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Analysis of the mechanism and source of contamination of diagnostic windows in fusion devices

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Abstract

Sputtering by charge exchange (CX) atoms of the diagnostic duct wall was suggested as the mechanism of the appearance of deposits on diagnostic windows of fusion devices, or on the "first mirrors" (FM) in ITER. The rate of deposit growth was estimated as a balance between the deposition rate of wall material, D, and sputtering of the deposit, S. For these estimation the dependencies of the sputtering yield on the projectile energy and incidence angle were used. It was found that the duct length to its diameter ratio, L/d, is an important parameter. The D value exceeds several times S value if $L/d > 2$, but D/S is less than 1 in the case of a short duct, $L/d \ll 1$, and also in the case of a very long duct, $L/d \geqslant 10$. Based on such a mechanism, the duct structure with diaphragms made of refractory metals was proposed to decrease significantly the rate of deposit growth.

1. Introduction

Some methods of plasma diagnostics in fusion devices require the use of diagnostic windows. The deposit formed on these windows after a long operation time deteriorates the transmission of electromagnetic radiation. Sometimes, it has been possible to clean the windows in situ by evaporating the deposit with laser [1,2]. Frequently, however, there is a need to replace the windows having lost the transparency. To decrease the rate of deposit growth, it is of practical importance to use special blinds to protect the windows during different stages of vacuum chamber preparation, i.e. during gettering, carbonization or boronization. However, during plasma discharges, the windows should be opened, and hence, the deposit will be increased steadily in the course of measuring the plasma parameters if there is net deposition. In a fusion reactor, this mechanism will result in contamination of the surface of the "first mirrors" (FM) for different diagnostics. These mirrors have to be located in direct visibility of the plasma near the first turn of periscopic channels [3]. In this paper, a possible mechanism is suggested and discussed. The mechanism can lead to contamination of diagnostic windows of fusion devices (as well as of first mirrors in a fusion reactor) due to net deposition on the window (or on FM) surfaces of the material from the walls of a diagnostic duct sputtered by charge exchange (CX) atoms.

2. Description of the mechanism of deposit appearance

The scheme of net deposition mechanism is shown in Fig. 1. The CX atoms (2) are atoms of hydrogen isotopes moving from the plasma (1) to the duct walls (3). Sputtered atoms of the wall material (4) are deposited on the opposite duct wall and on the surface of a diagnostic window (5). As a result, the deposition (6) is increased. This deposited material is also sputtered by CX atoms which bombard the window and sputtered deposit atoms (7) have to be redeposited on the duct walls. It is clear that the deposit thickness on the window will increase only in the case when the material flux from the walls onto the window exceeds the return flux due to sputtering of the deposited material on the window.

We considered quantitatively the dynamics of deposit formation on the window, taking into account published data on the dependence of the differential sputtering coefficient (DSC) on the angle of light particle incidence onto the surface being sputtered [4,5].

Peculiarities of the sputtering of the metal surface were observed when it is bombarded with ions (or

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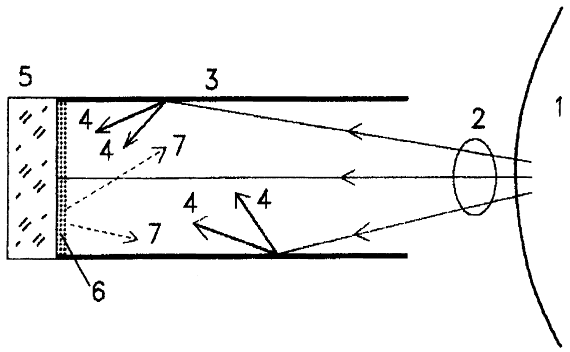

Fig. 1. Deposition scheme appearing on the diagnostic window. (1) – periphery plasma, (2) – flux of CX atoms, (3) – diagnostic duct, (4) – sputtered atoms of a duct material, (5) – diagnostic window, (6) – deposit on the window surface, (7) – sputtered atoms of a deposit material.

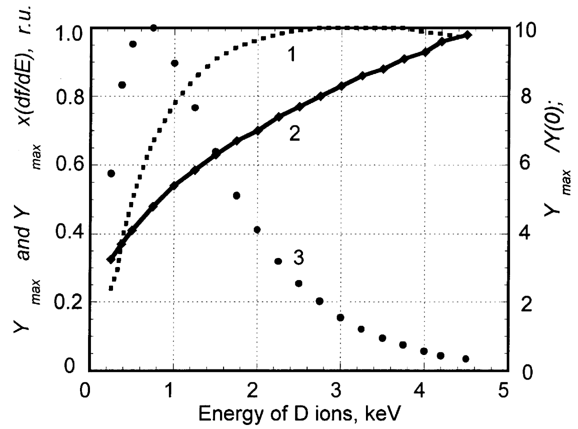

Fig. 2. Energy dependence of D on Ni pair the following variables: (1) – maximum sputtering yield, $Y_{max} \equiv Y(\Theta_{max})$; (2) – ratio of maximum sputtering yield to sputtering yield at normal incidence, $Y_{max}/Y(0°)$; (3) – product of Y_{max} and df/dE for the ion energy distribution with 0.5 keV mean energy.

atoms) of hydrogen or deuterium at a grazing angle. As it is shown by many authors, the sputtering yield increases, depending on the incidence angle Θ, measured from the normal to the surface, and attains its maximum at $\Theta \cong 80°$. The relative value of the sputtering yield at the maximum angle, $Y(\Theta_{max})/Y(0°)$, increases with increase of the bombarding particle energy for a given target material. The empirical formula proposed in Ref. [6] adequately describes a large body of experimental data. Later the authors of Refs. [7,8] have introduced amendments into the empirical equations of Ref. [6] which, however, are not very important for the angular dependencies in the case of light ion sputtering. The result of calculations of $Y(\Theta_{max})$ and $Y(\Theta_{max})/Y(0°)$ versus energy of the projectiles (E) [6] for the pair D–Ni are shown in Fig. 2. In principle, the angular and energy dependence $Y(\Theta, E)$ allow one to take into account the contribution into the sputtering yield of the duct wall of any part of the CX atom energy spectrum, which is rather broad in reality, as seen from measurements on the tokamaks PLT [9], ASDEX [10] and JFT-2M [11], with a mean atom energy of several hundred eV. This contribution is determined by the product of $Y(\Theta, E)$ and the corresponding value of the atom distribution function df/dE. In Fig. 2, we show the dependence of $Y(\Theta_{max})$ and $Y(\Theta_{max})/Y(0°)$ on E, as well as the values $Y(\Theta_{max}) \cdot (\mathrm{d}f/\mathrm{d}E)$ defined with the assumption of exponential dependence of df/dE on the mean atom energy of 500 eV. As is seen, with such mean atom energy, the main contribution in the sputtering yield at the grazing incidence angle will be due to <3 keV atoms for which the mean value of $Y(\Theta_{max})/Y(0°) \cong 6$.

Another peculiarity of sputtering at a grazing angle observed experimentally and verified by calculations [4,5] consists in the ejection of sputtered particles is directed for the most part, to the way of incident particle movement. However, the angle of maximum ejection, Θ'_{max}, is always less than the incidence angle, Θ_{in}. This difference decreases with decreasing energy of bombarding particles. For hydrogen ions of $E < 1$ keV at incidence angles $\Theta_{in} = 80°$, the major flux of Ni atoms being sputtered in the incidence plane is concentrated between angles $\Theta \cong 25°$ and $\Theta \cong 65°$ (Fig. 4 in Ref. [5]). As the energy of bombarding particles increases, the DSC distribution more and more approaches the surface normal. Therefore, for $E = 4$ keV the most part of the sputtered material flux is between $\Theta = 10°$ and $\Theta = 55°$ [4].

3. Estimation of deposit growth rate

Let us evaluate now the rate of growth of a dense deposit on the bottom of a duct of length, L, which exceeds its diameter $2r$. It is seen from Fig. 1 that the solid angle where the CX atoms come to the duct wall section located at a distance $\sim r$ from the diagnostic window (i.e., from the channel bottom) differs little from the solid angle for any part of the window. However, the density of the atom flux onto this part of the cylindrical wall will be $\langle \cos\, \Theta_w \rangle^{-1} \approx \cos\, \langle \Theta_w \rangle^{-1}$ times less than that onto the window surface with the deposit. The angle $\langle \Theta_w \rangle$ is inside the angle, limited by the channel wall and by the direction to the opposite edge of the duct. And, because the total sputtering coefficient decays at an incidence angle $\Theta > 80°$ after reaching its maximum [6–8], then, on average, the degree of the projectile flux density decrease, which is equal to $\cos\, \langle \Theta_w \rangle^{-1}$, will be less than $(\cos\, 80°)^{-1} = 6$. It can be seen that the decrease of the density of sputtered atoms onto the wall nearest to the window is compensated (with factor $\sim$1.2) by the increase in the sputtering coefficient due to the grazing incidence of sputtering atoms. In such an approximation, the ratio between the rate of sputtered material deposition on the window surface and the rate of deposit sputtering should be determined by the ratio of areas related to the change of the deposit density at the duct bottom.

As it was already mentioned, the experimental DSC distribution versus angle Θ_w shows that for the lower part of the CX energy spectrum, the main contribution to the deposit will be due to sputtering the part of the cylindrical duct wall which is seen from the window center as the band located between angles ~25° and ~65° from the normal. Thus, this band which passes parallel to the window surface through all the cylindrical duct surface located between the height $h_1 \cong r/2$ and $h_2 \cong 2r3^{1/2}$ has an area of $\sim 4\pi r^2$, while the window area is πr^2. Consequently, the average flux Γ_{on} of sputtered atoms from the duct wall onto the window surface will be several times higher than the inverse flux Γ_{out} from the window surface onto the wall: $\Gamma_{on}/\Gamma_{out} \geqslant 4$. However, we have to take into account the compensation factor mentioned above ($\geqslant 1.2$), as well as the increase of the solid angle of the CXA source (i.e., edge of the plasma confinement volume, Fig. 1) with moving off from the duct bottom. Thus, the estimated Γ_{on}/Γ_{out} ratio will approach or even exceed 6, and this means that the deposit on the diagnostic window will grow with time at the expense of the material sputtered from the walls if the duct is sufficiently long: $L > 2r$.

4. Discussion and conclusions

It follows from the foregoing that the geometry of the duct is a very important factor for the rate of deposit growth. In the case of a short duct, $L \ll 2r$, the ratio Γ_{on}/Γ_{out} will be less than one. The deposit formed at the expense of the material sputtered from the duct wall will be sputtered again by the large flux of CX atoms. With such duct geometry, the contribution from its wall to the deposit will be insignificant. The deposition dynamics will depend on the rate of material arrival to the window and on the rate of its erosion due to physical and, possibly, chemical sputtering. The deposit on the window will not grow in the opposite case (if i.e. the duct is very long, e.g. $L/2r > (\cos 85°)^{-1} \approx 10$). With such a geometry, the strongest sputtering erosion of the duct wall will take place far from the window, and the sputtered material will be again redeposited on the duct wall.

If the above-considered mechanism of window contamination is true, then it is believed that there are two possibilities for decreasing the rate of growth of the deposit in fusion devices. One of them is duct wall protection with a foil from the material having a significantly lower value of the sputtering coefficient in comparison with structural materials being used now. For example, the values Y for normal incidence of deuterium atoms with the energy of 1.0 keV are [7,12]: $Y(\mathrm{Ni}) \cong 4 \times 10^{-2}$, $Y(\mathrm{W}) \cong 3 \times 10^{-3}$, $Y(\mathrm{Ta}) \cong 2 \times 10^{-3}$. Disposition inside the duct of diaphragms made of W or Ta, as shown in Fig. 3, may be more effective. The distance between diaphragms (as marked in Fig. 3) and the relative magnitude of the diaphragm window for a given duct geometry have to be optimized on the basis of angular dependencies $Y(\Theta)$. The thickness of the diaphragms should be determined with taking into account the possible rate of sputtering by CX atoms.

Note that when the wall coatings (B, C, Si, Ti) are used for improvement of vacuum conditions in the installation, there should be permanent "diffusion" of the coating material deep into the duct. In time, all the duct wall will be coated with the coating material and the deposit on the window will grow at the expense of this material but not of the wall material proper. The rate of "diffusion" along the duct will depend on the rate of arrival of the coating material at the duct entry. From this, it follows that during conditioning procedure, it is more wise to place the protective blinds not directly in front of the window but at the duct entrance.

To date, there are only few measurements of chemical composition of the deposit on diagnostic windows from the tokamaks T-10 [13], TFTR [14] and JT-60U [15]. The T-10 tokamak window was mounted on one of the long spectroscopic ducts during the first months of machine operation, when the W–Re diaphragm was used as a limiter. Elementary analysis of the deposit has shown only the components of the chamber and duct material (inconel) approximately in the same proportion as in the structure of the vessel construction. But neither tungsten nor rhenium were detected. At the same time, both elements were registered in the region behind the limiter edge by using probes [16] after the W–Re

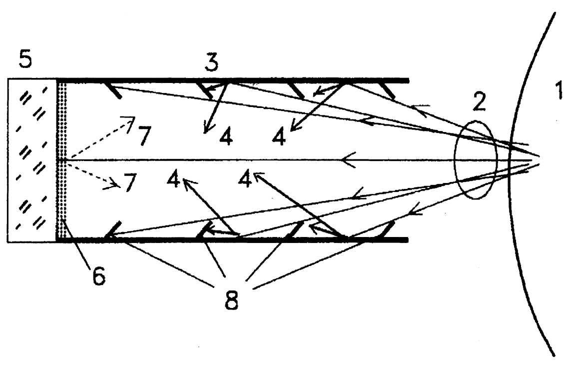

Fig. 3. A possible method to decrease the rate of deposit growth. Designations (1)–(7) are similar to Fig. 2. (8) – diaphragms made of material with low sputtering yield (e.g., Ta, W).

diaphragm has been replaced by limiters from another materials. Therefore, the result of this analysis can be considered as an indirect support of the mechanism described in the present paper. Results from two other devices were obtained after a long period of their operation with installed graphite limiters and tiles. In both cases, the main component of the deposit was found to be carbon. Therefore, to check the importance of the discussed mechanism, special experiments should be carried out on fusion devices with measurements of the deposit composition under conditions when the duct wall material is controlled.

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References

[1] K. Narihara, S. Hirokura, Rev. Sci. Instr. 63 (1992) 3527.
[2] B.W. Brown, C.W. Gowers, P. Nielsen, B. Schunke, Preprint JET (94) 21, April 1994.
[3] Publication of the ITER Diagnostic Group: ITER EDA-JCT, S 55 RE 95-07-11 F1, 11 July 1995.
[4] H.L. Bay, J. Bohdansky, W.O. Hofer, J. Roth, Appl. Phys. 21 (1980) 327.
[5] J. Bohdasky, G.L. Chen, W. Eckstein, J. Roth, J. Nucl. Mater. 103/104 (1981) 339.
[6] Y. Yamamura, Y. Itikawa, N. Itoh, Angular dependence of sputtering yields of monoatomic solids, Preprint IPP J-AM-26, Nagoya, June 1983.
[7] W. Eckshtein, C. Garcia-Rosales, J. Roth, W. Ottenberger, Sputtering data, IPP 9/82, Gaching bei Munchen, February 1993.
[8] C. Garcia-Rosales, W. Eckstein, J. Roth, J. Nucl. Mater. 218 (1994) 8.
[9] D.N. Ruzik, D.B. Heifetz, S.A. Cohen, J. Nucl. Mater. 145–147 (1987) 527.
[10] H. Verbeek and the ASDEX Team, Ibid., p. 523.
[11] Y. Miura and JFT-2M Team, Nuclear Fusion 37 (1997) 175.
[12] Y. Yamamura, H. Tawara, Energy dependence of ion-induced sputtering yields from monoatomic solids at normal incidence, Research Report NIFS-DATA-23, Nagoya, March 1995.
[13] Private communication.
[14] D.H. McNeil, Rev. Sci. Instr. 61 (1990) 1263.
[15] H. Yoshida, O. Naito, T. Hatae, A. Nagashima, Rev. Sci. Instr. 68 (1997) 256.
[16] D. Hildebrandt, W. Hintze, M. Laux et al., Charge state of metal impurities in the scrape-off plasma of the T-10 tokamak, Preprint 82-12 of ZIE, Berlin, November 1982.