Edge plasma effects in ITER-type TOKAMAK caused by an enhancement of DD/DT reaction in metals at high current-low energy deuteron bombardment

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Introduction I- Expected Sources of Radiation Corrosion of First Wall

- First wall/divertor of TOKAMAK is bombarded by intensive beams of keV charged particles ($d^+$, $t^+$, $He^{4++}$, $He^{3++}$) resulting in sputtering/erosion.

- ITER materials are bombarded by high intensity 14 MeV neutrons from DT reaction caused bulk radiation damage.
Introduction II- Possible LENR contribution to First Wall damage

- LENR effects could also affect the processes at the first wall and divertor of TOKAMAK. Now LENR are not taken into account as a possible source of radiation damage in thermonuclear reactors.

- What kind of LENR effects may potentially to destroy the first wall?

- DD/DT reaction enhancement producing excessive energetic He-4 and He-3 (blistering).

- Low energy He$^4$ from DD reaction (if any in W or St. steel) diffusing into the bulk.

- Soft X-ray deposition at the metal surface – sputtering increase
Enhancement of DD-reaction in metal targets at low deuteron energy (1.0<E_d<10 keV)

- Most metals show enhancement of DD-reaction yield at E_d << 10 keV compared to the standard yield obtained by extrapolation of the DD-reaction cross-section to these E_d (see accelerator experiments: F. Raiola et al., Nuclear Physics, A719, 61C (2003), J. Kasagi et al., J. Phys. Soc. Jpn., 71(12), 2881 (2002)).

- Recently, high-current glow discharge measurement showed strong enhancement of DD-yield – about 9 orders of magnitude at E_d =1 keV in Ti target (A. Lipson et al., JETP, 100, 1175 (2005)).
## Comparison of High Current- Low Energy D\(^+\) Accelerator and Pulsed GD parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>I, range</th>
<th>(E_d) (lab), keV, range</th>
<th>(W_{max}), [W]</th>
<th>P, mm Hg</th>
<th>T, K, target</th>
<th>(E(D^+)) spread</th>
</tr>
</thead>
<tbody>
<tr>
<td>*High Current Accelerator</td>
<td>10-400 (\mu)A</td>
<td>100.0-2.5</td>
<td>2.0</td>
<td>5(\times)10(^{-7}), vacuum</td>
<td>100-350</td>
<td>± 1.0%</td>
</tr>
<tr>
<td>**Pulsed Glow Discharge</td>
<td>100-600 mA</td>
<td>2.5-0.40</td>
<td>200.0</td>
<td>2.0-10.0, (D_2)</td>
<td>200-1000</td>
<td>± 10.0%</td>
</tr>
</tbody>
</table>
Comparative parameters of the edge plasma flux (ITER) and high-current glow discharge

- **ITER/DEMO**: power deposition at the first wall $W \sim 1\ kW/cm^2$; at ion temperate $T_i \sim 0.5\text{-}1.0\ keV$, the flux of bombarding ions with the energy $E_i \sim 1.0\text{-}2.0\ keV$ would be $J_i \sim 0.5\text{-}1.0\ A/cm^2$, $T \geq 800\ K$

- High current pulsed glow discharge (PGD) in $D_2$ at $p \sim 0.5\text{-}9.0\ mm\ Hg$: pulses $0.2\text{-}1.0\ ms$ duration (rising time $< 1.0\ \mu s$), $E_d \sim 0.5\text{-}2.5\ keV$, $J \sim 0.2\text{-}2.0\ A/cm^2$.

- The disadvantage of a larger energy spread in the PGD case, is outweighed by the higher current and lower voltage capability.

- This GD might well simulate the edge-plasma effects at the first wall of ITER.
Pulsed Glow discharge set up
Thick target yield and enhancement of DD-reaction

Thick target yield: All deuterons are stopped in the target: \( R(E_d) < h(\text{Target}) \)

\[
Y_t(E_d) = \int N_D(x)\sigma(E_{\text{lab}})(dE/dx)^{-1}dE
\]

- \( N_D(x) \) - D concentration in target,
- \( \sigma(E_{\text{lab}}) \) - cross section at \( E_{\text{lab}} \),
- \( dE/dx \) – stopping power in target

Enhancement factor:

\[
f(E) = \frac{Y_p(E)}{Y_b(E)} = \exp\left[\pi\eta(E)U_e/E\right]
\]

- \( Y_p(E) \) – experimental yield at \( E=E_d \), \( Y_b(E) \) – bare yield, \( 2\pi\eta(E) = 31.29 Z^2(\mu/E)^{1/2} \), \( U_e \) - screening potential of deuterons in target.
Yields of 3.0 MeV protons before and after normalization to deuterium concentration in PGD with Ti cathode

![Graph showing yields of 3.0 MeV protons from Ti-cathode vs deuteron energy.]

\[ R^2 = 0.8649 \]
\[ R^2 = 0.905 \]

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Normalization of PGD 3.0 MeV proton yields to that of 2.45 keV
DD-reaction enhancement factor \( f(E) = \frac{Y_p(E)}{Y_b(E)} = \exp[\pi \eta(E) U_s / E] \) for Ti-target: (1)-accelerator; (2)-PGD

\[
U_e = 610 \pm 150 \text{ eV}
\]

\[
U_e = 65 \pm 10 \text{ eV}
\]

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Thick target yields for accelerator (Ti and Au) and PGD (Ti) normalized to that at $E_d = 10$ keV compared to bare yield (solid line).
DD-reaction enhancement in Ti target depending on deuteron current and target temperature.

<table>
<thead>
<tr>
<th>Target/Ref</th>
<th>D^+ energy ( \Delta E_d \text{(lab)}, [\text{keV}] )</th>
<th>( &lt;I_d&gt; ), [mA]</th>
<th>T, [K]</th>
<th>( U_e ), [eV]</th>
<th>Fit: ( U_e = 68.23 \ln I_d + 219.9 ) [eV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ti, accelerator, Raiola</td>
<td>5.0-30.0</td>
<td>0.054</td>
<td>290</td>
<td>( \leq 30 )</td>
<td>20.7</td>
</tr>
<tr>
<td>Ti - accelerator, Kasagi</td>
<td>2.5-10.0</td>
<td>0.13</td>
<td>200</td>
<td>65( \pm )15</td>
<td>75.2</td>
</tr>
<tr>
<td>Ti - GD, Lipson-Karabut</td>
<td>0.8-2.45</td>
<td>310</td>
<td>( &gt; 700 )</td>
<td>610( \pm )150</td>
<td>609.2</td>
</tr>
</tbody>
</table>
Screening potential in Ti target is a logarithmic function of the bombarding deuteron flux $F$: $F = J \sim y = \frac{M_e}{D}$

Screening Potential vs. Deuteron Current on Ti-target

$y = 68.231 \ln(x) + 219.88$

$R^2 = 0.9991$
Data are taken from F. Raiola et al, Europhys. J.A19, 283 (2004) at $T_0 = 290K$, $J_0 = 0.03mA/cm^2$, $E_d \geq 5keV$. Points are consistent with increase in $y = \frac{Me}{D}$: Hf, Y, Lu, Sc, Gd, Tm, Ti, Ce, Yb, Sm, Zr, Er, Pr, Eu, Ho, La, Ge, C, W, Sr, Ir, Ba, Ru, Au, Ag, Re, Ni, Nb, Ta, Zn, Bi, Mo, Mn, Mg, Cu, Rh, Fe, Pt, V, Pb, Pd, In, Tl.
$U_e = (T/T_0)^{-1/2}[a \ln(y) +b]$ - semi empirical equation for screening potential vs. free deuteron concentration $y$ ($a$ and $b$ are numerical constants)

- $y = k \times y_0(J/J_0)$, where $y_0 = Me/D$ at $T_0=290K$ and $J_0=0.03$ mA/cm$^2$, $k = \exp(\varepsilon_d \Delta T/kBT_0)$, $\varepsilon_d$ - activation energy of D+ escape from the surface, $\Delta T = T-T_0$ and $k_B$ - Boltzman constant.

- Accordingly the equation for $U_e$ in ITER case at $J=1.0$ A/cm$^2$ and $T = 773$ K;

- For tungsten: $y_0(W) = 3.45$, $\varepsilon_d(W) = 0.05$ eV; $U_e(W)= 1200$ eV. Enhancement: $f_{DT}(2$ keV) $\sim 1.2\times10^4$;

- For iron: $y_0(Fe) = 16.7$, $\varepsilon_d(Fe) = 0.06$ eV, $U_e(Fe) = 1350$ eV. Enhancement: $f_{DT}(2$ keV) $\sim 4\times10^4$. 

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Rough estimate of DT-reaction intensity at the surface of W and Fe in ITER’s First Wall:

\[ I_{DT} = J_d N_{\text{eff}}(T) \times \int_0^{E_d} f(E)\sigma_{DT}(E)(dx/dE)dE \]

Here \( J_d \) – deuteron current density; \( N_{\text{eff}}(T) \) – effective concentration of bounded D/T in metal at temperature \( T \), captured at depth \( x \): \( N_{\text{eff}}(T) = N_0\exp(-\varepsilon_d\Delta T/k_B T_0) \), where \( N_0 \) – D/T concentration at \( T_0 = 290 \text{ K} \); \( f(E) \) – enhancement factor; \( \sigma_{DT} \) – is the bare DT- cross-section; \( dE/dx \) – is the stopping power in target calculated with Monte-Carlo code SRIM (J.F. Ziegler and J.P. Biersack, code SRIM 2003)
Numerical integration results

- Taking into account hypothetical First Wall bombardment parameters: \( J_d = 1.0 \text{ A/cm}^2 \), \( <E_d> = 2.0 \text{ keV} \), \( T \approx 773 \text{K} \) and screening potentials \( U_{e(W)} = 1200 \) and \( U_{e(Fe)} = 1350 \text{ eV} \), rough \( d(t, n)\alpha \) -reaction rate at the reactor’s edge would be: \( I_{DT} \approx (1-2) \times 10^4 \text{ s}^{-1} \text{-cm}^{-2} \).

- During one year of operation: DT-reaction alpha fluence \( \Phi_\alpha \approx 7 \times 10^{11}/\text{cm}^2 \) or up to \( N_{4\text{He}} \approx 10^{15} \text{ cm}^{-3} \) atoms over depth \( \lambda \approx 6 \mu\text{m} \) for 3.6 MeV alphas from dt-reaction.
X-ray yield per deuteron increases exponentially with the applied deuteron current at $E_d \sim 1.5-2.0$ keV
Possible Consequences of DD/DT- Reaction Enhancement and X-ray Generation at High Current Low Energy Deuteron Bombardment I

- Vacancy generation over near-surface layer of reactor’s edge by MeV alphas.
- The He-atom precipitation along dislocations or capturing by dislocation atmosphere.
- Additional stress and blistering, plasticity reduction even at low level ($\sim 10^{15}$ cm$^{-3}$) $^4$He accumulation.
- Sputtering rate may also increase due to vacancy generation and soft X-ray absorption at the First Wall surface.
Consequences II

- Reduction in plasticity (e.g. in W) due to the He-4 capture would cause a micro-crack generation over intermediate area between surface and the bulk (1-10 μm depth). Enhancement of First wall fracture and shortening of ITER/DEMO operation time.

- Intense soft X-ray emission at the surface may also enhance erosion of first wall caused by X-ray energy deposition in the near-the-surface layer during charged particle bombardment.
Conclusions

- The edge plasma effects at the first wall, including corrosion, would be partially underestimated because the enhancement of DD/DT reaction and accompanying radiation processes at very low deuteron energy are neglected.

- The high current pulsed GD with appropriate cathode materials (W, St. steel) could be a suitable instrument to simulate edge plasma effects at ITER’s first wall.