Modelling of Beryllium Erosion/Deposition and Local Transport at ITER First Wall Blanket Modules Using the ERO code

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Blanket module (BM) shapes optimized for heat loads (P.C. Stangeby)

Aim – predictive modelling of ITER, including first wall life time

FLFS close to 2nd separatrix => First PFC *life time* estimates assuming limiter-like contact on outboard BM11

Banana-shaped far SOL region

Be
+ low Z
- high erosion
**High density case**

- $<Y_{eff}> \sim 7\%, \sim 50\%$ particles locally redeposited
- Net peak erosion $\sim 0.06$ mm/h
  - PFC lifetime $\sim 1500$ shots
- T-retention* $\sim 0.083$ gT/h for one module
  - $3$ gT/h for $36$ BM11-18
  - Limit $\sim 1920$ shots
  (assuming: $50:50$ D:T plasma, maximum safety limit $\sim 640$g)

**Low density case**

- $<Y_{eff}> \sim 6\%, \sim 10\%$ particles locally redeposited
- Net peak erosion $\sim 0.0025$ mm/h
  - PFC lifetime $\sim 36000$ shots
- T-retention* $< 1.3$ mgT/h for $36$ BM11-18

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* 2D estimation of $(D+T)/Be = f(T_{surf}, E_{imp}, \Gamma_D/\Gamma_{Be})$
  [PICSES-B scaling law, G. De Temmerman, R. Doerner]

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Important issue for ITER: benchmark with ERO focusing on life time
3D MC impurity transport code ERO

**Background Plasma**

- \( \vec{B} \)
- \( \vec{E} \)
- \( \rho \)
- \( \rho \)
- \( B \)
- \( C, Be, \ldots \)
- \( CD_{4}^{0,+} \)

**Input:**
- \( n_{e}, T_{e,i} \)
- geometry

**PFC (substrate Be, C, W, Mo, …)**

**Local transport:**
- ionisation, dissociation
- friction (Fokker-Planck), thermal force
- Lorentz force
- cross-field diffusion

**Plasma-surface interaction:**
- physical sputtering/reflection
- chemical erosion (CD\(_{4}\))
- (re-)erosion and (re-)deposition
- HMM and SDTrimSP surface models
**Aim** – predictive modelling of ITER first wall life time

LIM predicted life time due to transient events is not a limiting factor – we concentrate on steady state

**Complications:**
- Complex geometry e.g. leading to shadowing
- Uncertainty in atomic and surface data for Be
- Other uncertainties: enhanced re-erosion, carbide and alloy formation, Be-D molecules, etc.

**Electron density [cm⁻³]**

- **High density case (HDC)**

- **BM11**

- **BM**

- **FLFS**
Plasma parameters at limiter surface

High density case (HDC)

\[ T_e = 10 \text{eV} = \text{const} \]
\[ T_i = 20 \text{eV} = \text{const} \]

Low density case (LDC)

\[ T_e = 7.1 \text{eV} = \text{const} \]
\[ T_i = 18.6 \text{eV} = \text{const} \]
Shadowing patterns (LIM and ERO)

BM11, steady state

In shadowed areas we assume no BG erosion and re-deposition of intrinsic Be impurity.

BM15, start-up

Modelling is in progress, out of the scope!
## LIM and ERO overview

<table>
<thead>
<tr>
<th>Code</th>
<th>ERO</th>
<th>LIM</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Type</strong></td>
<td>Monte-Carlo impurity tracing (BG plasma import)</td>
<td></td>
</tr>
<tr>
<td><strong>BM implementation</strong></td>
<td>Shape, shadowing, plasma parameter, etc. - SIMILAR</td>
<td></td>
</tr>
<tr>
<td><strong>Geometry</strong></td>
<td>3D</td>
<td>2D</td>
</tr>
<tr>
<td><strong>Test-particle tracing</strong></td>
<td>resolving gyro-motion</td>
<td>guiding centre</td>
</tr>
<tr>
<td><strong>Intrinsic Be impurity</strong></td>
<td>concentration in D⁺ flux</td>
<td>possible</td>
</tr>
<tr>
<td><strong>Collisions with surface</strong></td>
<td>resolved angle and energy</td>
<td>sheath potential</td>
</tr>
<tr>
<td><strong>Multiple BM tiles</strong></td>
<td>periodic boundary</td>
<td>particle &quot;mirrors&quot;</td>
</tr>
</tbody>
</table>

Many routines in ERO for ITER BM are “imported” from the LIM code.
Poloidal positions of toroidal profiles

Background (BG) plasma erosion; BM11, HDC

[Be/cm²]

For LDC the maximal erosion point is elsewhere . . .
Erosion/deposition profiles

BM11, ‘HDC’: profile at y=-187mm

Deposition

Erosion by background (BG) plasma

Very good agreement between ERO and LIM
Erosion profiles

BM11, ‘HDC’: profile at y=-187mm

Self-sputtering in ERO is larger and more concentrated near the ridge

Small influence on total erosion . . .
The net erosion in LIM and ERO is in a very good agreement.
Erosion/deposition profiles

BM11, ‘HDC’: profiles at y=-187mm

Layer evolution [mm/h]

Life time limiting erosion: 1[cm]/0.05[mm/h] = 200h

ERO uses in this case angle averaged W.Eckstein 2002 data for sputtering yields from LIM and ADAS ‘93’ Be ionization . . .
Deposition in LDC is very low (in difference to HDC)

Life time limiting erosion:

\[
1\text{[cm]} / 1.5 \times 10^{-4}\text{[cm/h]} = 6600\text{h}
\]

Maximal erosion for BM11, LDC is at y=-367mm!..
Deposition: low vs. high density plasma

**Density of Be\(^+\) [cm\(^{-2}\)] – High density case (HDC)**

Be is ionized close to surface . . . Large redeposition.

**Density of Be\(^+\) [cm\(^{-2}\)] – Low density case (LDC)**

Be is ionized far away from surface . . . Small redeposition.

In both LIM and ERO deposition dependence on plasma parameters is feasible!
ERO vs. LIM benchmark summary

- **ERO in agreement with LIM . . .**
  a) Shadowing patterns, plasma parameters, etc. implemented in a similar way.
  b) Erosion, deposition and finally net erosion profiles are in good agreement for BM11 (steady state).
  c) Plasma conditions dependence is in agreement.

- **ERO vs. LIM disagreements**
  a) Self-sputtering in ERO is larger and more concentrated near the ridge. May indicate some difference in Be transport assumptions . . .

Benchmark with existing experiments would be useful!
Be by D⁺ sputtering

Only the ‘calculated’ data are included!
1) “maximum” – static TRIM + MD
2) “minimum” – SDTrimSP with 50% of D (reasonable limit)

Experimental data too much scattered!
1) Large deviations: no sense to analyse shape of curves
2) Various effects are difficult to separate

Normal incidence! Angle dependence should be taken into the account!
Be sputtering yields – self sputtering

**Normal incidence**

\[ \text{Be} \rightarrow \text{Be}, \text{normal incidence} \]

<table>
<thead>
<tr>
<th>Sputtering yield (atoms/ion)</th>
<th>Ion energy (eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TRIM</td>
<td>20</td>
</tr>
<tr>
<td>MD</td>
<td>40</td>
</tr>
<tr>
<td>Eckstein 2002</td>
<td>60</td>
</tr>
<tr>
<td>Maximum</td>
<td>80</td>
</tr>
<tr>
<td>Minimum</td>
<td>100</td>
</tr>
</tbody>
</table>

"ERO-max" "ERO-min"

**Angular dependence**

\[ 1000 \text{eV Be} \rightarrow \text{Be} \]

- Eckstein 2007
- Experiment

Angular part is essential!

Estimation based on calculated data as for Be by D\(^{+}\) sputtering

For following BM simulations ERO uses Eckstein 2007 fit.
Sputtering by BG plasma (and intrinsic Be) - “integration” produces effective sputter yields -

Injection of D\(^+\) or Be\(^+\) with Maxwell energy around \(T_i\) and uniform initial angle distribution

**ERO pre-calculation**

\[ \eta (\text{“B-angle”}) \]

\[ \alpha (\text{angle of incidence}) \]

\( B = 4.8 \text{T} \)

**Calculation of sputtering yield according to Eckstein’s fit 2007 for \(Y(E, \alpha)\), using angle and energy distribution as calculated by ERO (including gyration and sheath)**
Be by $D^+$ sputtering yields – assumptions

**Incidence energy dependence**

Sputtering of Be by $D^+$

- $\text{ERO-min}$
- $\text{ERO-max}$
- $\text{Eck2002}$
- $\text{LIM}$

- Normal incidence
- Averaged by angle!

‘Eck2002’ is $W.\text{Eckstein}$, IPP-report 2002

**Integrated yields**

- **HDC** conditions ($T_e=10\text{eV}, T_i = 20\text{eV}$)

- $E_{\text{LIM}} = 3T_e+2T_i = 70\text{eV}$

$LIM$ data is ‘Eck2002’ averaged by incidence angle assuming **uniform** distribution
Be self-sputtering yields – assumptions

Incidence energy dependence

Integrated yields

- HDC conditions \( (T_e = 10\text{eV}, T_i = 20\text{eV}) \)

\[
E_{\text{LIM}}(\text{Be}^+) = Z \times 3T_e + 2T_i = 70\text{eV}
\]

LIM data is ‘Eck2002’ averaged by incidence angle assuming uniform distribution
Sputter yields assumptions and net erosion

BM11, ‘HDC’: net erosion (deposition) profile at y=-187mm

In most pessimistic case life time about 30% less than in earlier LIM predictions
Intrinsic Be impurity influence on net erosion

BM11, ‘HDC’: net erosion (deposition) profile at y=-187mm

Intrinsic Be concentration
Surface evolution [a.u.]
BM11, HDC. 'ERO-max'

Total erosion
Deposition
Net erosion

- Deposition of Be impurity from plasma dominates over additional Be self-sputtering
Intrinsic Be impurity and sputter yields effect

BM11, ‘HDC’: net erosion (deposition) profile at y=−187mm

**Deposition (ERO-min +3%Be)**

Sputtering yield and intrinsic Be assumptions determine the outcome to a large extent!

Influence of enhanced Be re-erosion (typical ERO assumption) of is not yet studied!
Summary

1) ITER Organization requested a benchmark of LIM erosion-re-deposition simulations made for steady state plasma exposure on shaped, Be-armoured FW panels → ERO code

2) Using same input plasma parameters, shadowing geometry, Be sputtering yields, ERO (3D) in excellent agreement with LIM (2D) → LIM low limit for FW panel erosion lifetime reproduced by ERO (~1500 ITER reference $Q_{DT} = 10$ discharges)

3) Large range of erosion lifetime dominated by uncertainties in input plasma parameters and Be sputtering yields → inclusion of different sputtering models in ERO yields variation of lower limit from 1100 ↔ 4200 reference discharges for BM11, HDC. This variation can also be influenced by other assumptions e.g. intrinsic Be impurity.
To make progress now we require:

A) Experimental benchmarking of the impurity transport codes in ITER-relevant geometry

→ IO planning dedicated benchmark on EAST (MAPES manipulator with shaped tiles similar to ITER FW panel profile

→ JET ILW the ideal location for a dedicated experiment looking at erosion of Be tiles (e.g. upper part of the vacuum vessel in the secondary X-point region)
B) Improvement in sputtering yield uncertainty
→ model testing in PISCES-B

Perfect for Be sputtering yields benchmark
1. Spectroscopy
2. Target weight loss
3. Witness plate

The ERO was earlier applied for modelling of PISCES-B
The End