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Exercises

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Exercises: Codeposition and Plasma Interaction with Deposited/Mixed Materials (JW Davis)

1.1) a) Based on a maximum implantation energy of ~ 1 keV/T, and ignoring diffusion/permeation, show that retention due to implantation is not a major concern in ITER.

b) Consider the case where neutron damage leads to an internal trap concentration of ~ 0.005 traps/metal atom, and diffusion leads to such traps being filed to a depth of $\ell = \sqrt{D\,t}$ where $D = 2.9 \times 10^{-7} \exp(-0.39\,eV/kT)\; m^2/s$, and T = 500K. (ρ_W = 19300 kg/m^3)

1.2) Estimate the amount of tritium used per full power, 400s, ITER shot. What % of the injected tritium is retained (assuming 1 g is retained). Base your calculations on a divertor pressure of 2 Pa and a pumping speed of 75 m^3/s.

1.3) Given a 1 GW_e fusion power plant, with a 10 kg in-vessel tritium inventory limit, calculate the maximum allowable deposition rate to allow one year of continuous operation.). Base your calculations on a $T_{injected}/T_{consumed}$ ratio of 25:1.

2.1) a) Calculate the ionization mean-free-path for a Be atom with 1 eV entering the scrape-off plasma of a fusion reactor: $n_e = 10^{19}\ m^{-3}$, T_e = 100 eV.

b) Calculate the dissociation mfp for a CH_4 molecule (0.2 eV) entering the scrape-off plasma.

c) Repeat a) and b) for a divertor plasma with $n_e = 10^{20}\ m^{-3}$, T_e = 2 eV.

d) Given a uniform SOL with a thickness of 2 cm, what fraction of 1 eV Be atoms will penetrate to the core plasma.

2.2) a) Given a core impurity content of 1% Be and $n_e \sim 10^{20} m^{-3}$ just inside the last closed flux surface, estimate the flux of Be to the divertor plates for a tokamak the size of ITER. Assume a SOL thickness of 2 cm and $D_{Be} \sim 1\ m^2/s$.

b) If this impurity flux is distributed uniformly over the CFC target area, how long will it take to build up a 10 nm thick Be coating? (ρ_{Be} = 1850 kg/m^3)

2.3) Carbon atoms are sputtered from a surface where there is a 3 T magnetic field with grazing incidence. If the C atoms leave the wall with ~ 1 eV, how small does the ionization mfp need to be for the majority of atoms to be promptly redeposited? What plasma conditions are implied?

3.1) ITER is limited to an in-vessel inventory of 700 g T. Assume all of this T is contained in codeposits having a density of 1.2 g/cm^3, a T/C = D/C ratio of 0.1, and coverage area of 10 m^2. How thick will the deposits be?

4.1) Using SRIM (www.srim.org), estimate the rate of W atom sputtering due to 1 keV D^+ ions for a) pure W, b) 90 at% W and 10 at% C, c) 50 at% W and 50 at% C.

4.2) Repeat 4.1) for 1 keV C^+ ions.

Table 1: ITER surface Areas (Federici, 2001)

Component	Approximate Surface Area
First Wall (Be)	680 m^2
Divertor Target (CFC)	55 m^2
Divertor side wall, baffle (W)	50 m^2
Divertor dome (W)	30 m^2
Divertor private region, liner (W)	60 m^2

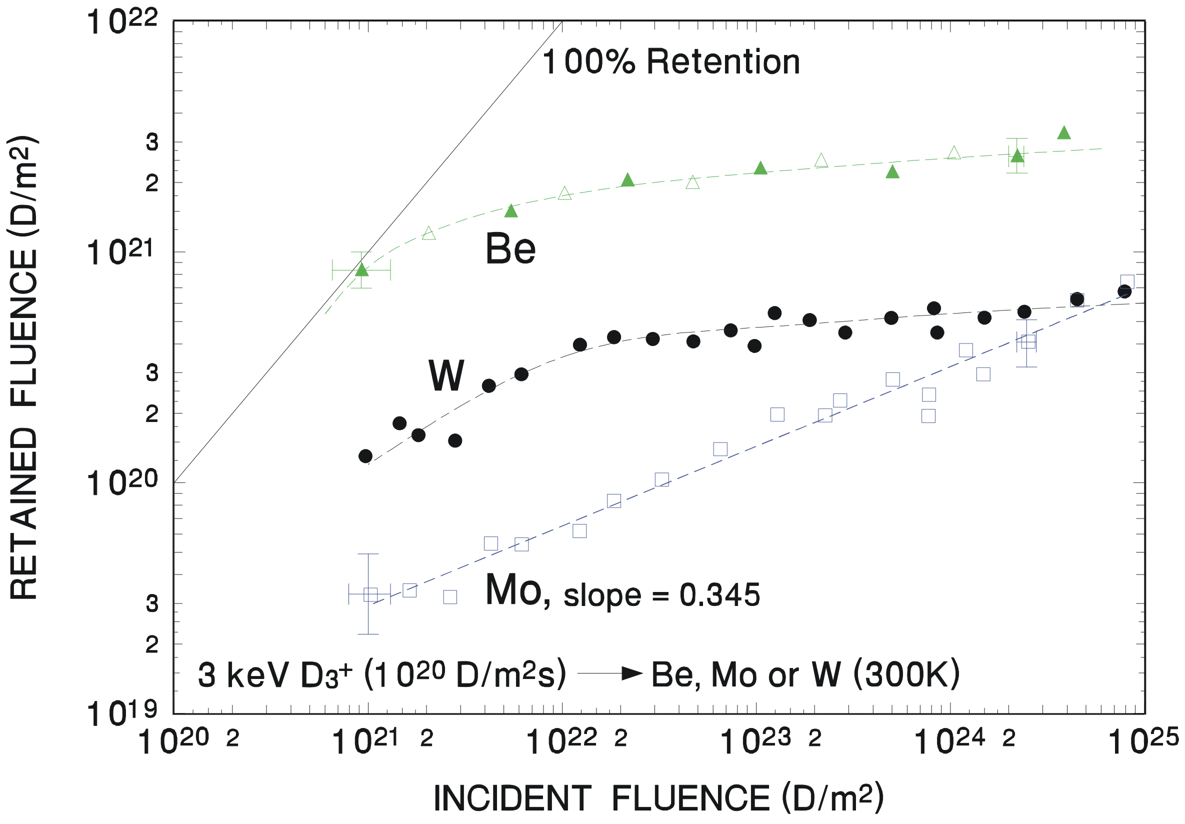

Figure 1: 1 keV D^+ retention in Be, Mo and W at room temperature as a function of incident fluence. From Haasz and Davis, J. Nucl. Mater, 241-243 (1997) 1076.

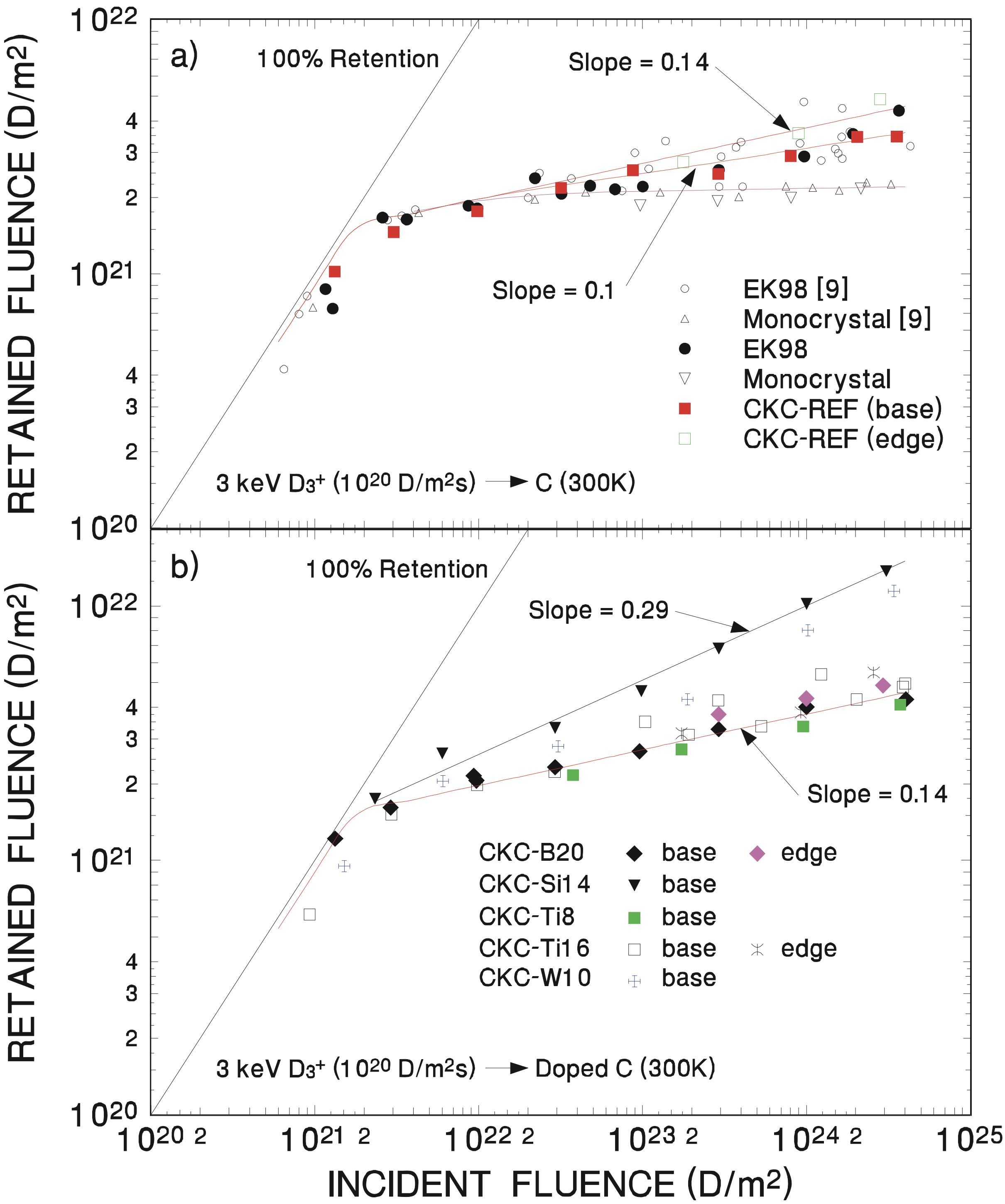

Figure 2: 1 keV D^+ retention in various graphites at room temperature as a function of incident fluence. From Haasz and Davis, J. Nucl. Mater, 232 (1996) 219.

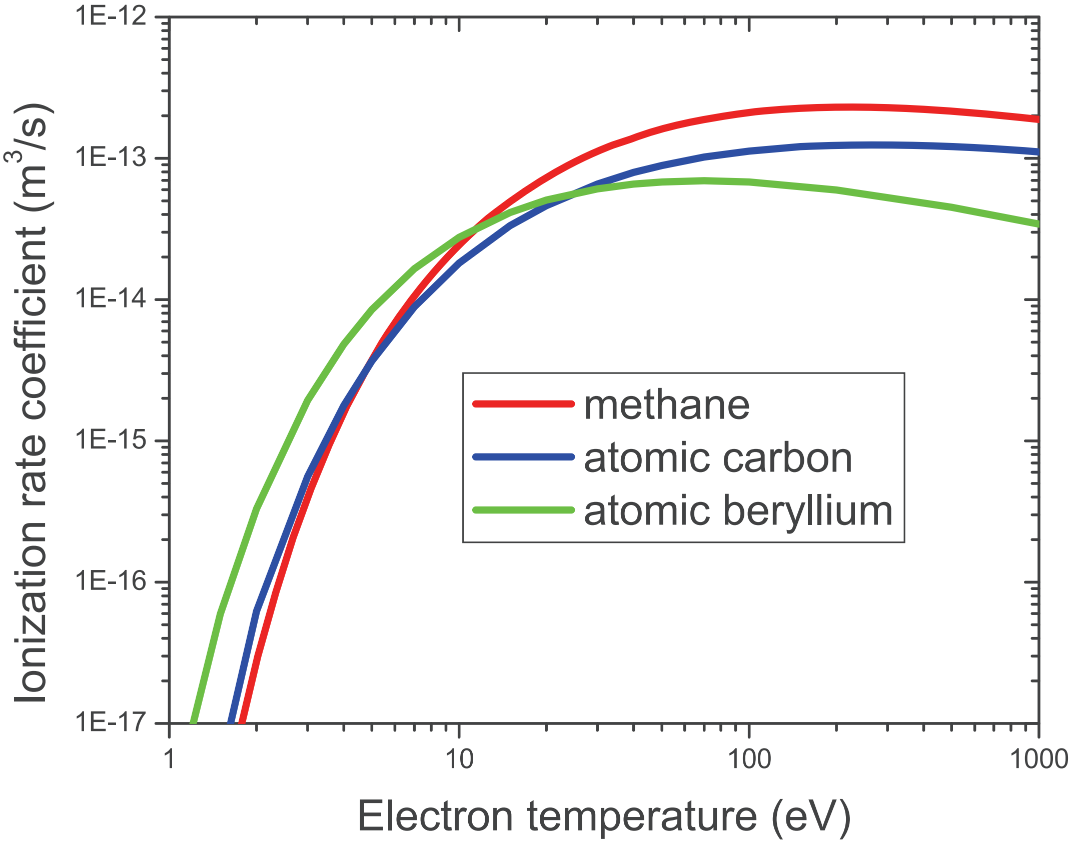

Figure 3: Ionization rate coefficients for CH_4 molecules, C atoms and Be atoms due to electron impact ionization. Atomic data from open-ADAS, methane data from http://www.eirene.de.

Exercises: Codeposition and Plasma Interaction with Deposited/Mixed Materials (JW Davis)

1.1) a) Based on a maximum implantation energy of ~ 1 keV/T, and ignoring diffusion/permeation, show that retention due to implantation is not a major concern in ITER.

b) Consider the case where neutron damage leads to an internal trap concentration of ~ 0.005 traps/metal atom, and diffusion leads to such traps being filed to a depth of $\ell = \sqrt{D\,t}$ where $D = 2.9\times 10^{-7}\exp(-0.39\,eV/kT)\,m^2/s$, and T = 500K. (ρ_W = 19300 kg/m^3)

a) At low temperature, 1keV T^+ implantation leads to saturated retention levels ~ 10^{21} T/m^2 in Be, W; perhaps as high as 10^{22} T/m^2 in CFC materials.

Total wall area in ITER ~ 875 m^2

$\Rightarrow$ retention $\lesssim$ 815 × 10^{22} T atoms

M_T = 3 × 1.67 × 10^{-27} $\Rightarrow$ 0.044 kg << 1 kg

Note that implantation is a "one time only" effect; this amount does not get implanted with every discharge.

b) $D = 2.9\times10^{-7}\exp\left(-0.39\,eV / 8.62\times10^{-5}\,eV/K \cdot 500\,K\right) \cdot 3.4\times10^{-11}\ m^2/s$

$\therefore\ \ell \simeq \sqrt{Dt} = \sqrt{3.4\times10^{-11} \times 10{,}000 \times 400\,s} = 0.012\ m = 1.2\,cm$

Number of W atoms: 19300 kg/m^3 $\Rightarrow \dfrac{19300}{184 \times 1.67\times10^{-27}} = 6.3\times10^{28}$ W/m^3

surface area ~ 500 m^2 $\Rightarrow$ 500 m^2 × 0.012 m = 6 m^3

$\Rightarrow$ 3.8 × 10^{29} W atoms.

0.005 traps / W atom $\Rightarrow$ 0.0025 T atoms / W atom

$\Rightarrow$ 9.4 × 10^{26} T atoms

$\Rightarrow$ 9.4 × 10^{26} × 3 × 1.67 × 10^{-27} = 4.7 kg

1.2) Estimate the amount of tritium used per full power, 400s, ITER shot. What % of the injected tritium is retained (assuming 1 g is retained). Base your calculations on a divertor pressure of 2 Pa and a pumping speed of 75 m^3/s.

pressure 2 Pa $\Rightarrow \frac{2}{10^5} \times 2.7 \times 10^{25} = 5.4 \times 10^{20}$ molecules/m^3

$\Rightarrow \sim 5.4 \times 10^{20}$ T/m^3 (assume DT molecules)

pumping speed 75 m^3/s $\Rightarrow$ 75 $m^3/s \times 400s = 30{,}000\ m^3$

T throughput: 5.4×10^{20} T/m^3 $\times$ 30,000 m^3 = 1.6×10^{25} T atoms

$\Rightarrow$ 0.081 kg

$\Rightarrow$ Approximately 80g of T will need to be injected into the torus during a discharge to maintain a steady pressure.

$\Rightarrow$ For 1g retained per shot, ~ 1% injected T retained

1.3) Given a 1 GW_e fusion power plant, with a 10 kg in-vessel tritium inventory limit, calculate the maximum allowable deposition rate to allow one year of continuous operation.). Base your calculations on a $T_{injected}/T_{consumed}$ ratio of 25:1.

Amount of T burned per day :

Energy per day : 3×10^9 W $\times$ 24 $\times$ 60 $\times$ 60 = 2.6×10^{14} J

Energy per T : 17.58×10^6 eV $\times$ 1.6×10^{-19} J/eV = 2.8×10^{-12} J

$\therefore$ T per day = $\dfrac{2.6 \times 10^{14}}{2.8 \times 10^{-12}}$ ~ 10^{26} atoms

@ 5×10^{-27} kg/atom $\Rightarrow$ 0.5 kg / day

T flow through : 25 $\times$ 0.5 = 12.5 kg / day.

For 1 year : 365 $\times$ 12.5 $\simeq$ 4563 kg

Allowable retention = 10 kg

$\Rightarrow$ $\dfrac{10}{4563}$ $\simeq$ 0.2 %

2.1)
a) Calculate the ionization mean-free-path for a Be atom with 1 eV entering the scrape-off plasma of a fusion reactor: $n_e = 10^{19}$ m^{-3}, $T_e = 100$ eV.
b) Calculate the dissociation mfp for a CH_4 molecule (0.2 eV) entering the scrape-off plasma.
c) Repeat a) and b) for a divertor plasma with $n_e = 10^{20}$ m^{-3}, $T_e = 2$ eV.
d) Given a uniform SOL with a thickness of 2 cm, what fraction of 1 eV Be atoms will penetrate to the core plasma.

Mean free path : $\lambda = \dfrac{v_{beam}}{n_e \langle \sigma v_e \rangle}$

a) $T_e = 100\,eV \Rightarrow \langle \sigma v_e \rangle^{iz}_{Be} \simeq 7\times10^{-14}\ m^3/s$

1eV Be atom : $v = \sqrt{\dfrac{2E}{m}} = \sqrt{\dfrac{2\times1.6\times10^{-19}}{9\times1.67\times10^{-27}}} = 4600\ m/s$

$\therefore \lambda_{iz} = \dfrac{4600}{10^{19}\cdot7\times10^{-14}} = 6.6\times10^{-3}\ m = \boxed{6.6\ mm}$

b) $T_e = 100\,eV \Rightarrow \langle \sigma v_e \rangle^{iz}_{CH_4} \simeq 2\times10^{-13}\ m^3/s.$

0.2eV CH_4 : $v = \sqrt{\dfrac{2\cdot0.2\cdot1.6\times10^{-19}}{16\times1.6\times10^{-27}}} = 1550\ m/s$

$\therefore \lambda_{iz} = \dfrac{1550}{10^{19}\cdot2\times10^{-13}} = 7.7\times10^{-4}\ m = \boxed{0.8\ mm}$

c) $T_e = 2eV \Rightarrow \langle \sigma v_e \rangle^{iz}_{Be} = 4\times10^{-16}\ m^3/s$

$\langle \sigma v_e \rangle^{iz}_{CH_4} = 2\times10^{-17}\ m^3/s$

$\lambda^{Be}_{iz} = \dfrac{4600}{10^{20}\cdot4\times10^{-16}} = 0.12\ m = \boxed{12\ cm}$

$\lambda^{CH_4}_{iz} = \dfrac{1550}{10^{20}\cdot2\times10^{-17}} = 0.775\ m = \boxed{80\ cm}$

d) $\Gamma = \Gamma_0 e^{-x/\lambda} \Rightarrow \dfrac{\Gamma}{\Gamma_0} = e^{-20/6.6} = 0.048 \Rightarrow \boxed{\sim5\%}$

2.2) a) Given a core impurity content of 1% Be and $n_e \sim 10^{20} m^{-3}$ just inside the last closed flux surface, estimate the flux of Be to the divertor plates for a tokamak the size of ITER. Assume a SOL thickness of 2 cm and $D_{Be} \sim 1\ m^2/s$.

b) If this impurity flux is distributed uniformly over the CFC target area, how long will it take to build up a 10 nm thick Be coating? ($\rho_{Be} = 1850\ kg/m^3$)

a) At edge of SOL: $D_{Be} \simeq 1\ m^2/s$

$n_{Be} \simeq 0.01 \times 10^{20}\ m^{-3} \simeq 10^{18}\ m^{-3}$

Flux into SOL $\simeq D_{Be} \times \frac{\Delta n_{Be}}{\Delta x} \times$ Area of plasma

$\simeq 1\ m^2/s \times \frac{10^{18}\ m^{-3}}{0.02\ m} \times 500\ m^2 = 2.5 \times 10^{22}$ Be/s

b) 10 nm layer on 55 m^2

$\Rightarrow 10^{-8}\ m \times 55\ m^2 \times 1850\ kg/m^3 = 0.001\ kg$

$\Rightarrow \frac{0.001\ kg}{9 \times 1.67 \times 10^{-27}} = 6.7 \times 10^{22}$ Be atoms

$\therefore \frac{6.7 \times 10^{22}}{2.5 \times 10^{22}} \simeq$ **2.7 s**

2.3) Carbon atoms are sputtered from a surface where there is a 3 T magnetic field with grazing incidence. If the C atoms leave the wall with ~ 1 eV, how small does the ionization mfp need to be for the majority of atoms to be promptly redeposited? What plasma conditions are implied?

$$r_L = \frac{m v_\perp}{q B} \qquad v_\perp \simeq \sqrt{\frac{2E}{m}} = \sqrt{\frac{2 \cdot 1 \cdot 1.6\times10^{-19}}{12 \times 1.67\times10^{-27}}}$$

$$\simeq 4000 \text{ m/s}$$

$$\Rightarrow r_L = \frac{12 \times 1.67\times10^{-27} \cdot 4000}{1.6\times10^{-19} \cdot 3} = 1.7\times10^{-4} \text{ m} = 0.17 \text{ mm}$$

$\therefore$ we need to have $\lambda_{iz} \lesssim 10^{-4}$ m

For $T_e \gtrsim 10$ eV, $\langle \sigma v \rangle_c^{iz} \simeq 10^{-13}$ m²/s

$$\lambda = \frac{v}{n_e \langle \sigma v \rangle} \Rightarrow n_e \simeq \frac{v}{\lambda \langle \sigma v \rangle}$$

$$\simeq \frac{4000}{10^{-4} \cdot 10^{-13}}$$

$$= 4\times10^{20} \text{ m}^{-3}$$

This would be a very intense plasma to have right next to a solid surface.

3.1) ITER is limited to an in-vessel inventory of 700 g T. Assume all of this T is contained in codeposits having a density of 1.2 g/cm^3, a T/C = D/C ratio of 0.1, and coverage area of 10 m^2. How thick will the deposits be?

$700\ g\ T \Rightarrow \frac{0.7\ kg}{5 \times 10^{-27}\ kg} = 1.4 \times 10^{26}$ T atoms

$\frac{T}{C} = 0.1 \Rightarrow 1.4 \times 10^{27}$ C atoms.

total mass : $1.4 \times 10^{26} \times 3 \times 1.67 \times 10^{-27}$

$+ 1.4 \times 10^{26} \times 2 \times 1.67 \times 10^{-27}$

$+ 1.4 \times 10^{27} \times 12 \times 1.67 \times 10^{-27}$

29.2 kg

density 1200 kg/m^3 $\Rightarrow \frac{29.2}{1200} = 0.024\ m^3$

deposition area : 10 m^2 $\Rightarrow$ thickness $\frac{0.024}{10} = 0.0024$

$\Rightarrow$ **2.4 mm**

4.1) Using SRIM, estimate the rate of W atom sputtering due to 1 keV D^+ ions for a) pure W, b) 90 at% W and 10 at% C, c) 50 at% W and 50 at% C.

4.2) Repeat 4.1) for 1 keV C^+ ions.

10,000 particles.

Incident particle	Target	Yields at 0°	Yields at 60°
1 keV D^+	W	$Y^W = 0.012$	$Y^W - 0.015$
	90%W, 10%C (10 to 1.1)	$Y^W = 0.011$ $Y^C = 0.0013$	$Y^W = 0.016$ $Y^C = 0.0026$
	50%W, 50%C (1 to 1)	$Y^W = 0.0078$ $Y^C = 0.011$	$Y^W = 0.012$ $Y^C = 0.027$
1 keV C^+	W	$Y^W = 0.46$ $Y^C_{backscatter} = 0.39$	$Y^W = 0.57$ $Y^C_{backscatter} = 0.58$
	90%W, 10%C (10 to 1.1)	$Y^W = 0.74$ $Y^C = 0.04$ $Y^C_{backscatter} = 0.30$	$Y^W = 0.53$ $Y^C = 0.05$ $Y^C_{backscatter} = 0.56$
	50%W, 50%C (1 to 1)	$Y^W = 0.38$ $Y^C = 0.32$ $Y^C_{backscatter} = 0.20$	$Y^W = 0.34$ $Y^C = 0.46$ $Y^C_{backscatter} = 0.44$