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Erosion of installations in ports of a fusion reactor by hot fuel atoms

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ABSTRACT

Charge-exchange interactions between plasma ions and neutrals, recycling from the first wall of a fusion reactor, generate c-x atoms of high energy. These may get into openings of diagnostic ports in the wall, leading to enhanced erosion of installations there, e.g., first mirrors. The energetic spectra of c-x atoms are modeled with the plasma density, electron and ion temperatures varying across the flux surfaces and by taking into account the inhomogeneity of the neutral density along the surfaces due to the absence of recycling at the opening position. The rate of erosion caused by physical sputtering with hot atoms on installations inside the port is computed for the plasma conditions expected in the DEMO fusion reactor, for several fusion relevant materials (beryllium, iron, molybdenum and tungsten), versus the port opening radius and clearance to the installation surface.

1. Introduction

In a fusion reactor like DEMO [1,2] interactions with neutral particles in the divertor will result in a very slow parallel plasma flow in the main part of the scrape-off layer (SOL), with a velocity by a factor of 20 smaller than the sound speed [3,4]. Consequently, a significant fraction, up to 25%, of plasma particles, leaking from the confined plasma region into the SOL, will hit the vessel wall before they are removed into the divertor volume. The intensification of the radial transport in the SOL by additional resonant magnetic perturbations, being proposed to mitigate edge localized modes (ELM) [5], will further amplify this transfer pattern. Plasma flows to the first wall, with a particle flux density above $10^{20}\ m^{-2}$s, lead to the wall saturation with fuel particles during seconds, i.e. a time much shorter than the discharge duration. Under such conditions a comparable influx of recycling neutrals into the plasma should be expected. These particles are not confined by the magnetic field and can penetrate deep, at several centimeters into the SOL plasma. Here charge-exchange interactions with plasma ions generate atoms of energies much higher than that of primary recycling particles. A noticeable fraction, up to 60%, of such secondary hot neutrals will escape to the wall and can get into diagnostic ports, see Fig. 1. The main purpose of the present consideration is an assessment of the erosion rates of installations in ports, e.g., first mirrors, of different materials, versus the port radius ρ_0 and the clearance h of the surface in question from the port entrance, see Fig. 1.

2. Transport model for c-x atoms

Neutral particles, molecules and atoms, recycling from the first wall into the plasma, are dissociated and ionized by the electrons and undergo charge-exchange (c-x) collisions with the ions. In the latter case c-x atoms with a broad energy spectrum are generated and a kinetic description of them seems to be mandatory. However, often a diffusion approximation is used for this purpose which is based on the assumptions that (i) the mean free path length (mfpl) between charge-exchange collisions is shorter than that till the ionization [6] and (ii) the characteristic scales for the change of plasma parameters are large compared to the mfpl of atoms, i.e. the Knudsen number is much smaller than 1. The diffusion approach is very attractive due to fast and numerically stable realization. Moreover, it does not provide numerical noise, as, e.g., Monte Carlo methods, and therefore can be straightforwardly and reliably coupled to fluid models for charged plasma components. In Ref. [7] a very good agreement between both approaches to describe c-x atoms has been demonstrated for a cold divertor plasma where the conditions above are well satisfied. In the reactor SOL the situation is different since neutrals, spreading across flux surfaces from the wall to the separatrix, pass through the region where the temperatures of plasma components change by hundreds of electron-volts and the Knudsen number may exceed 1. Very recently [4] this

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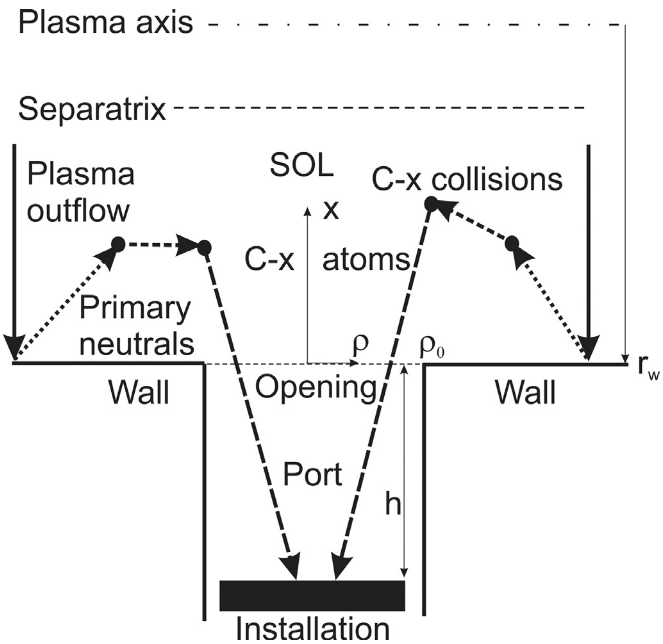

Fig. 1. Scheme for generation of hot c-x atoms, impinging installations in ports.

case has been studied by applying the approach of Ref. [8] to solve the kinetic equation for c-x atoms. In Ref. [8] this equation is reduced to an integral one for the particle density of c-x atoms, n_{cx}, which can be straightforwardly solved by iterations. This equation includes, however, integrals over normal and velocity spaces and therefore its solutions demands a large CPU time. In Ref. [4] to perform a thorough comparison of SOL modeling with either kinetic or diffusion description of c-x atoms the calculation of integrals over the velocity space has been speeded up by, at least, a factor of 30–50, by applying an approximate pass method.

The span of neutral species of hydrogen isotopes released from the first wall into the SOL plasma is defined by the phenomena at the wall surface. The following picture underlies the model of Ref. [4], whose results are used below as input for the present calculations. Because of transport processes in the plasma electrons and ions hit the wall and recombine into atoms. Also c-x atoms, escape partly from the plasma. Some fraction of such runaways is back-scattered as atoms, without a noticeable loss of energy, to the plasma. Here their density decays due to ionization and charge-exchange collisions with electrons and ions. Atoms caught in the wall give up their energy to its particles and recombine into molecules. Finally, these also are released into the plasma and are destroyed in dissociation, ionization and charge-exchange collisions. Through these processes the so called Franck-Condon atoms with a characteristic energy of 3.5 eV are generated. The variation with the distance x from the wall of the densities of the primary neutral species described above, n_{bs}, n_m and n_{fc}, respectively, have been calculated in Ref. [4], by assuming them moving with certain characteristic velocities predefined by the generation mechanisms. Computations were done with the data input from the European DEMO project [1,2]. In Fig. 2 we show several parameters, being relevant for the present study, found with the model of Ref. [4], by using either kinetic or diffusion description of c-x atoms. Here

$$S_{cx} = n\left[k_{cx}^m n_m + k_{cx}^a\left(n_{bs} + n_{fc}\right)\right], \quad (1)$$

is the density of the source of c-x atoms due to charge-exchange of primary neutrals, with k_{cx}^m and k_{cx}^a being the charge-exchange rate coefficients for molecules and atoms, correspondingly; n is the plasma density; T_e and T_i are the temperatures of electrons

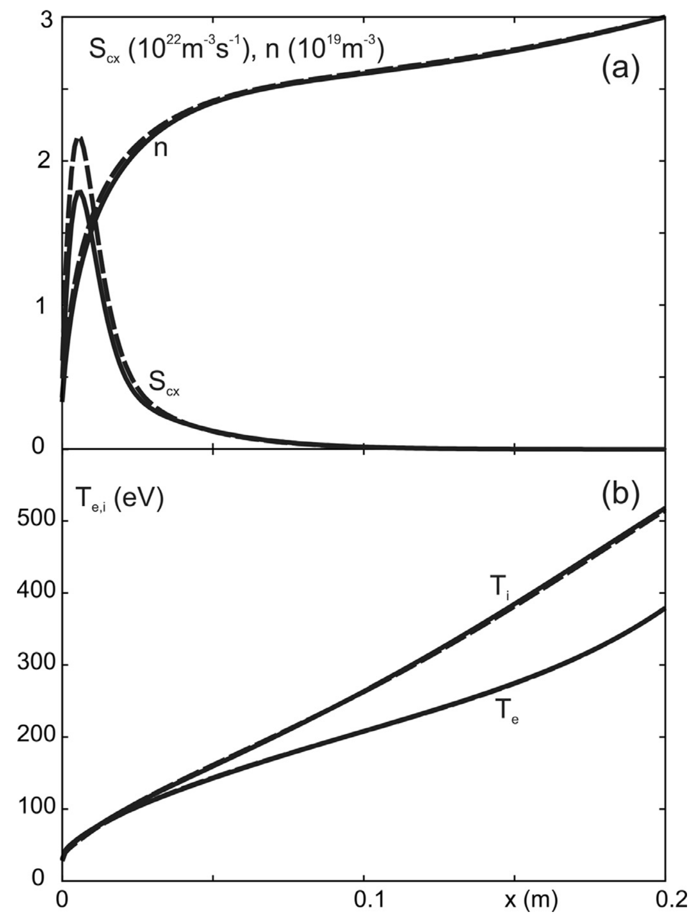

Fig. 2. The profiles of the source density of c-x atoms from primary neutrals and the plasma density (a), the electron and ion temperatures (c), found by applying the model of Ref. [4] with either kinetic (solid curves) or diffusion (dashed curves) descriptions of c-x atoms, for conditions without opening.

and ions. The density of c-x atoms, n_{cx}, is involved into S_{cx} through their outflow from the plasma. One can see good agreement between the profiles obtained with both approaches to describe c-x atoms. An ultimate comparison of kinetic and diffusion descriptions for c-x atoms in multi-dimensional geometries has still to be done. Nonetheless, we apply the latter for our two-dimensional study in the vicinity of a circular opening in the wall. This is motivated, on the one hand, by the 1-D consideration of Ref. [4] for the SOL conditions in question, and, on the other hand, by good agreement of two approaches found in 2-D calculations for a cold plasma in the divertor region [9]. The diffusion equation for c-x atoms is applied to the pressure $p_{cx} = n_{cx}T_i$ and in the cylindrical coordinate system (x, ρ) is as follows:

$$\partial_x(-d_a\partial_x p_{cx}) + \partial_\rho\left(-\rho d_a\partial_\rho p_{cx}\right)/\rho = \sigma_{cx} - k_{ion}^a n n_{cx}. \quad (2)$$

Here $d_a = 1/(\nu_a m)$ is the pressure "diffusion" coefficient, $\nu_a = n\left(k_{cx}^a + k_{ion}^a\right)$ the total frequency of atom attenuation by charge-exchange and ionization collisions, with $k^a{}_{ion}$ being the ionization rate coefficient; m is the atom mass; the 2-D density of the source of c-x atoms due to charge-exchange of primary neutrals

$$\sigma_{cx}(x, \rho) = n\left[k_{cx}^m n_m\omega_m + k_{cx}^a\left(n_{bs}\omega_{bs} + n_{fc}\omega_{fc}\right)\right], \quad (3)$$

where the factors $\omega_l \approx \left(1 + \exp\frac{\rho_0-\rho}{\lambda_l}\right)^{-1}$ take into account that, although there is no recycling from the wall at the opening position, $0 \le \rho \le \rho_0$, primary neutral species of the kind l spread into the area above the opening at a distance of their penetration depth $\lambda_l = V_l/\nu_l$; V_l is the characteristic velocity of the l-species

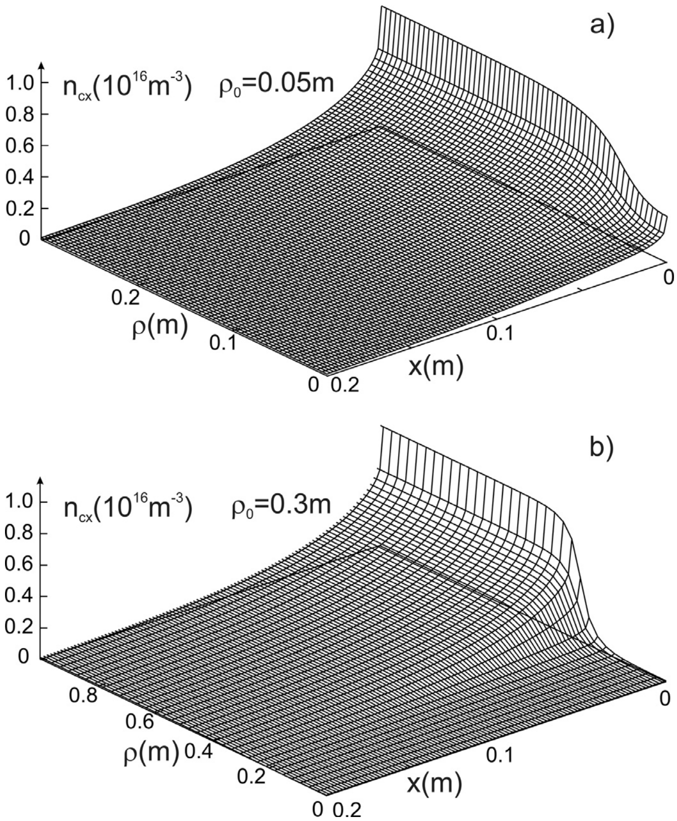

Fig. 3. The 2-D profiles of c-x atom density n_{cx} calculated from the numerical solution of Eq. (1) for narrow (a) and wide (b) ducts.

and the destruction frequency ν_l is equal to $\left[n\left(k_{cx}^m + k_{ion}^m + k_{dis}^m\right)\right]^{-1}$ and ν_a for molecules and atoms, respectively, with k_{ion}^m and k_{dis}^m being the molecule ionization and dissociation rate coefficients.

The boundary conditions to Eq. (2) imply: (i) c-x atoms leave the plasma with their thermal velocity, i.e. $d_a \partial_x p_{cx} \approx n_{cx}\sqrt{T_i/m}$ at $x = 0$; (ii) all fluxes reduce to zero at the plasma axis, $x = r_w$, with r_w being the wall minor radius, see Fig. 1; therefore $\partial_x p_{cx}(r_w) = 0$. Additionally, $\partial_\rho p_{cx} = 0$ for $\rho = 0$ and $\rho \to \infty$.

Eq. (2) has been integrated numerically and the found 2-D profiles of the density of c-x atoms, $n_{cx}(x, \rho) = p_{cx}(x, \rho)/T_i(x)$, are shown in Fig. 3. The results are presented for $\rho_0 = 0.05$ m, being characteristic for first mirror narrow ports, and wide ducts with $\rho_0 = 0.3$ m, intended for large installations. The drop in the c-x atom density at the opening center, $n_{cx}(x, 0)$, with respect to the level at $\rho \gg \rho_0$ increases with the growing opening radius ρ_0. However, with the increasing distance from the wall the difference between $n_{cx}(x, 0)$ and $n_{cx}(x, \rho \gg \rho_0)$ diminishes because atoms with larger thermal velocity spread easier over the flux surfaces.

3. Energetic spectrum of hot atoms

The diffusion approximation applied above to calculate the density of hydrogen c-x atoms in the plasma presumes that the averaged energy of atoms entering the opening in the wall is close to the ion temperature at the wall position, $T_i(0)$. However, the ion temperature increases by several times at the penetration depth of c-x atoms, see Figs. 2 and 3. C-x atoms generated in whole this plasma region partly escape without further collisions with electrons and ions. Thus, the distribution over the energies E of atoms, hitting the opening, can significantly differ from the local Maxwellian one of magnetized ions:

$$\varphi_i(x, E) = \frac{2\sqrt{E}}{\sqrt{\pi}T_i^{1.5}(x)} \exp\left[-\frac{E}{T_i(x)}\right]. \tag{4}$$

Consider an infinitesimally thin ring of the width $d\rho$, thickness dx, with the radius ρ and situated in the plasma at the distance x from the wall. C-x atoms of the energy within the range $E, E + dE$ are generated in this ring at the rate:

$$dR_{cx}(x, \rho, E) = \Sigma(x, \rho, E)\varphi_i(x, E) 2\pi\rho d\rho dx dE, \tag{5}$$

where

$$\Sigma(x, \rho, E) = \sigma_{cx}(x, \rho) + k_{cx}^a n n_{cx}(x, \rho) \tag{6}$$

is the total density of the c-x atom source including the charge-exchange of c-x atoms themselves. The c-x rate coefficient k_{cx}^a is a function, although weak, of the energy E_{ai} of the relative motion between interacting atom and ion, $k_{cx}^a[m^3 s^{-1}] \approx 10^{-14} E_{ai}^{0.3}[eV]$ [10]. In the diffusion approximation for c-x atoms their averaged energy is of $1.5T_i$ and, by estimating k_{cx}^a for Σ, we assume $E_{ai} = E + 1.5T_i(x)$.

C-x atoms move in all directions and some of them hit the installation surface located inside the port at the distance h from port entrance, see Fig. 1. Henceforth we consider the surface position at the port axis only. A simple geometric analysis shows that c-x atoms from rings with $\rho \le \rho_{max} = \rho_0(1 + x/h)$ can hit this surface point. The contribution of the plasma volume in question to the density of the c-x atom flux perpendicular to the installation surface is:

$$dj_{cx}(x, \rho, E) = dR_{cx} \frac{s \exp(-\lambda/s)}{4\pi\left[(x+h)^2 + \rho^2\right]}, \tag{7}$$

where $s = [1 + \rho^2/(x + h)^2]^{-1/2}$ is the cosine of the atom incidence angle with respect to the port axis. The exponential factor, in Eq. (7), with $\lambda = \int_0^x \nu_a dx'/\sqrt{2E/m}$, takes into account the destruction, due to ionization and charge-exchange collisions, of the atoms in question on their way through the plasma. By ionization the atom completely disappears. By charge-exchange a new atom is generated. The latter is taken into account by the second term in the source density Σ and by the summation/integration of dj_{cx} contributions from rings situated in the plasma at all possible x. Through ν_a the dependence of k_{cx}^a on the relative motion energy is involved into λ. In this case the atom energy is fixed but the plasma ion temperature is changing. Therefore, $E_{ai} = E + 1.5T_i(x')$.

The energy spectrum of atoms hitting the installation is characterized by their flux density in the energy range dE, $\gamma = \int dj_{cx}/dE$, where the integration is performed over the ring radius ρ and distance from the wall x. By proceeding from ρ to s, according to the relation $\rho = (x + h)\sqrt{1/s^2 - 1}$, one gets:

$$\gamma(h, \rho_0, E) = \int_0^{r_w} \varphi_i(x, E) dx \int_{h/\sqrt{h^2+\rho_0^2}}^{1} \frac{\Sigma}{2} \exp\left(-\frac{\lambda}{s}\right) ds. \tag{8}$$

Fig. 4 demonstrates $\gamma(h, \rho_0, E)$ found for different clearances h between the installation surface and port openings with $\rho_0 = 0.05$ m and 0.3 m, the plasma and neutral parameters shown by dashed curves in Fig. 2. The deeper the installation surface is retracted into the port the narrower is the plasma cone from which hot atoms can hit the surface. Therefore, the atom flux to the surface decreases with increasing h. For a fixed h, the larger ρ_0 the smaller γ because of decreasing $n_{cx}(x, \rho \le \rho_0)$, see Fig. 3.

In a situation without opening, $h, \rho_0 = 0$, expressions (7) and (8) coincides with those following from the 1-D kinetic description of c-x atoms [4,8]. Consider a plasma of extremely high collisionality, n, ν_a, $\lambda \to \infty$. One could think that formula (7) predicts $dj_{cx} \to 0$ and, thus, zero outflow of c-x atoms. In this case, however, $\lambda \approx$

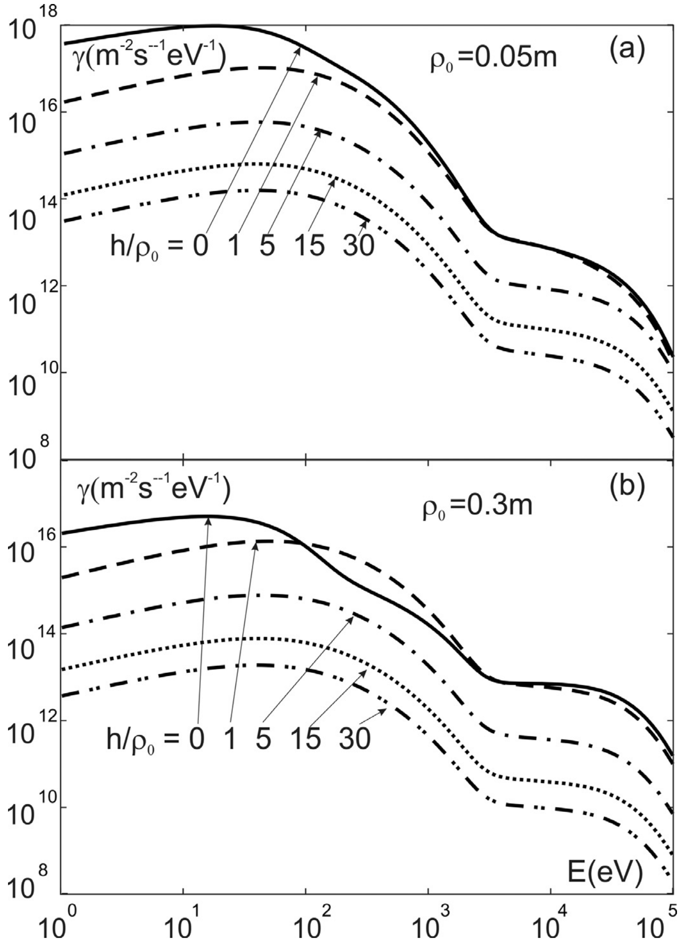

Fig. 4. The energetic spectra of c-x atoms, impinging installations at different distances from the port opening.

x/x_0, with $x_0 = \sqrt{2E/m}/\nu_a(0)$, and dj_{cx} is finite for c-x atoms generated at $x \lesssim x_0 s$. The integral over s in formula (8) can be assessed by applying the pass method:

$$\int_0^1 \frac{\Sigma}{2} \exp\left(-\frac{\lambda}{s}\right) ds \approx \frac{\Sigma(0,E)}{2} \frac{\exp(-x/x_0)}{2 + x/x_0} \tag{9}$$

Finally, after the integration over x and using the definitions of Σ and ν_a, we get:

$$\gamma(0,0,E) \approx \sqrt{\frac{2E}{m}} \frac{\varphi_i(0,E)}{3} \frac{k_{cx}^m n_m + k_{cx}^a n_a}{k_{ion}^a + k_{cx}^a}(0) \tag{10}$$

where $n_a = n_{bs} + n_{fc} + n_{cx}$ is the total density of atoms. Thus, $\gamma(0, 0, E) \sim \varphi_i(0, E)$ and is finite.

Formulas (7) and (8) are derived by assuming that there is no plasma and, correspondingly, no collisions of hot atoms inside the port. This, probably, will not be the case in DEMO. A rough estimate shows that for a duct of a 1 m length the effect of c-x collisions in the port is noticeable for a plasma density above 10^{18} m^{-3}. Any quantitative consideration of plasma effects in the port is out the scope of the present paper but has to be undertaken in future studies.

4. Erosion rate of installations

The density of the outflow of the installation material eroded by physical sputtering with c-x fuel atoms can be assessed as follows:

$$\Gamma_{sp}(h,\rho_0) = \int_0^\infty dE \int_0^{r_w} \varphi_i(x,E)dx \times \int_{h/\sqrt{h^2+\rho_0^2}}^1 \frac{\Sigma}{2} \exp\left(-\frac{\lambda}{s}\right) Y_{sp}(E,s) ds \tag{11}$$

Here Y_{sp} is the sputtering yield, whose dependence on the projectile energy E and the cosine s of its incidence angle has been calculated by applying semi-empirical formulas from Ref. [11]. The erosion rate $h_{sp} = \Gamma_{sp}/n_{sp}$, with n_{sp} being the particle density of the installation material and measured in μ m/year, is demonstrated in Fig. 5 as a function of the installation surface position h inside the port, for different fusion-relevant materials.

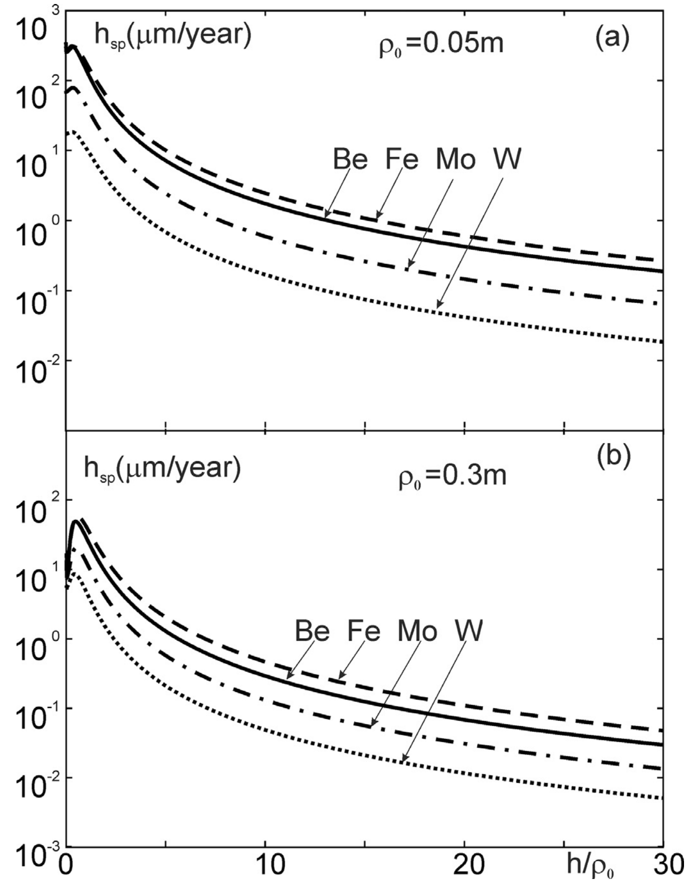

Fig. 5. The erosion rate of surfaces of different materials, versus the surface position inside ports.

One can see for installations posed at short distances from the port opening position the erosion rate of surfaces of all material considered may be very significant, from tens to hundreds of μ m/year. This rate decreases significantly, by order of magnitude, with retracting the installation from the duct opening at a distance h much larger the opening radius ρ_0. It is interesting to note that in spite of the same duct aperture, the erosion rate of a surface posed at a particular h/ρ_0 decreases with increasing ρ_0. This is explained by the 2-D pattern of the hot atom density, being reduced within the opening area, see Fig. 3.

5. Conclusion

It is demonstrated that the SOL modeling either with kinetic or with diffusion description of atoms, generated by charge-exchange collisions with ions of neutrals, recycling from the wall of a fusion reactor, provide very close results. The diffusion description of c-x atoms is applied to consider the 2-D situation in the vicinity of a port opening in the wall, with the atom density inhomogeneous along the flux surfaces because of the absence of plasma recycling at the opening position. The energy spectrum of c-x atoms, impinging the installations inside the ports, is assessed by taking into account the Maxwellian energy distribution of ions with the density and temperature changing with the distance from the wall. This spectrum is used to assess the erosion of installation surfaces through physical sputtering by c-x atoms. The erosion rate is calculated for different fusion-relevant materials, Be, Fe, Mo and W, versus the surface position h in the port and the port opening radius ρ_0.

Calculations have been done for the parameter set chosen according to the European DEMO and ITER projects. For installations posed close enough to the port opening position, at $h \lesssim \rho_0$, the erosion rates for all materials considered will be larger than tens of μ m/year. It is decreased by orders of magnitude by retracting the installation away from the duct entrance at distances much larger than ρ_0. For a given h the energy spectrum of atoms, impinging the installation, is controlled by the interplay between the duct aperture and the atom density reduction in the plasma near the opening. With increasing ρ_0 the latter effect prevails, leading to a smaller erosion of installations in wider ports. Therefore, it seems reasonable to put first mirrors in ports with large openings and aperture narrowing by approaching to the mirror. In all cases considered the sputtering rate of Mo mirrors exceeds 10 nm during the whole exploitation time of several years, considered as an acceptable level. Thus, some additional measures, e.g. baffles, reducing the flux of hot atoms, have to be foreseen.

By concluding, we have to mention that, additionally to the erosion by energetic "shining through" atoms, there are other processes potentially leading to undesirable modifications of installation surfaces. Thus, the atoms sputtered from the vessel wall can be driven by elastic collisions with the plasma ions into the duct opening. Here they can reach the installation due to side-to-side free transport and be deposited on its surface. Although a recent study [12] indicates that the re-erosion of these impurities by hot atoms from plasma will normally dominate over the deposition process, such effects have to be included in future investigations.

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