrZr plate excellent; **HHF testing**: 5MW/m²-1000cycles passed
Parts joining – E-beam welding

- Joining between monoblock units with endbox/manifold and flat baffle

- Joining of two-half parts for dome structural design

- Supporting legs and inlet/outlet cooling tubes joined to CuCrZr heat sink
Global He leak check for PFCs

Evaluation of welding quality and reliability for EAST OVT, IVT and DOME components. Acceptance criteria: $1 \times 10^{-10} \text{ Pa.m}^3\text{s}^{-1}$ during baking: @ 180°C for 20 min under 1.5 MPa (He inside) (Background vacuum: < $5.4 \times 10^{-3}$Pa; leak level: $2 \times 10^{-11}$ Pa.m$^3$.s$^{-1}$)
ASIPP

OVT/IVT/DOME-PFCs

HIPed Flat-type PFUs

HIPed Monoblock PFUs

DOME

OVT

IVT

HIPed Monoblock PFUs
Assembly of PFCs+CB

ASIPP
Highlights

PFCs+CB assembly: 80
IVT/OVT/DOME: 80 each
Monoblock PFUs: 720
Monoblock W: 15,000
Flat-type PFUs: 240
Flat W tiles: 24,000
E-beam seam: > 5000
W raw powders: > 10 tons
CuCrZr plates: > 8 tons
CuCrZr tubes: 720pcs/360m

W/Cu PFCs for EAST upper divertor
Commissioning in 2014

ASIPP

• Twice leak events during baking at 170°C, and first repaired and second evacuated (given-up)
• Baking at the end of campaign at 280°C to test PFCs and find put weak points (possible leaks)
• After campaign, found 13 leak points and some W tile damages, certain and uncertain causes!
Improvement in 2015

• Cooling tube connection: hard welding -> soft bellows
• QA&QC for EBW btw tube and heat sink enhanced
• PFCs+CB baking at 250°C prior to assembly in VV
W materials development
- National program and activities
R & D needs for W

**Synergy effects on PFMC:**
- Particle irradiations: n + D/T + He + impurity
- High heat fluxes: \(\sim 10\text{MW/m}^2\) (steady), \(\sim \text{GW/m}^2\) (transient)
- Impact of thermal stresses & EM loads
- Huge use of radioactive tritium

**Failure modes**
- PFM: sputtering/bubble&blistering/melting&evaporation
- PFC: structural damage due to stresses & loads (fatigue!)
- Safety: material degradation & tritium inventory with dpa

**Requirements**
- Resistance to sputtering/bubble&blistering/n radiation
- High thermal conduct. & nice PFC design & engineering
- Low DBTT & high recrystal. T & high mechanical strength
National Magnetic Confinement Fusion Program
Ministry of Science and Technology (MOST-CN)

Tungsten related R&D activities

• ASIPP & SWIP: PFMC design and PWI studies
• AT&M & XTC: PFMC commercialization(W/Mo)
• USTB: W nanofiber/thick coatings/alloying
• ISSP: Alloying w/ high ductility & low DBTT
• HFUT: Fine-grain/ODS/alloying W
• CSU: Sintering densification/alloying
• ……
ITER-FW-PA (Be/Cu/SS-HV-PFC) and HHF testing facilities

EMS-60 (60kW Electron-beam Materials testing Scenario)
- EB Gun
- HV
- IR Camera
- IR Pyrometer
- Cooling Circuits
- Process Chamber
- Mock-up
- Thermal couples
- X-Y Table

EMS-400 (400kW Engineering Mockup test Scenario)

Main parameters:
- Max. power 400kW with max. accel. voltage 60kV
- Max. heating area: 0.5×0.8m²
- Max. scanning frequency: 10kHz
- ITER water cooling condition: 3-5MPa, 70-130°C, 4-10m/s (FW/divertor)
- Beryllium handling
Minor project for tungsten PFMC

<table>
<thead>
<tr>
<th></th>
<th>SPS Grain size</th>
<th>Relative density</th>
<th>+HIP Grain size</th>
<th>Relative density</th>
</tr>
</thead>
<tbody>
<tr>
<td>W-0.1TiC</td>
<td>10 μm</td>
<td>92.4%</td>
<td>10 μm</td>
<td>97%</td>
</tr>
<tr>
<td>W-0.2TiC</td>
<td>10 μm</td>
<td>96%</td>
<td>10 μm</td>
<td>98%</td>
</tr>
<tr>
<td>W-0.5TiC</td>
<td>5 μm</td>
<td>96.8%</td>
<td>5 μm</td>
<td>99.1%</td>
</tr>
<tr>
<td>W-1La2O3</td>
<td>10 μm</td>
<td>94%</td>
<td>10 μm</td>
<td>94.1%</td>
</tr>
<tr>
<td>W-3La2O3</td>
<td>6 μm</td>
<td>95%</td>
<td>6 μm</td>
<td>95.2%</td>
</tr>
</tbody>
</table>

Thermal conductivity

Micro-hardness

W-TiC (Ф80*10mm)

Microstructure (TEM)

W-0.5%TiC re-crystallization temperature larger than 1750 °C

1700°C  1750°C
ASIPP

- Leading domestic W/Mo product supplier
- Leading expert on hot isostatic pressing (HIP)
- Capable of packing-sintering-rolling-machining

R&D & batch production of EAST W-DIV-PFCs
Finger-like PFC development

Tile: Pure W

Thimble: W+1vol.% La (MIM-W1La)

CVD Tungsten on Cu or CFC

Metallurgical bonding at W and W1La interface

<table>
<thead>
<tr>
<th>Property</th>
<th>MIM-W</th>
<th>MIM-W1La</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>19.12 g/cm³</td>
<td>18.98 g/cm³</td>
</tr>
<tr>
<td>Relative density</td>
<td>98.85%</td>
<td>99.12%</td>
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<tr>
<td>Hardness</td>
<td>375 HV30</td>
<td>355 HV30</td>
</tr>
<tr>
<td>Grain size</td>
<td>18-25 μm</td>
<td>6-10 μm</td>
</tr>
</tbody>
</table>

Deposition rate: 0.3-0.5 mm/h
Thickness: 1-3 mm
Purity: 99.9999%
Thermal conductivity: >180 W.m/K
Hardness: 430
Hardness (HV): 430
Bonding strength: W/Cu >50 Mpa

2.2 MW/m², 100 cycles
Tungsten nanowires in batch using amorphous CNT as template

- Hydrogen reduction of carbon coating on W nanowire -> Key issue to achieve batch preparation
- W nanowire / fiber-strengthened composite (\(W_f\),W) is targeting -> Both micro & macro functions

Thick tungsten coatings via electrodeposition from molten salt

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deposition temperature (K)</td>
<td>1173</td>
</tr>
<tr>
<td>Density (g·cm(^{-3}))</td>
<td>18.91 ± 0.091</td>
</tr>
<tr>
<td>Porosity (%)</td>
<td>&lt; 1%</td>
</tr>
<tr>
<td>Roughness (Ra, (\mu)m)</td>
<td>10.87 ± 1.86</td>
</tr>
<tr>
<td>Microhardness (HV)</td>
<td>465 ± 13</td>
</tr>
<tr>
<td>Oxygen Content</td>
<td>0.018</td>
</tr>
<tr>
<td>Thermal Conductivity (W·m(^{-1})K(^{-1}))</td>
<td>150.87</td>
</tr>
</tbody>
</table>
Oxide dispersion-strengthened W alloys via co-precipitated process
Carbide dispersion-strengthened W alloys via precipitate-coating process

Chemical solutions
Powder precipitation
Sintering-Rolling

Interior Y₂O₃

Interior TiC

W-0.25wt% Y₂O₃

W-0.5wt% TiC

Interior strengthened W exhibited close strength to commercial pure W
DBTT decreased by 200K due to the interior nanoparticles
To be continued: further optimization of process
Bulk W-0.5%ZrC alloy plate with extraordinary ductility

Milling - Sintering - HR

Average grain size 2-3μm
ZrC & ZrO₂ fine grains

8.5 (6.0) × 130 × 220 mm

- RT plasticity, fracture strength: 2.5GPa; DBTT ~ 100°C;
- 500°C, UTS ~ 600MPa, TE as large as ~ 45%;
- Excellent high temperature strength and plasticity.
- Activation of surfaces of W powders and TiC nanoparticles -> Dense sintering!
- Series of rare-earth ODS-W by wet chemical preparation of nano W powders
- Wet chemical preparation of W-1%TiC powders and SPS sintering (99% dense)
Effects of nano-size powder, powder surface modification and high-energy activation on sintering densification in traditional and MIM processes

Preliminary work on La$_2$O$_3$, Y$_2$O$_3$, ZrC, TiC strengthened W materials

- Activation measures increased density and decreased sintering T
- Alloyed W materials have average grain size 5-10μm
- Oxide particles distributed both grain boundary and inside grains
- Carbide particles formed mixed inter-compound, e.g., (W,Ti)C phase
Summary and outlook
Summary & Outlook

- EAST has upgraded its upper divertor into full W/Cu-PFCs, employing HIP technology and e-beam welding. Ready for studying plasma-tungsten interactions (PWI).

- Commissioning in 2014 found leak and damage in the EAST W divertor. Repairing and improvement have been made in 2015 and now ready for new campaign.

- National program has been organized aiming at new grades of W materials and new ways for PFC production.

- New program will be launched exploring new divertor concepts and corresponding engineering design of PFMC towards CFETR and future DEMO.
Thanks for your attention!
Welcome to collaborations!