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).

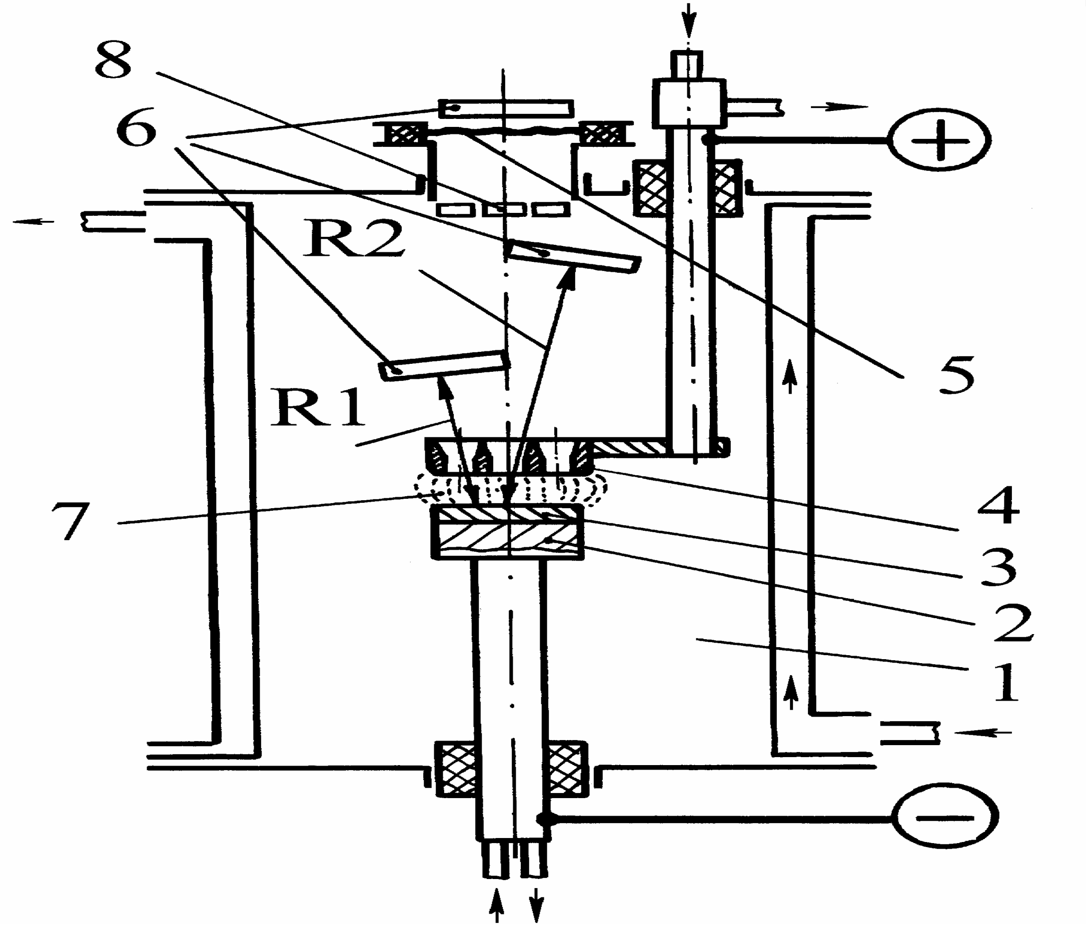
Comparison of High Current- Low Energy D^+ Accelerator and Pulsed GD parameters

Parameter	I, range	E_d(lab), keV, range	W_{max}, [W]	P, mm Hg	T,K, target	$E(D^+)$ spread
*High Current Accelerator	10-400 µA	100.0- 2.5	2.0	5×10^{-7}, vacuum	100-350	± 1.0%
**Pulsed Glow Discharge	100-600 mA	2.5- 0.40	200.0	2.0-10.0, D_2	200-1000	± 10.0%

Comparative parameters of the edge plasma flux (ITER) and high-current glow discharge

- ITER/DEMO: power deposition at the first wall W ~ 1 kW/cm^2; at ion temperate T_i ~ 0.5-1.0 keV, the flux of bombarding ions with the energy E_i ~ 1.0-2.0 keV would be J_i ~ 0.5-1.0 A/cm^2, T $\geq$ 800 K
- High current pulsed glow discharge (PGD) in D_2 at p ~ 0.5-9.0 mm Hg: pulses 0.2-1.0 ms duration (rising time < 1.0 μs), E_d ~ 0.5-2.5 keV, J ~ 0.2-2.0 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: $R(E_d) < h(\text{Target})$

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

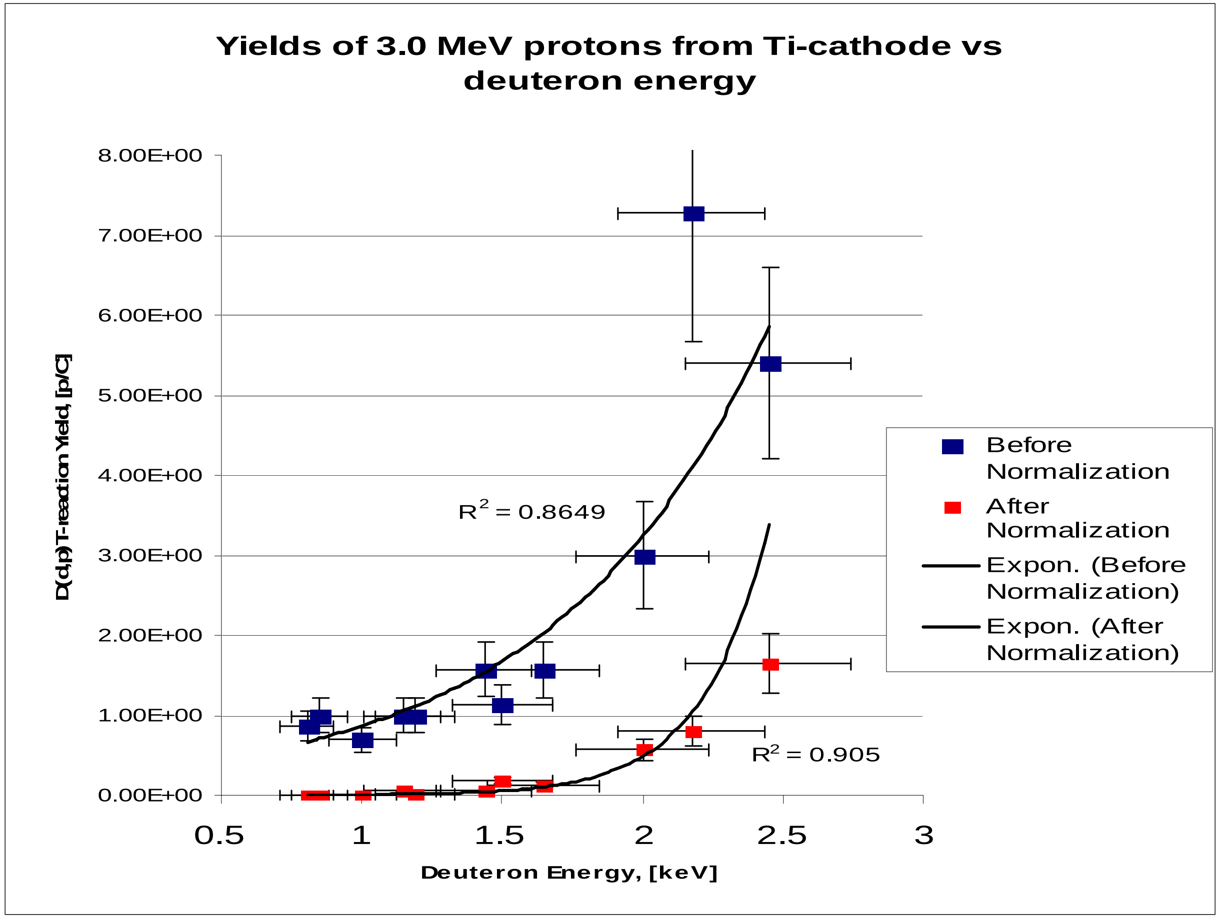
$N_D(x)$- D concentration in target,
$\sigma(E_{lab})$ - cross section at E_{lab},
dE/dx – stopping power in target

Enhancement factor:

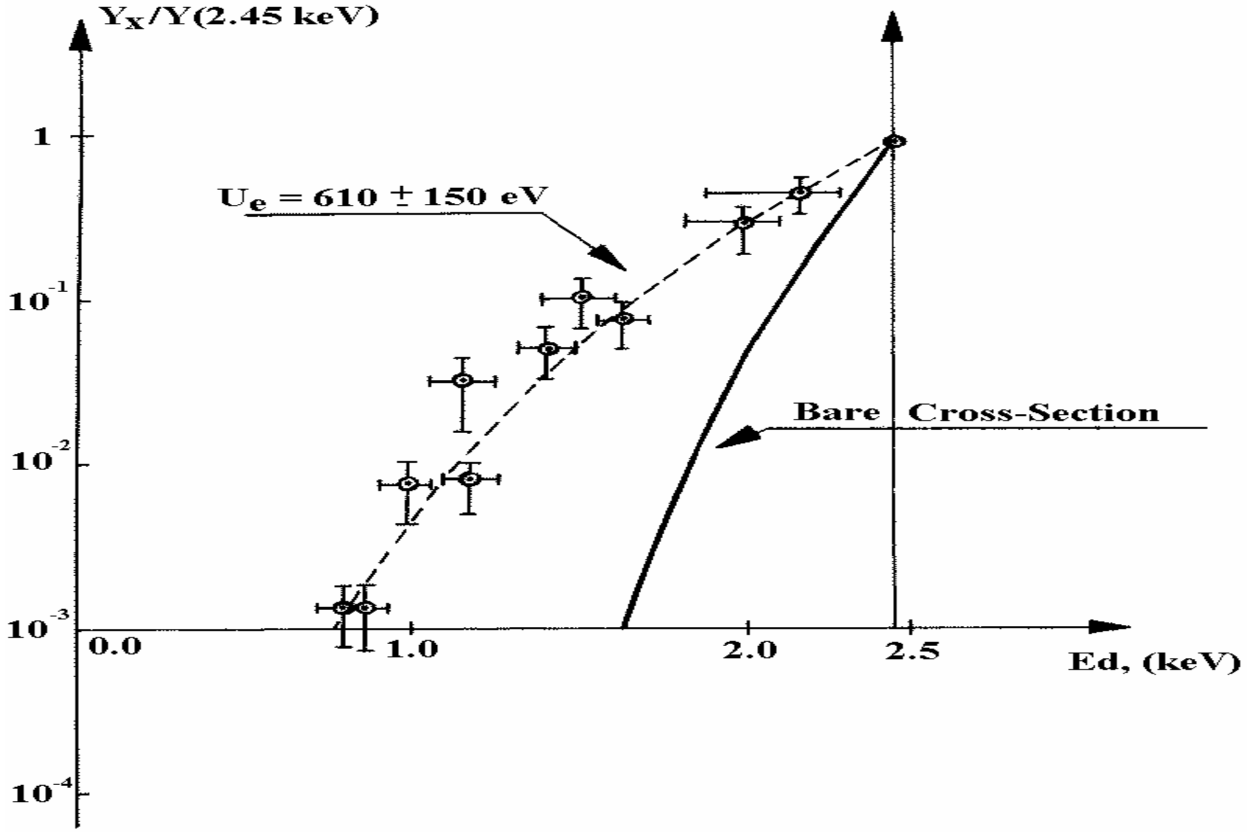
$$f(E) = Y_p(E)/Y_b(E)=\exp[\pi\eta(E)U_e/E]$$

$Y_p(E)$ – experimental yield at E=Ed, $Y_b(E)$ – bare yield, $2\pi\eta(E) = 31.29\, Z^2(\mu/E)^{1/2}$, U_e- screening potential of deuterons in target.

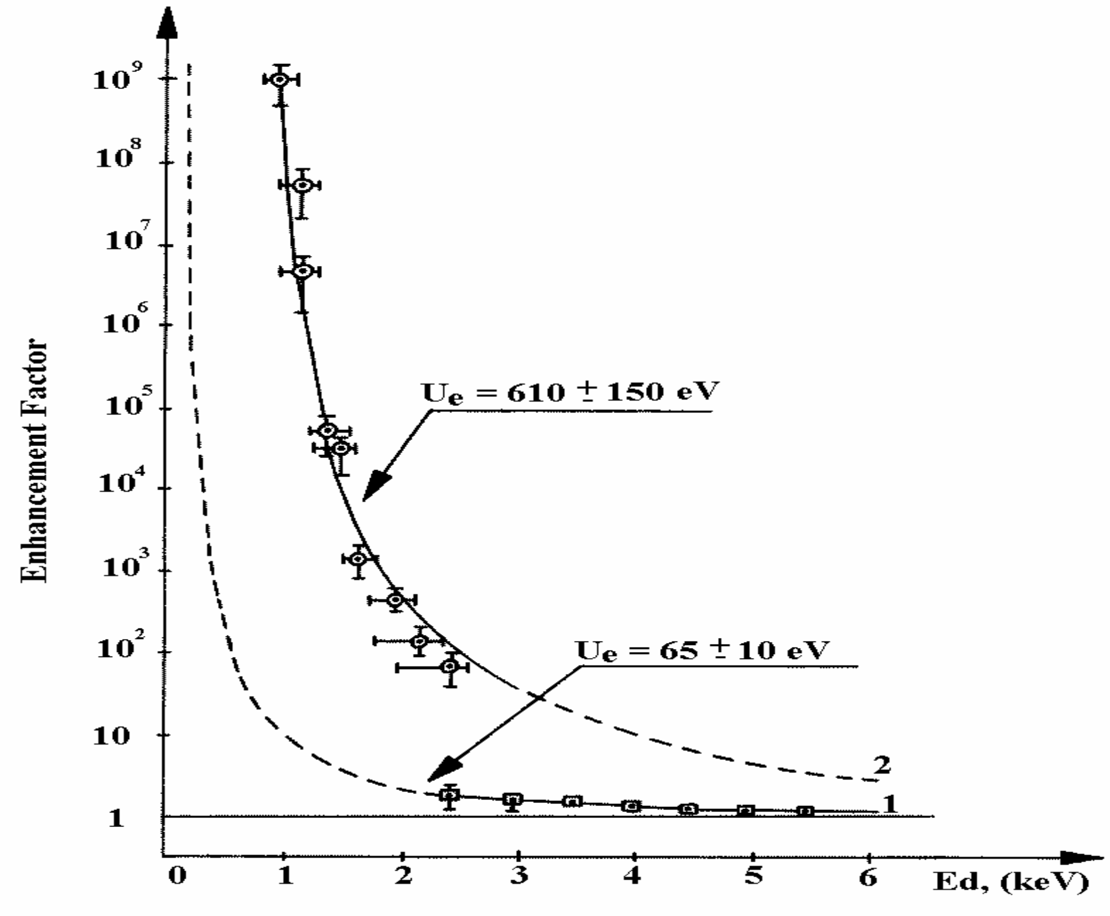
Yields of 3.0 MeV protons before and after normalization to deuterium concentration in PGD with Ti cathode



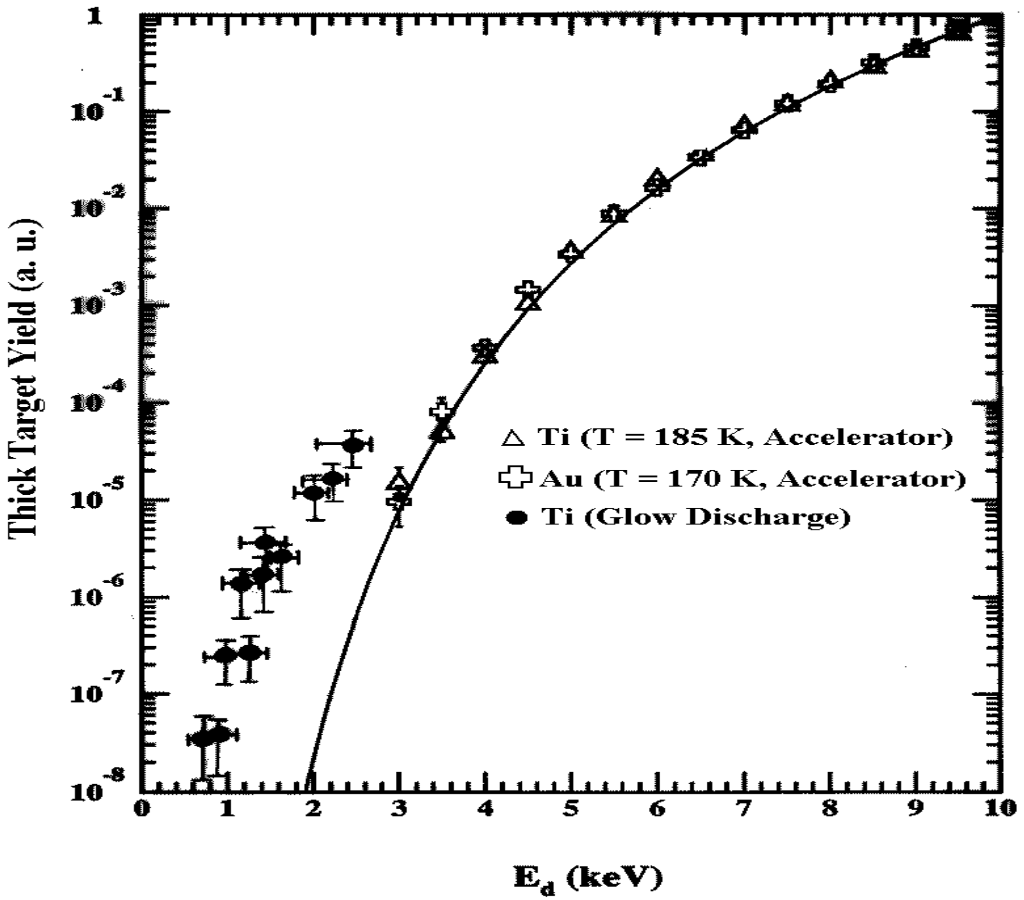
Normalization of PGD 3.0 MeV proton yields to that of 2.45 keV



DD-reaction enhancement factor ($f(E) = Y_p(E)/Y_b(E)=\exp[\pi\eta(E)U_s/E]$ for Ti-target: (1)-accelerator; (2)-PGD



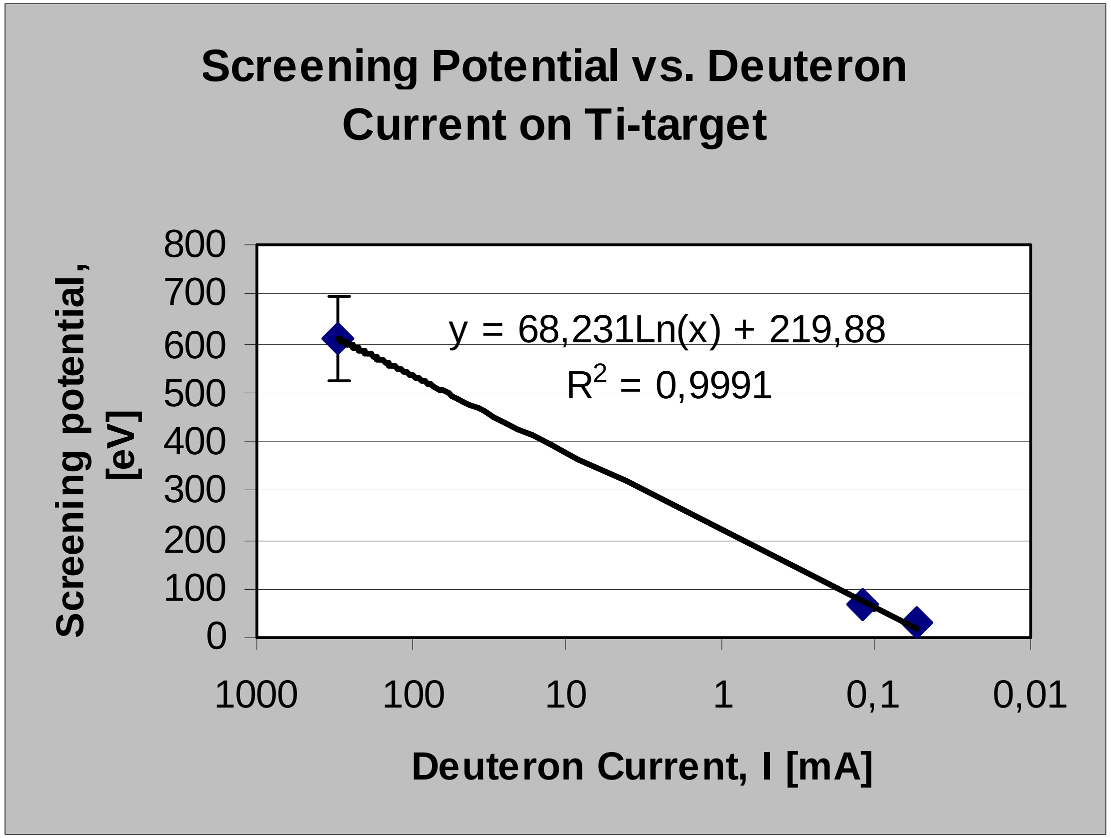
Thick target yields for accelerator (Ti and Au) and PGD (Ti) normalized to that at E_d = 10 keV compared to bare yield (solid line)



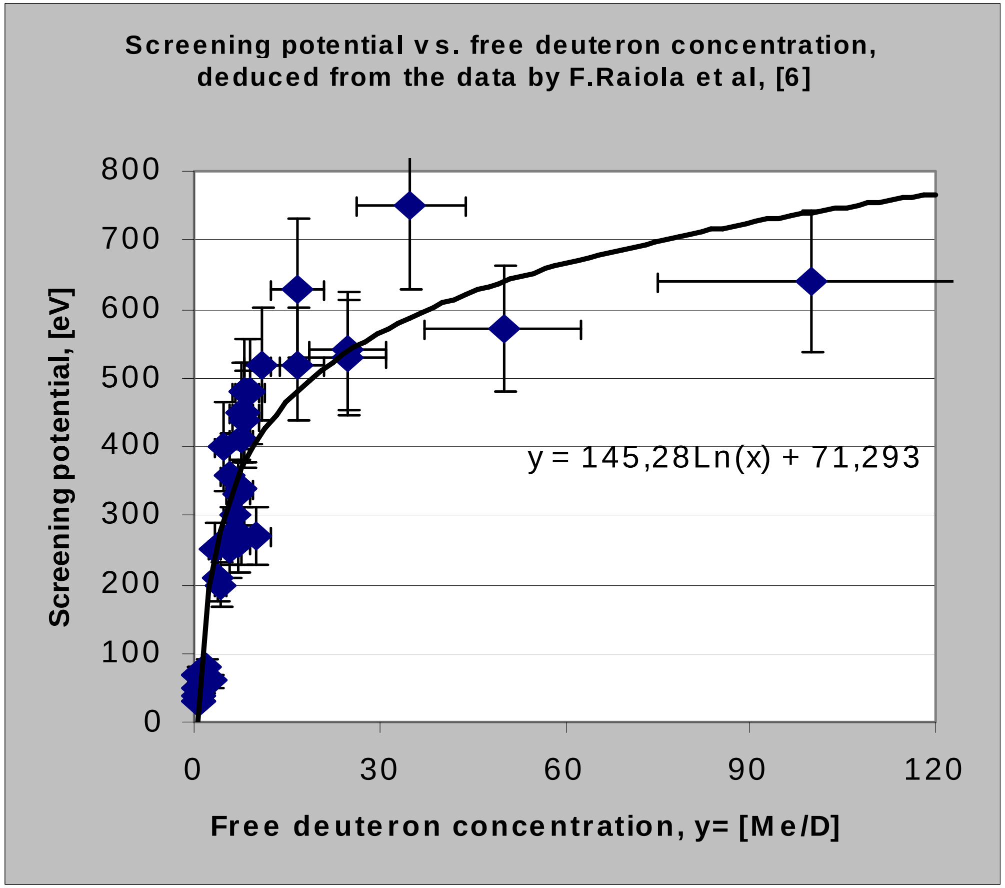
DD-reaction enhancement in Ti target depending on deuteron current and target temperature.

Target/Ref	D^+- energy ΔE_d(lab), [keV]	$\langle I_d \rangle$, [mA]	T, [K]	U_e, [eV]	Fit: $U_e = 68.23 \ln I_d + 219.9$ [eV]
Ti, accelerator, Raiola	5.0-30.0	0.054	290	≤ 30	20.7
Ti - accelerator, Kasagi	2.5-10.0	0.13	200	65±15	75.2
Ti - GD, Lipson-Karabut	0.8-2.45	310	> 700	610±150	609.2

Screening potential in Ti target is a logarithmic function of the bombarding deuteron flux F: F = J ~ y=Me/D



Data are taken from F. Raiola et al, Europhys. J.A**19**, 283 (2004) at T_0=290K, J_0=0.03mA/cm^2, E_d≥5keV.
Points are consistent with increase in y = 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, $k = \exp(\varepsilon_d \Delta T/kBTT_0)$, ε_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) ~ 1.2x10^4;
- For iron: $y_0(Fe) = 16.7$, $\varepsilon_d(Fe) = 0.06$ eV,

$U_e(Fe)$ = 1350 eV. Enhancement: f_{DT}(2 keV) ~ 4x104.

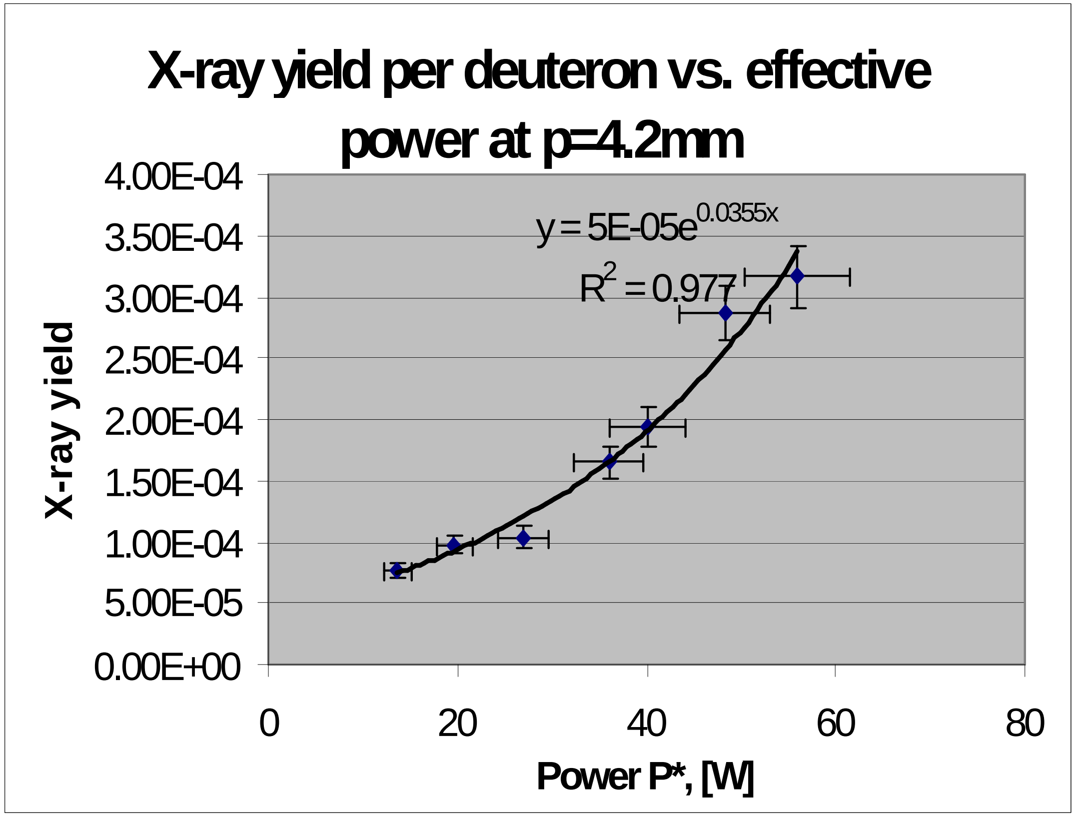
Rough estimate of DT-reaction intensity at the surface of W and Fe in ITER’s First Wall:

- $I_{DT} = J_d N_{eff}(T) \times \int_0^{E_d} f(E)\sigma_{DT}(E)(dx/dE)dE$
- Here J_d – deuteron current density; $N_{eff}(T)$ – effective concentration of bounded D/T in metal at temperature T, captured at depth x: ($N_{eff}(T) = N_0 \exp(-\varepsilon_d \Delta T / k_B T T_0)$, where N_0 – D/T concentration at T_0 = 290 K; f(E) – enhancement factor; σ_{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 A/cm^2, $\langle E_d \rangle$ = 2.0 keV, T ≈773K and screening potentials U_e(W) = 1200 and U_e(Fe) = 1350 eV, rough d(t, n)α -reaction rate at the reactor's edge would be: $I_{DT} \approx (1\text{-}2) \times 10^4$ s^{-1}-cm^{-2}.
- During one year of operation: DT-reaction alpha fluence $\Phi_\alpha \sim 7\text{x}10^{11}$/cm^2 or up to $N_{4He} \approx 10^{15}$ cm^{-3} atoms over depth $\lambda \sim 6$ µm 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 (~ 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.