“What should be the surface material for CTF and DEMO?”

C.P.C. Wong, B. Chen, A. Hassanein¹, M. Sawan², K. Umstadter³, T. Palmer³

¹Purdue University
²University of Wisconsin, Madison
³University of California, San Diego

US Department of Energy
OFES Research Needs Workshop (ReNeW)
University of California, Los Angeles

March 2–6, 2009
Surface Material is critically important to advanced tokamaks:

- Plasma performance is affected by impurities transport.
- Surface heat removal, tritium co-deposition and inventory will have impacts on material selection, and for devices beyond ITER.
- Radiation effects from neutrons and \( \text{He}^+ \), and components lifetime will have to be taken into consideration.

Surface material options:

- C
- Mo
- W
- Be/W/C
- C/W
- Be/W/C
- ?
- ?

Experiments to ..................... >>>>>>>>>>>>>> CTF >>>> DEMO
Boronization--Wall Conditioning

All high performance MFE machines have been boronized or siliconized:

- DIII-D, C-Mod, JET, JT-60U, AUG, NSTX, TEXTOR, JFT-2M, LHD, HT-7…etc

- Basic physics interaction between B and plasma not fully understood

- C-MOD with Mo wall requires routine BZN for high performance (Lipshultz, J of Nu Mat., 363-365 (2207) 1110-1118)

Different boron compounds ($B_2H_6$, $B(CD_3)_3$, $B_{10}D_{14}$, $C_2B_{10}H_{12}$) have been used with success
He\textsuperscript{+} Irradiation on W Results Can Simulate DEMO Parameters, and Compare to ITER He\textsuperscript{+} Flux

<table>
<thead>
<tr>
<th>Simulating DEMO first wall</th>
<th>Simulating DEMO Divertor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flux,#/m\textsuperscript{2}.s</td>
<td>$10^{18}$-$10^{19}$</td>
</tr>
<tr>
<td>Fluence,#/m\textsuperscript{2}</td>
<td>$10^{21}$-$10^{22}$</td>
</tr>
<tr>
<td>He\textsuperscript{+} energy</td>
<td>200 eV to 8 KeV</td>
</tr>
<tr>
<td>Temperature</td>
<td>100-1000° C</td>
</tr>
</tbody>
</table>

Results from ion beam, plasma devices, TRIAM-1M and LHD discharges

First wall: Flux $10^{17}$-$10^{18}$#/m\textsuperscript{2}.s
Divertor: Flux $\sim 10^{21}$#/m\textsuperscript{2}.s

For the same experimental fluence, it would amount to a few hundred to thousand ITER 400 s discharges

Kukushkin, ITER D 27TKC6, 14/04/08
Low Energy He\(^+\) Irradiation in Plasma Simulator NAGDIS-H

Bubbles and Holes Formation on W Surface \(\geq 10\) eV

<table>
<thead>
<tr>
<th>Fluence</th>
<th>2.6 \times 10^{27} /m^2</th>
<th>0.9 \times 10^{27} /m^2</th>
<th>0.8 \times 10^{23} /m^2</th>
<th>0.8 \times 10^{27} /m^2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ion flux</td>
<td>3.7 \times 10^{23} /m^2s</td>
<td>1.2 \times 10^{23} /m^2s</td>
<td>1.1 \times 10^{23} /m^2s</td>
<td>1.1 \times 10^{23} /m^2s</td>
</tr>
<tr>
<td>Time</td>
<td>7200 s</td>
<td>7200 s</td>
<td>7200 s</td>
<td>7200 s</td>
</tr>
<tr>
<td>Temperature</td>
<td>2100 K</td>
<td>2600 K</td>
<td>2200 K</td>
<td>2950 K</td>
</tr>
</tbody>
</table>

**Surface**

- W1 \(\sim 30\) eV
- W2 \(\sim 10\) eV
- W3 \(\sim 5\) eV
- W4 \(\sim 1\) eV

**Cross section**

Growth of W Nano Structure from the Bottom, the Thickness Increases with Plasma Exposure Time

SEM cross-sections of W targets exposed to PISCES-B pure He plasmas.

Consistent He plasma exposures: $T = 1120$ K, $\Gamma_{He^+} = 4 - 6 \times 10^{22}$ m$^{-2}$s$^{-1}$, $E_{ion} \sim 60$ eV

Baldwin and Doerner, Nuclear Fusion 48 (2008) 1-5
C Plasma Impurity Can Inhibit Morphology Change with D₂-He with C Discharges

Similar results were obtained with Be and could be projected for B

At $E_i = 15$ eV, C deposited on W has not been sputtered away.

- At $E_i = 15$ eV, C deposited on W are not sputtered away.
  - W-C layers inhibit He induced morphology.

Baldwin and Doerner, PISCES, UCSD
A Boron Tungsten-surface Concept (BW-surface)  
“Boron Infiltrated W Surface”

The concept:

• Infiltrate B into a drilled W-surface such that all the W holes and surfaces are filled covered with B and protected from the plasma.

• B coating could protect W due to the low range of charged particles.

• The plasma would only see B, thereby retaining needed plasma performance.

• Exposed W will have a low erosion rate.

• Design example: the W-disc can be about 1 mm thick and ~50% dense, high effective kth of BW-surface could be maintained.

• It should trap enough B to withstand some ELMs and a few disruptions (vaporized B layer ~60 μm/disruption including vapor shielding effect) “W-T_{melt}@ 3410° C, B-T_{melt}@2300 C, B-T_{boil}@ 2550 C”

• Should be able to control tritium inventory at temperature ~400-500° C.

• But for steady-state operation real time boronization will be needed to replenish B.
Supporting Results and Observations

- Wall conditioning—Boronization
- Real time boronization
- Release of hydrogen isotope @ 400-500 C
- $^{11}B$ would reduce B depletion
- SRIM* modeling code shows that the ranges of He$^+$ in B layer: ~100 nm for 10 keV and ~2 nm for 100 eV ions
- Initial W-drilled surface for DiMES testing fabricated

*SRIM code: J.F. Ziegler, Particle Interactions with Matter http://www.srim.org/
Boron Film Works as a Hydrogen-isotope-free Wall at 400–500° C

Basic chemistry: For $T > 300°$ C, $B_2H_6$ rapidly decomposes into boron and hydrogen

• It was confirmed by experiment that most hydrogen isotope atoms are re-emitted from a boron film at $T$ 300-400° C. (For carbon film, corresponding temperature for tritium release would be as high as 1000° C)

• B-film became a protective layer, hydrogen isotopes did not penetrate into the substrate of stainless steel in this temp. range. The glow discharge hydrogen implanted depth was ~10 nm in a B-film thickness of 110 nm

H$_2$ pressure versus B-film temperature, all implanted hydrogen atoms are released ~300°-400°C

(Noda, J of Nu Mat. 266-269 (1999) 234-239)
Real Time Boronization/Siliconization Has Been Applied to Many Machines

- Many MFE machines have tried real time boronization: DIII-D, NSTX, TEXTOR, Tore Super, JT-60U, C-Mod, JFT-2M, HT-7, LHD (Rm T) “not a complete list”
- Different B-gaseous compounds have been tried
- General results: reduced oxygen, He influx and impurities improved confinement
- Local in-situ deposition of Silane gas on ALT-II limiter in TEXTOR-94 demonstrated*

Tokamak plasma is actually an excellent surface coater

* After a series of 12 ohmic discharges with a total deposition time of 24s, the max. thickness is 800 nm near the point of gas injection. The layer decreases to about 100 nm within a toroidal distance of about 30 mm. The average thickness of the layer was ~160 nm in the observed area, with a deposition efficiency of about 8.7%.
BW-surface Concept can be Tested with the DiMES and MiMES Systems in DIII-D

- Divertor DiMES system
- Mid-plane material system-MiMES
- Material sample buttons
A Boron Tungsten-surface Concept
“BW-surface”

Need to demonstrate:

- Production of B-infiltrated BW-surface sample
- Tolerance to ELMs and disruptions
- Acceptable trapping and release of tritium in a tokamak
- Acceptable transmutation effects from neutrons
- Real time boronization at acceptable deposition rate and spatial distribution
- D (T) mobility and accountability in tokamak and linear machines
- Acceptable physical and thermal attachment to a ferritic steel substrate
- Ability to remove high surface heat flux
- Robustness of the BW-surface under transient events
- Adjustments on vacuum pumping and tritium extraction technologies

Supported by modeling
BW-surface Concept can be Demonstrated by Operating Tokamaks, Linear Machines and Test Stands

- Test of BW-surface (e.g. DiMES and MiMES in DIII-D and other tokamaks) including transient tolerance of BW-surface, ELMs and disruptions
- Detail migration and accountability of boron
- Real time boronization: demonstration of deposition rate and necessary surface uniformity, it is never too early to enhance the coordinated research in all operating tokamaks
- Accountability of tritium (D) absorption, release and distribution
- Test of BW-surface in high heat flux test stands
- Other?

Note: Real time boronization approach could also be applied to CTF and ITER to reduce the deposition of tritium