Low energy beryllium and carbon sputtering issues in ITER

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Argonne National Laboratory
**Plasma Facing Component sputtering erosion/redeposition issues for ITER**

- **Lifetime of first wall** beryllium coating due to sputtering erosion.
- **Lifetime of carbon (tungsten) divertor** with mixed material (Be/C) sputtering/transport.
- **Tritium codeposition** in deposited carbon and beryllium.
- **Plasma contamination** by divertor and wall sputtering.

--Erosion/redeposition analysis helps us to choose: 1) surface materials, 2) plasma regimes, 3) tritium removal schemes, recoating methods, etc.

--Previous studies have focused on **single material divertor** analysis; we are focusing now on **wall** and wall/divertor **mixed-material** effects; PFC response with **convective** plasma boundary transport.
Critical sputtering issues in ITER

- Carbon divertor chemical sputtering and transport for ~ 5-20 eV D, T (plasma temperature $T_e = 1-4$ eV)
- Beryllium wall sputtering/transport for ~ 20-300 eV D, T
- Mixed material (Be, C) sputtering of divertor by D-T, O, self-sputter.
- Tritium codeposition in redeposited Be and C; role of oxygen.
- Important to understand, but not critical: physical sputtering of carbon (all energies), carbon chemical sputtering for > 20 eV incidence ($T_e > 4$ eV), tungsten sputtering
Chemical sputtering is critical in detached plasma

Plasma temperature, density and particle fluxes along the ITER outer divertor target

ITER “semi-detached regime”

Carbon erosion
REDEP/WBC analysis

Physical sputtering only

Chemical sputtering only
# REDEP /WBC Analysis, ITER Tritium Codeposition, Semi-Detached Plasma Regime

<table>
<thead>
<tr>
<th>Case</th>
<th>Tritium Codeposition Rate*</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>1. Reference</strong> <strong>[</strong></td>
<td><strong>14 g /1000 s pulse</strong></td>
</tr>
<tr>
<td>2. No fast-molecule chemical sputtering ( Y_{\text{MOL}} = 0 )</td>
<td>13</td>
</tr>
<tr>
<td>3. ( Y_{\text{MOL}} = 0.01 )</td>
<td>24</td>
</tr>
<tr>
<td>4. No chemical sputtering (physical sputtering only)</td>
<td>2</td>
</tr>
<tr>
<td>5. Carbon erosion reduced due to beryllium mixing</td>
<td>11</td>
</tr>
<tr>
<td>6. Shallow detached plasma - &quot;Case 133&quot;</td>
<td>17</td>
</tr>
</tbody>
</table>

* total (inner + outer divertor) resulting from ITER carbon coated vertical target sputtering.

** Reference: "Case 98" plasma, physical and chemical sputtering, non-thermal D-T molecule sputtering yield \( Y_{\text{MOL}} = 0.001 \)
ITER Plasma Facing Component Tasks at ANL

• Initiate analysis of ITER mixed material (Be/C/W) Plasma Facing Component performance. (ANL, LLNL)
  (J.N. Brooks, J.P. Allain, M. Nieto, T. Rognlien)

• Supporting science: PISCES beryllium/carbon mixed-material experiments modeling. (ANL, UCSD)
  (J.N. Brooks, J.P. Allain, M. Nieto, R. Doerner, D. Nishijima)
Initiate analysis of mixed material PFC erosion/redeposition performance for ITER

- Key issues: first **wall lifetime**, effect of transported beryllium on carbon (tungsten) **divertor erosion** and **tritium codeposition, plasma contamination**. Steps (2 yr goal):
  - Method (follows FIRE-type analysis*): **Package-OMEGA**
  - 1) Compute sputtering of ITER beryllium wall with and without plasma convective flux to wall.
  - 2) Compute transport of sputtered beryllium to wall, divertor, plasma.
  - 3) Mixed material code analysis of Be/C mixing/sputtering on the ITER vertical divertor target.
  - 4) Compute erosion/redeposition, and surface-temperature dependent tritium codeposition in resulting growth layers of beryllium and carbon with inputs of oxygen flux to divertor and Q/Be and Q/Be-O codeposition rates.

Initiate analysis of mixed material PFC erosion/redeposition performance for ITER

**Package-OMEGA***

- **UEDGE/DEGAS**: D-T ion and neutral flux to wall, scrape-off layer (sol) plasma parameters
- **TRIM-SP, ITMC**: wall sputter yields
- **WBC+**: wall-sputtered beryllium transport in scrape off layer
- **REDEP/WBC**: divertor erosion/redeposition analysis
- **ITMC, SIBIDET**: mixed-material evolution, divertor sputter yields
- **BPHI-3D**: Sheath analysis
- **Data** (where available)

*Omnibus Modeling of Erosion Generalized Analysis*
UEEDGE ITER boundary plasma results (Rognlien LLNL)

Ion flux to the “wall” (at $\psi = 1.035$) comparing standard case and on with strong convection.

Conversion from the dg format 08.01.02

Plasma particle flux ($s^{-1}m^{-2}$)

Poloidal distance along wall from inner plate (m)

Strong convection (70 m/s at wall)

No convection
Detail of divertor-to-wall PACKAGE-OMEGA ITER calculation geometry

Flux surfaces at outer midplane for $\psi_{\text{max}} = 1.035$

UEDGE Grid
Conversion from the dg format 08.01.02

"GAP REGION"

$\psi = 1.035$

Wall

Separatrix ($\psi = 1.0$)

VERTICAL POSITION (m)

RADIAL POSITION (m)

carbon divertor target

sputtered particle (Be)
**Plasma parameters near ITER wall-UEDGE code**

**with convection**

- **Plasma and Neutral Densities - Midplane**
  - Plasma density
  - 100 x Neutral density

- **Electron and Ion Temperatures - Midplane**
  - Electron temperature
  - Ion temperature

**wall impingement energy**

D, D⁺ ~ 100-200 eV

**no convection**

- **Plasma and Neutral Densities - Midplane**
  - Plasma density
  - 100 x Neutral density

- **Electron and Ion Temperatures - Midplane**
  - Electron temperature
  - Ion temperature

**wall impingement energy**

D, D⁺ ~ 300-500 eV
Sputtering yields for D\(^+\) on Be with incident energies between 10 and 1000 eV, and with incident energies of 37°, 52°, and 67° (TRIM)
Package-OMEGA wall sputtering/transport calculation/assumptions

- Wall beryllium sputtering computed using UEDGE ion and neutral flux (@45° D yields).
- Gas puffing not included.
- Plasma sheath at wall.
- Neutral beryllium transport: initial/simplified Be/plasma elastic collision model, electron impact ionization w/ADAS rates.
- Divertor-Wall “gap region” density, $n_e(x)=n_0 \exp(-x/\lambda)$
- Ionized, Be$^{+k}$, transport in gap region: initial/simplified collision model.
- Partially self-consistent code-coupling.
ITER Package-OMEGA *preliminary* results: beryllium sputtering and transport

<table>
<thead>
<tr>
<th>Plasma Case</th>
<th>Sputtered beryllium current from wall</th>
<th>Peak wall erosion rate*</th>
</tr>
</thead>
<tbody>
<tr>
<td>With convection</td>
<td>$3.9 \times 10^{22} \text{ s}^{-1}$</td>
<td>$1 \text{ nm/s}$</td>
</tr>
<tr>
<td>Diffusion only</td>
<td>$1.8 \times 10^{21}$</td>
<td>$0.02$</td>
</tr>
</tbody>
</table>

* w/o gas puffing
## ITER Package-OMEGA: beryllium sputtering and transport, preliminary results

<table>
<thead>
<tr>
<th>Plasma Case</th>
<th>Sputtered beryllium current from wall</th>
<th>Wall-sputtered fraction to carbon divertor target</th>
<th>Average beryllium growth rate on carbon divertor target*</th>
<th>Wall-sputtered fraction to edge plasma</th>
</tr>
</thead>
<tbody>
<tr>
<td>With convection</td>
<td>3.9 x 10^{22} s^{-1}</td>
<td>5.1%</td>
<td>1 nm/s</td>
<td>0.37%</td>
</tr>
<tr>
<td>Diffusion only</td>
<td>1.8 x 10^{21}</td>
<td>50</td>
<td>0.6</td>
<td>3.7</td>
</tr>
</tbody>
</table>

* gross, not including sputtering/redeposition processes at divertor
ITER Package-OMEGA tritium/beryllium codeposition; initial, rough estimate

<table>
<thead>
<tr>
<th>Plasma Case</th>
<th>Q/Be trapping data assumption</th>
<th>Codeposition for 400 s pulse</th>
</tr>
</thead>
<tbody>
<tr>
<td>With convection</td>
<td>Mayer et al.* (Na abundant O)</td>
<td>12 g T</td>
</tr>
<tr>
<td></td>
<td>Causey et al.** (low/no oxygen)</td>
<td>2</td>
</tr>
<tr>
<td>Diffusion only</td>
<td>Mayer et al.* (Na abundant O)</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td>Causey et al. ** (low/no oxygen)</td>
<td>0.1</td>
</tr>
</tbody>
</table>

* (Q/Be ~ 0.3 @ 250 °C  

** (Q/Be ~ 0.05 @ 250 °C  
Modeling of PISCES mixed material; Be/C experiment

- **Purpose:** Understand mixed-material Be/C sputtering and transport, Q/Be codeposition.

- Similar to expected conditions on ITER carbon divertor target subject to high beryllium flux from wall sputter/transport.

- Key code/data comparisons: Be-I photon emission and Be-I density profiles, surface growth of Be/C target.
Modeling of PISCES beryllium seeded mixed-material experiment

REDEP/WBC code simulation of 2.1 cm diameter carbon target bombarded by \( T_e = 5, 7, 8 \) eV, Be-seeded multispecies deuterium plasma. Key inputs from TRIM-SP code.

- \( T_e = 5, 7, 8 \) eV, uniform in plasma. \( N_e = \sim 3.0 \times 10^{18} \) m\(^{-3}\) at target center, uniform over target radially, radial variations (past-target) and axial variations in \( N_e \) per PISCES data

- Pre-sheath field, radial diffusion coeff. per previous work (D.G. Whyte et al., Nuclear Fusion 41(2001)47.). Plasma Mach number varies from 1.0 at target to 0.2 at 20 cm axially from target.

- Be/plasma-electron/ion collisions from full kinetic theory. Ion mass = 2.0 AMU in collision routine (corrections for \( D_2, D_3 \) mass should make 2\(^{nd}\) order difference).
  - Be/background-neutral collisions (elastic) using 5 mtorr \( D_2 \) @ rt.

  - Be atoms launched from points on the target per incident \( D^+, D_2^+, D_3^+ \) flux profile, with velocity per results of TRIM-SP runs w/ 40, 70 eV \( D^+ \) normal incidence on Beryllium-Carbide.

  - Detailed Be-I photon emission diagnostic simulated.

  –ADAS rate coefficients (per T. Evans GA) for electron-impact ionization of Be-I, Be-II, at 5-8 eV, at. e.g., at 5 eV, \( N_e = 2.5 \times 10^{18} \) m\(^{-3}\):

    - \( \text{BeI}\rightarrow\text{BeII}, \ <\sigma v> = 1.428 \times 10^{-14} \) m\(^{3}\)/s,

    - \( \text{Bell}\rightarrow\text{Bellll}, \ <\sigma v> = 5.171 \times 10^{-16} \) m\(^{3}\)/s
PISCES deuterium ion composition and sputter yields*

<table>
<thead>
<tr>
<th>Plasma Species</th>
<th>Ion</th>
<th>Sputter Yield</th>
<th>Be target 40 eV</th>
<th>Be$_2$C target 40 eV</th>
<th>Be target 70 eV</th>
<th>Be$_2$C target 70 eV</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>D$^+$</td>
<td>55%</td>
<td>0.0071</td>
<td>0.0025</td>
<td>0.0135</td>
<td>0.0063</td>
</tr>
<tr>
<td></td>
<td>D$_2^+$</td>
<td>25%</td>
<td>0.0040</td>
<td>0.0019</td>
<td>0.0100</td>
<td>0.0053</td>
</tr>
<tr>
<td></td>
<td>D$_3^+$</td>
<td>20%</td>
<td>0.0012</td>
<td>0.0006</td>
<td>0.0045</td>
<td>0.0027</td>
</tr>
<tr>
<td>$Y_{eff}$</td>
<td></td>
<td></td>
<td>0.0052</td>
<td>0.0020</td>
<td>0.0108</td>
<td>0.0053</td>
</tr>
</tbody>
</table>

*Be/ion, normal incidence ions, TRIM-SP code
Sputtered beryllium energy distribution for PISCES analysis

$D^+, D_2^+, D_3^+$ on $Be_2C$, normal incidence [TRIM-SP, J.P. Allain]

distribution shown for PISCES combination of incident particles

40 eV incidence

70 eV incidence
PISCES PHOTON DIAGNOSTIC SIMULATION

PISCES Be sputtering experiment- WBC computed
Bel photon emission axial dependence
(sample dia. = 2.2 cm, Te = 5 eV)

---code/data comparison is marginally acceptable
WBC code computed Be-I density, PISCES “8 eV Case (Nishijima et al. 3.14.05)”
**Next steps–near future**

- Refine estimates of D-T ion and neutral flux to the ITER first wall, and sputtered beryllium flux.
- Refine calculations for sputtered Be neutral and ion collisions with plasma ions/neutrals/electrons in divertor/wall region.
- Compute spatial profiles of beryllium transport to the ITER carbon divertor target, tungsten dome, wall.

- Continue code/validation effort on PISCES Be/C target.
- ANL IMPACT facility tests on exposed PISCES Be/C targets.

- DIII-D/DiMES Carbon “slot” experiment modeling.
Conclusions

• Preliminary results for ITER 1st wall sputtering/transport obtained with Package-OMEGA coupled code analysis show:
  - Major effect of convective transport on wall erosion, codeposition.
  - Wall erosion rates may be tolerable (for low duty-factor ITER).
  - Substantial flow of wall material (Be) to divertor; might be beneficial?
  - Significant potential for tritium codeposition in redeposited beryllium.

• PISCES Be/C ITER simulation mixed-material modeling and code/data comparison underway.
  - Be-I photon emission comparison being used to validate REDEP code mixed-material sputtering and transport models.
  - Be density, Be, C growth profiles under comparison.