PLASMA WALL INTERACTION AND ITS CONTROL BY WALL CONDITIONING

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I. INTRODUCTION

The surrounding material walls in fusion devices must fulfil three important tasks:

provide high vacuum conditions necessary to provide clean fusion plasmas

absorb the power produced by the α-particles in the fusion processes and injected by auxiliary heating

enable the exhaust of the helium ash by thermalisation of the helium plasma ions on material surfaces in the vicinity of helium pumps.

The interaction of the plasma with the surrounding wall surfaces (PSI: plasma surface interaction) is therefore a necessary condition for fusion devices and not to avoid. In the plasma wall interaction a variety of bulk material and surface processes are involved on one side together with various special processes in the near surface plasma region on the other side. They can modify the properties of the boundary and main plasma in a feed back like behaviour.[1,2] A prominent example is the release of impurities from the walls by plasma particle impact which increases the energy loss of the plasma by radiation and reduces thereby the particle fluxes to and impurity release from the walls.

For the realisation of a fusion plasma under steady state conditions the interaction of the plasma with the walls represent severe problems. The exploration of the material and plasma conditions under which the negative consequences of plasma wall interaction for the plasma performance can be tolerated, the wall material resists the plasma impact and a "peaceful coexistence" of both media is possible is one of the most difficult tasks in fusion research. The important conditions which must be fulfilled in a coherent way are

the steady state power exhaust (limit 10 MW/m^2) which allows simultaneously a sufficient helium exhaust

an acceptable lifetime and mechanical integrity of the wall components (e.g. 3000 discharges for ITER)

a limited long term retention of the radioactive tritium in the wall materials. This limit is presently at 350gT due to safety concerns .[3]

This contribution describes first basic properties of the power out flow to the wall surfaces in fusion devices. In section II the basic processes of the interaction of particles with matter are outlined which lead to the release of wall materials from the walls by various mechanism. In chapter V the local transport of eroded wall material is discussed and finally the use of wall conditioning methods by which some of the PSI processes can be controlled.

II. Power exhaust in magnetic fusion

II.1. Steady state heat exhaust

The aim of the magnetic confinement is to provide the plasma conditions in the plasma core for the fusion process and this implies to minimise the energy transport perpendicular to the field lines. Good energy confinement leads thus to steep radial gradients of temperature (T_e), density (n_e) and parallel power flow. In TEXTOR plasmas the radial decay lengths of power, density and temperature are typically 0.8-3cm. Even steeper gradients are achieved in the edge of diverted plasmas under high confinement conditions (H-mode), e.g. 3-5 mm in JET Elmy H-modes. As a consequence of this (and thus of the magnetic confinement) the convective energy loss out of the plasma is concentrated within a narrow radial zone outside the last closed flux surface (LCFS) where the

plasma interact at first with material surfaces. If.e.g., the heating energy in ITER is only exhausted by heat conduction in this zone (no radiation losses) the parallel power density at the LCFS is about 120 MW/m^2. The first method to reduce these excessive heat flows to the first wall structures is to decline the target with respect to the magnetic field lines, increasing thereby the effective wall area. In ITER, the plasma will impinge with about 2° on the target tiles but the effective strike zone area will nevertheless be only about 6-8 m^2 (Table 1). Control of maximum heat loads by target inclination has a limit due to non perfect alignment of tiles and toroidal and poloidal field ripple of the magnetic field. Not perfectly aligned tiles can lead under grazing plasma incidence to hot spots. This has been observed in many tokamaks leading to plasma contamination by sublimation and failure of wall components. The total power conducted in ITER towards the divertor , $P_{con,}$ is given by

$$P_{con} = (1\text{-}f) (P_{\alpha} + P_{aux}) \quad (1)$$

with P_{α} = 20% of the fusion power (100 MW of 500 MW), P_{aux} the external heating (50 MW) and f the fraction of the power that is radiated before it reaches the target. Under worse circumstances (attached plasma), f is large (0.75) giving a total power flow of 112 MW to the divertor.

	Inner	Outer
Maximum power [MW]	37	74
Target area (first decay length) [m^2]	2.9	3.8
Peak heat flux [MW/m$^{2]}$	13	19.5

Table1: Expected power deposition on the ITER divertor targets. The assumed power distribution between the inner and outer target is 1:2

In steady state the target surface temperature T_{sur} is given by the temperature at the cooling channels T_c (K) the power flux Q (MW/m^2), the thickness of the tile (m) and the heat conductivity λ (W/mK) of the target material

$$T_{sur} = T_c + Q\, d / \lambda \quad (2)$$

Optimal power exhaust requires maximal λ and thin tiles, but the later property must be compromised with an acceptable target lifetime. The present choice for the ITER high heat flux divertor areas is a Carbon Fiber Composit (CFC) with a conductivity λ of 300 W/mK (at RT) and a thickness off 1.5cm cooled with Cu-water tubes in a monoblock design. 20 MW/m^2 (Table1) is above the technical limit of the target in steady state operation and requires additional power exhaust schemes provided e.g. by radiation as e.g. discussed in ([4])

II.2 Off normal heat deposition

Much more challenging is the power load problem of the wall structures in off normal events. In disruptions and edge instabilities (ELMs) a large fraction of the total stored energy in the plasma (W_{th}) is released in short pulses to the wall which can lead to evaporation /sublimation or melt layer loss in case of metals. Extrapolations to ITER show that in type I ELMs a fraction of 2-6 % of the stored energy will be released in short times (200- 500μs) to a target area which is only slighty larger compared to normal operation (broadening of a factor of 1.5, A_{eff} ~10 m^2). Under these conditions the power is absorbed in the target material by thermal diffusion and the heat capacity (inertial cooling). The maximal surface temperature of the target T_{max} can be given by the solution of the heat diffusion equation in a semi-infinit solid

$$T_{max} = (W_{th} * f*B) / A * (2 / \pi\ \lambda\ \rho\ c)^{0.5} * t_{elm}^{0.5} \quad (3)$$

With f the fraction of energy release, B the fraction of energy radiated, λ the heat conductivity, ρ the density and c the heat capacity of the target material. With W_{th} = 500 MW, f = 0.04, B=0.5, λ= 150 W/mK, ρ= 1.8 g/cm^3, c=1800 W/kgK , t_{elm} = 250 μs, T_0 = 1000K and A = 6.2 m^2, T_{max} is about 5000K. Thus this type of ELMs are not allowed in ITER and the fraction of energy losses by ELMs for ITER must be kept below a ceratin limit which is about 2 %.

When the energy loss in disruptions or ELMs exceeds a limit, the target material will start to evaporate/sublime and/or melt. It is the big advantage of carbon materials that they do not melt, retain therefore their shape at any temperature and show no melt layer loss. Sublimation/evaporation of surface atoms or atom complexes occurs if the surface binding energy is exceeded by temperature fluctuations. Sublimation of graphite consists mainly of the emission of C_1 atoms and C_2 and C_3 clusters with rates of the different species $N_{1,2,3}$ (T) given by

$$N_{1,2,3}(T) = c\, \alpha_{1,2,3}\ P_{1,2,3}(T)\, (M\, T)^{-1/2} \text{ (particles/cm}^2\text{s)} \quad (4)$$

with c = 2.6x10^{22} , P the vapour pressure in mbar, M the molecular weight of the molecules and P_n (T) the vapour pressures of the species given by :

$$P_n(T) = P_{n0} \exp(-H_{\mu n} / k\, T),\ n= 1,2,3... \quad (5)$$

with $H_{\mu n}$ the heats of sublimation and k the Boltzmann constant.

Fig. 1 shows the sublimation rates of C_1 and C_2/C_3 clusters of graphite. Sublimation dominates the carbon release from surfaces in fusion devices for temperatures in excess of about 2500K.

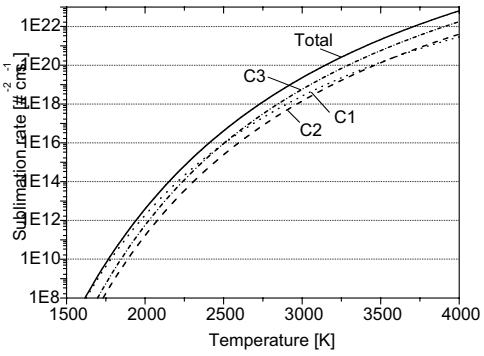

Fig 1: Sublimation rates of C1, C2 and C3 species and total release of C-atoms (C1+2C2+3C3) from graphite.

For metal targets a melt layer with a certain thickness can develop and the molten material can be lost from the surface. This can be done by gravitation but more serious is the ejection by electromagnetic forces. Two mechanisms of melt-layer loss are observed[2], melt splashing due to the formation of vapour bubbles in the liquid layer and growth of hydrodynamic instabilities. The latter can be caused due to momentum impact from the plasma ("plasma wind") or forces generated by induced currents in the liquid metal layer which interact with the toroidal magnetic field. Liquid droplets can be formed by this which can be transported away by the plasma wind. The amount and rate of melt-layer loss is difficult to predict and depend on many parameters.

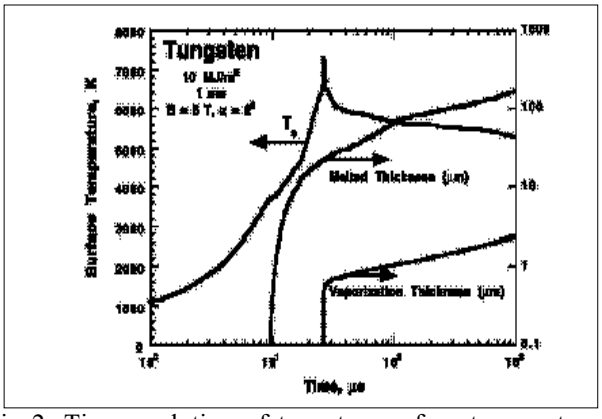

Fig 2: Time evolution of tungsten surface temperature, melt layer, and eroded thickness following a plasma disruption [2].

However it is clear that the material erosion by melt layer loss of metallic components is much larger than erosion by surface vaporisation. This is illustrated in Fig. 2 which shows the calculated time evolution of the tungsten surface temperature, melt-layer thickness and vaporisation losses during a disruption for an incident plasma energy of 10 MJ/m^2 deposited in a time of 1 ms. The sharp initial rise in surface temperature is due to the direct energy deposition of the incident plasma.

II.3 Thermal instabilities, hot spots

Similar to thermal sublimation electrons will be emitted form the solid if the temperature is large enough to overcome the binding energy of the electrons to the solid (work function). If the thermal electron flux is of the order of the impinging ion flux the sheath potential breaks down which then leads to an enhanced power flux by heat transfer from the electrons. The heat transported by the electrons can pass the "sheath" now without being stopped by the negative surface potential in the sheath. Such an enhanced power flux has been observed on TEXTOR graphite limiters leading to a sudden temperature step at around 2300 °C[5] corresponding to a steep increase of the power flux by about a factor of 3.

III. PARTICLE IMPACT

III.1. BASIC PROCESSES

If a plasma particle hits the solid of the first wall material, it will penetrate into the solid and implanted except a smaller part which is directly backscattered. Along the trajectory the projectile transfers energy and momentum to atoms and electrons in the solid. The energy is lost mainly by transfer to the electrons via inelastic collisions, transferring finally the energy of the moving particle into heat (inelastic collisions). For low impact energies which are of interest in plasma wall interactions the inelastic energy losses are proportional to the velocity of the projectile. This is approximately valid for energies up to $E= 25\ Z_1^{4/3} * M_1$, (in keV) with Z_1 and M_1 the charge and mass of the projectile.

Elastic collisions with the target atoms can lead to radiation damage, backscattering or sputtering. In these collisions the energy which is lost by the projectile is transferred to the target atom which starts to move. The energy transfer T can be expressed as

$$T= T_m \cos^2 \delta \qquad (6)$$

with

$$T_m = 4\, M_1M_2/(M_1+M_2)^2\, E_0 = \gamma\, E_0 \qquad (7)$$

and E_2 the energy of the projectile, δ the angle between the direction of the projectile and the recoil atom and M_1 and M_2 the mass of the projectile and recoil respectively. As can be seen, T_m is maximal for equal masses and direct head-on collisions (δ=0).

If the energy transfer by these elastic collisions exceeds a threshold value, called displacement energy, E_d, the target atom leaves its lattice site and occupies a non-regular so called interstitial position, leaving behind an empty site, called vacancy. For energy transfers smaller than E_d lattice vibrations or phonons are excited which in addition convert the kinetic energy into heat. Elastic collisions change the flight direction of the projectile such that the projectile might cross the surface and leave the solid, this process is called reflection. Target atoms for which the transferred energy exceeds E_d are so called recoil atoms, which themselves can create other recoils if the energy is large enough, establishing a group of moving atoms, called collision cascade. Some of the recoils may leave the solid leading to the process of physical sputtering.

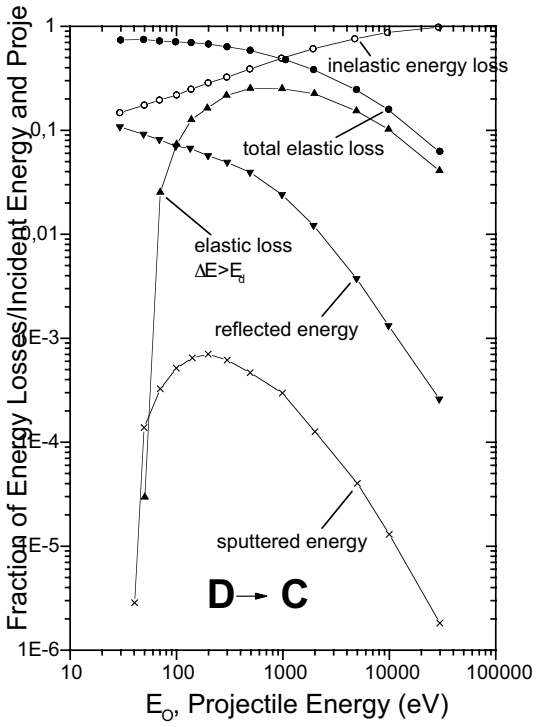

Fig 3: Contribution of different energy losses by bombarding graphite with deuterium projectiles depending on the impact energy.

It turns out that sputtering occurs nearly exclusively for atoms situated in the first few surface layers since only those atoms can gain momentum in the direction outward the solid with energies exceeding the surface binding Fig. 3 shows exemplarily the different contributions to the energy losses for deuterium impinging on carbon as function of the deuterium impact energy. As can be seen, only a very small part of the energy transferred in nuclear collisions results in sputter events.

III. 2. PHYSICAL SPUTTERING

Physical sputtering is the most important mechanism of impurity release since it occurs for all materials independently of the chemical nature, wall condition and wall temperature. The basic concept of physical sputtering is that the projectile or recoil atoms transfer energy to a surface (or subsurface) atom such that it exceeds the surface binding energy. It is obvious that the sputtering yield, defined as the ratio of sputtered atoms per projectile, decreases with increasing surface binding energy and that sputtering yield must have a threshold since no surface atoms leave the solid if the maximum transferable energy is below the binding energy. In the simplest case, illustrated in Fig 4, a projectile of energy

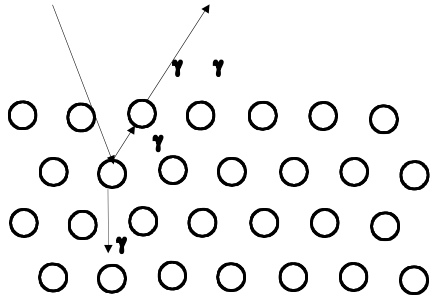

Fig 4: Schematic sketch of energy transfer in sputtering processes

E_1 and mass M_1 hits an atom in the second atom layer in a central collision transferring an energy of γE_1*, with γ defined in equation 2, and is backward reflected with an energy $(1-\gamma)\ E_1$. This reflected atom can then, in the extreme case, hit a surface atom again in a central collision, transferring again an energy of $\gamma\,(1-\gamma)\ E_1$, To evaluate the threshold, this energy has just to exceed the surface binding energy U_s. Thus

$$E_{th}\,(1-\gamma)\,\gamma \geq U_s \qquad (8)$$

which gives, e.g., for deuterium (M1 = 2) impact on carbon (M_2 = 12, Us= 7.5eV) a threshold energy of 16 eV, but for deuterium on tungsten (M_2 = 184, Us = 8.6eV) E_{th} = 180 eV.
In the plasma wall interaction we aim to reduce the sputter rates as much as possible, which can basically be done in two ways: reducing the impact energy of the impinging ions, establishing thus cold plasmas in front of the targets and/or maximise the mass ratio between the impinging projectile and the target atom and minimising thus the transferable energy in a collision. The later is a main argument for the use of high Z wall components like tungsten in fusion devices, aiming to keep the impact energy of deuterons and tritons below E_{th}. A serious problem in this concept is the tungsten sputtering by impurities like carbon and oxygen, which have higher impact energies due to their higher charge state and can transfer more energy in collisions.

For fusion conditions, the sputtering yield of different targets by hydrogenic ions and the self-sputtering yields are of special interest. Many experimental data exist on sputtering of different target materials[1] and useful analytical formula have been developed based on fitting of experimental data. Most known and used is the "Bohdansky" formula which fits the sputtering yield under many conditions reasonably well. These analytical formulas have in general the form

$$Y(E) = Fd(E)/ Us \ (1- E_{th}/E)^x \qquad (9)$$

as published i.e. in[5] where Fd is the amount of energy deposited in the near surface regions in form of elastic collisions, U_s is the binding energy and E_{th} the threshold energy. Formulas to calculate the energy transfer in elastic collisions have been developed i.e. in[5]. Equation 4 shows that the sputter yields for impact energies far away from the threshold (1- E_{th}/E $\delta \approx 1$) variy inversely with the surface binding energy and are proportional to the collisional energy transfer. Close to the threshold the yields decrease drastically. The threshold energy is a strong function of the target mass and can be approximated by[5]

$$E_{th} \approx M_2 \, U_s/8 \qquad (10)$$

The advantage of low sputtering rates can be strongly degraded by the selfsputtering: target atoms once released comes back to the surface and produce further impurities which themselves sputter additional target atoms and so on. This behaves like a geometrical progression and the effective sputter yield is

$$Y_{eff} = Y_D/ 1- Ys \qquad (11)$$

with Y_D the sputter yield by deuterium and Y_S the selfsputter yield of the target material.

Non perpendicular impact of the ions on the surface enhances the sputter yield. Angular enhancement can be pronounced at higher impact energies and well flat surface (up to a factor of ten), but the effect decreases for lower impact energies and more rough surfaces. It has been shown that for not to shallow angles between target and field lines (>10°) ions impinge on the first wall with an angle at around 60° independent on the geometrical angle of the field lines with the solid. As result of this, the low impact energies and rough surfaces, the angular enhancement of the sputter yield with respect to normal incidence is not very pronounced in fusion conditions.

Fig 5 shows sputter yields for different target materials depending on the temperature of the plasma.

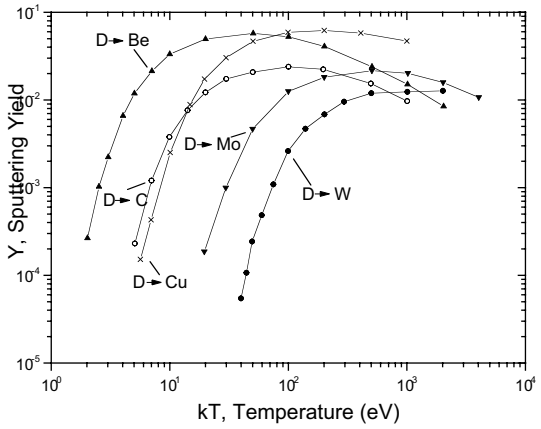

Fig 5: Calculated sputtering yield versus deuterium ion impact temperature for different target materials. The target is bombarded assuming a maxwellian energy distribution which is shifted in the sheath potential of 3 kT and have a isotropic angular distribution.

The data are calculated assuming a Maxwellian energy distribution of the ions which is shifted by a sheath potential of 3 kT_e. The figure shows that at low plasma edge temperatures only the low Z wall materials (Be, B, C) show physical sputtering. Beryllium has a significant larger sputtering than carbon due to the lower surface binding energy (3.5 versus 7.5 eV). Tungsten is sputtered by deuterium only for plasma temperatures above about 80 eV.

As a consequence of the collisions of the projectile with the solid target atoms, the energy distribution of the sputtered atoms extends from zero to a high energy limit which depends on the maximal transferable energy (equation 2) and the surface binding energy. For most of the conditions the energy distribution can be reasonably well described by the so called Thompson formula[6] .

$$dY/dE = E/(E+E_S)^3 \qquad (12)$$

This energy distribution shows a maximum at about half the surface binding energy. The most probable energy of the sputtered atoms is about $E_S/2$.

In most cases the angular distribution of sputtered atoms is a cosine distribution

III.3. CHEMICAL EROSION

While physical sputtering can occur for all projectile target systems, the formation of volatile molecules by interaction of the projectile with the target occurs only for some projectile target combinations. This process is called chemical erosion and of large importance for present and future fusion experiments since graphite is the most favourable choice for the high heat flux areas of the divertor. Graphite can form hydrocarbons by interaction with the hydrogenic fuel and also by the formation of CO and CO_2 due to impact of oxygen. Hydrogen species can also chemically react with metaloxides forming some hydrogen-oxygen complex which then can become mobile.

Formation of hydrocarbons by interaction of hydrogen with carbon materials is a complex process depending on a variety of parameters, such as the target temperature (in strong contrast to physical sputtering), the impact energy and flux[7,8] of the hydrogen. The general trends will be outlined here.

When hydrogen atoms of thermal energy ($E \approx <0.2$ eV) impinge on carbon materials the reaction rate depends on the physical structure of the graphite surface. Well ordered crystalline graphite shows reaction rates smaller then 10^{-3} C_xH_y/H, but the yield increases if the surface is damaged, e.g. by particle impact producing a damaged graphite surface with dangling bonds. The highest yields (up to 10^{-1}) are on amorphous carbon layers obtained from chemical plasma deposition (a-C:H films, see fig 4). The importance of the surface structure for the hydrocarbon formation is also clearly seen by a "synergistic effect": if a small amount of energetic particles (i.e. inert ions like argon) impinges on the graphite surface simultaneously with atomic hydrogen the reaction rate of the hydrogen atoms increases by at least one order of magnitude[9]. The understanding is that the hydrogen reacts on the free bonds created by the ion bombardment. Under thermal hydrogen exposure a large family of C_1, C_2 and C_3-type hydrocarbons are formed and the overall graphite erosion is dominated by C_2H_x hydrocarbons, followed by the CH_3 radical and higher hydrocarbons. The observation of the emission of unsaturated CH_3 is surprising but has been explained in recent models of hydrocarbon formation [10].

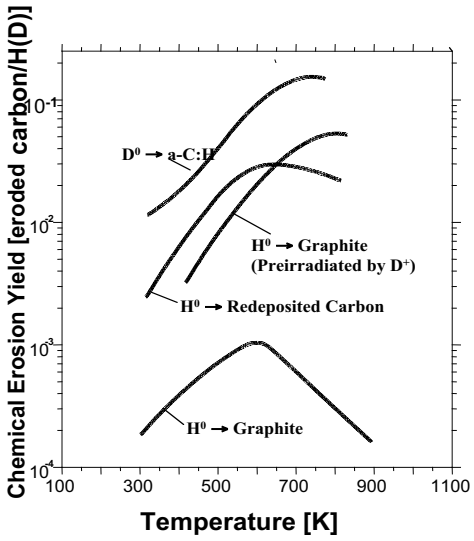

Fig 6: Temperature dependence of the total chemical erosion for different types of graphite materials: graphite, amorphous a-C:H films (deposited by glow discharge plasma deposition), redeposited carbon material from TEXTOR, and graphite preirradiated with 2.5 keV D^+ ions.

When energetic hydrogen ions impinge on carbon, saturated CH_4 molecules are released which are formed at the end of the trajectory diffusing then through the porous graphite structure to the surface. In beam experiments with higher impact energies and low flux densities the chemical yield shows a strong temperature dependence as shown in Fig. 7 with a maximum near 800K. Under fusion conditions with low hydrogen ion impact energies and much higher flux densities (up to 10^{24} H/cm^2s) the hydrocarbon formation rates decrease in the maximum of the erosion (400 - 600 °C) but they increase for lower temperatures. As a result the temperature dependence 'flattens' with only a weak

dependence on temperature from room temperature to about 1100K from which on they fall off[10]. Also, higher hydrocarbon formation becomes more important in comparison with methane formation under these conditions.

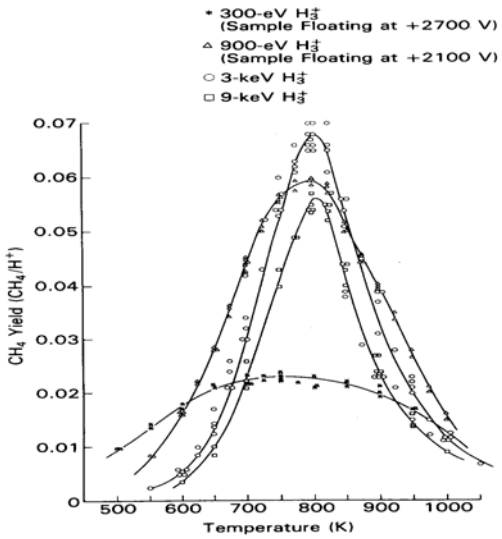

Fig 7: Methane formation rate of graphite by bombarding with hydrogen at different impact energies. Flux densities are in the range 10^{14}-10^{15} H/cm^{2}s.

The present understanding of the hydrocarbon formation is that the decrease towards higher temperatures is due to recombination of hydrogen to molecules before they react to hydrocarbons. In the temperature region of the maximum the hydrocarbon formation is a thermally activated reaction of hydrogen with the graphite and reasonable models for this process have been developed [10]. The thermally activated process decreases towards lower temperatures but hydrocarbon formation can go on which is believed to be due to the release of loosely bounded hydrocarbon complexes by collisional energy transfer. This branch becomes increasingly important with low impact energies but can also contribute to the hydrocarbon formation in the maximum of the thermal reaction at high flux densities This collisional term is also responsible for the observation that deuterium shows larger yields than hydrogen impact under certain conditions. Thus even larger yields are expected for tritium impact.

Hydrocarbon formation will dominate the erosion of the graphite targets at the strike zones in future fusion devices under the envisaged cold divertor plasma operation (detached plasma) and thus also determines the lifetime of the target. Several attempts have been done to dope the graphite with material like Si, Ti, B and others to reduce chemical hydrocarbon erosion. Some pronounced reduction of hydrocarbon formation have been achieved in beam experiments but the general observation is that the benefit of the reduction is reduced at the low impact energies in fusion experiments and may thus not be very helpful. The other way to reduce the net erosion and increase the lifetime is that released wall material might be redeposited nearby its origin and thus reduce the net erosion. This will be discussed in chapterV.

Interaction of oxygen with carbon materials lead to the formation of CO and CO_2. The formation of CO and CO_2 by molecular oxygen impact is complex[7] but the behaviour is easier for energetic oxygen impact for energies above about 50 eV: a complete transformation of the impinging oxygen to CO and CO_2 occurs (yield $CO+2CO_2/O$ near unity).[11]

The reaction of oxygen to CO and CO_2 can play an important role in plasma wall interaction which has lead to the development of special wall conditioning to reduce the oxygen content as much as possible. It is also observed that photon impact release CO and CO_2 [12]. Wall conditioning will be more discussed in chapter VI.

III.4. RADIATION ENHANCED SUBLIMATION

It is a speciality of graphite materials that they show an additional erosion process, called **R**adiation **E**nhanced **S**ublimation (RES). This effect has been observed so far for carbon materials but recent data indicate similar effects also for metallic targets. It consists of the emission of C-atoms with thermal energies under energetic particle bombardment[13]. The yield scales with the mass and energy of the impinging particle in a manner very similar to physical sputtering but, in strong contrast to that, the emitted atoms are thermal, which requires thermalization of the atoms before they leave the surface. The yield increases with temperature with an exponential increase with the reciprocal temperature with an activation energy of 0.75-0.85 eV. This is also in strong opposite to physical sputtering. The effect occurs always simultaneously with physical sputtering and overcomes the physical sputter yield of graphite in low flux beam experiments at temperatures of around 1200 K.

Within the present understanding[13] RES is due to the production of vacancy interstitial pairs by collisonal energy transfer and subsequent diffusion of both species. Vacancies and interstitial undergoes various possible

processes (recombination, clustering etc.) but a small number of migrating interstials survive and arrive at the near graphite surface where they desorb thermally due to low binding forces. It is believed that the arriving interstitials are first weakly bonded to the surface, during which time they can desorb , until they are finally bonded at free bonds at the surface. Beam data predict that RES is the dominate carbon influx channel above target temperatures of about 1300K. However RES erosion is not clearly observed on the highly exposed graphite limiters in TEXTOR and also in several divertor experiments and the present understanding is that RES is reduced under high flux densities. However, RES erosion has been reported from other fusion experiments under conditions not largely different from TEXTOR.

IV. PHOTON INDUCED IMPURITY RELEASE

A large part of the fusion energy will be dissipated by electromagnetic radiation which is absorbed by the first wall within a few microns depth. Impurity release by photon impact will not occur for regular bounded target atoms but release of adsorbed impurities or hydrogen is a possible process. This mechanism is a well known phenomenon in large accelerators where the high vacuum requirements suffer from the release of CO, CO_2, H_2 and other molecules due to impact of synchrotron or other electromagnetic radiation. Release of these molecules by photon impact has also clearly demonstrated in TEXTOR[12] and is partly responsible for the oxygen impurity content in the plasma boundary under special conditions.

There are two possibilities by which adsorbed molecules are released by photon impact: first, the photon can directly interact with an adsorbed molecule and excite it to an energy level which is not bonded anymore. Calculations show that the cross section for this process is low and that no significant release of impurities is expected. Second, electron hole pairs are produced in the near surface by the photons which diffuse and recombine with the charge of the adsorbed molecule. This process requires that the adsorbat is bounded in an ionic state, which is a common behaviour on surfaces due to charge transfer of the adsorbat with the substrate. This process occurs thus preferentially on oxidised metal surfaces which behave in this sense like a semiconductor.

V. EROSION AND REDEPOSITION, LOCAL TRANSPORT

Besides the quantification of the (gross)-impurity release rates the transport of the released atoms and molecules in the vicinity of the target is of most importance. As mentioned, all impurities will come back to the surfaces within the typical particle confinement times. To reduce the net erosion, the re-deposition should be nearby the production and the lifetime of the target depends on the question, how far the wall material is re-deposited from the location of its origin. Long range migration leads finally to material redistribution, lifetime problems and deposition of large amounts of material which can store also large amounts of tritium via codeposition.

The transport of material in the vicinity of surfaces and over longer distances is a complex process which depends on

- The strength of the impurity sources
- The penetration of impurities into the plasma
- The transport of impurities along and perpendicular to the field lines
- The sticking and possible re-erosion of redeposited species from the surface

These processes are illustrated in figure 8.

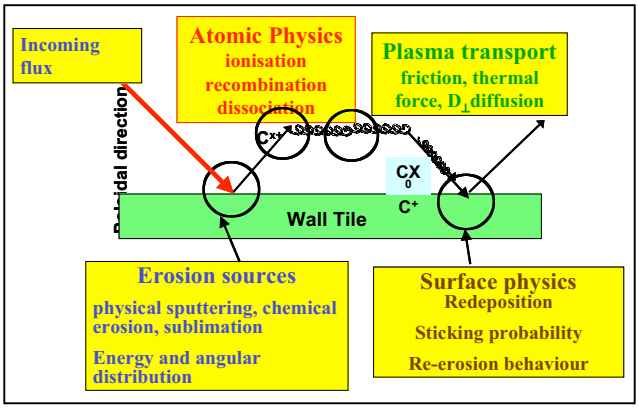

Fig 8: Schematic illustration of the basic processes determining the re-deposition and material migration of wall material

The local penetration depth of the neutrals produced at the walls is given by the ionisation length s which is proportional to the velocity of the particles and scales inversely with the electron density and the cross section for ionisation. The latter decreases with decreasing plasma temperature.

$$s \propto v / n \langle \sigma v \rangle \qquad (13)$$

Sputtered atoms have deeper penetration depths than thermally emitted particles due to their higher velocities and cold (detached) plasmas have large penetration depths due to low ionisation cross sections.

If the ionisation length is very small and the gyroradius large as it is the case i.e. for tungsten atoms, the ion might be redeposited directly within the first gyration since the gyroradious is larger than the ionisation length. This effect can reduce the gross erosion of high Z materials significantly, but can act only on zones with high plasma electron density in front of it. Particles penetrating deeper might be redeposited following open magnetic field lines on other material objects or driven back to the surface by diffusion processes or friction with the background plasma.

Of particular importance is the local redeposition behaviour of hydrocarbons both for the plasma contamination, target lifetime and tritium retention via codeposition. The process is complex since the molecules undergo various processes in the vicinity of the limiter in the course of which they might be neutralised and being redeposited on the surface. Since in addition their velocity is small resulting in short ionisation lengths their redeposition rate is expected to be large, which is very desirable to reduce the gross erosion.

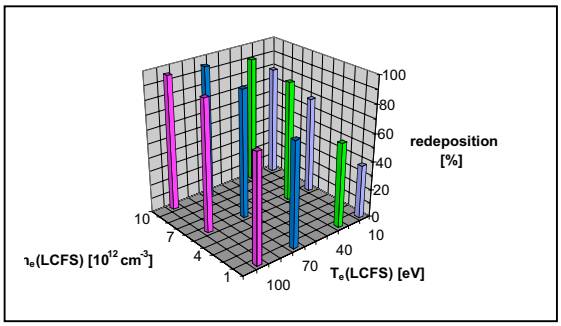

Fig 9: Calculated redeposition efficiency of methane on a testlimiter in TEXTOR at different local plasma densities and temperature. For these calculations a sticking probability of unity for the redeposited species is assumed (calculated with ERO-TEXTOR).

Using standard assumptions for the erosion and re-erosion of re-deposited carbon and for the sticking probability of carbon species, the local Monte Carlo calculations with the ERO-TEXTOR code show that the fraction of species returning back to the surface as function of the plasma temperature is large ranging between 60% up to a maximum value of about 86% for typical conditions in front of the limiters in TEXTOR.[14]

Fig 10 shows the distribution of the redeposited species for these plasma edge conditions. Redeposition occurs mainly by the ions of CD_4^+, CD_3 and CD_3 neutrals.

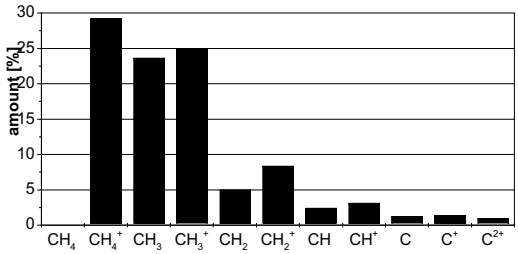

Fig 10: Typical calculated distribution of redeposited carbon fragments (starting as methane) on a TEXTOR testlimiter (calculated with ERO-TEXTOR).

However there is a strong experimental evidence that the effective re-deposition of hydrocarbons on wall surfaces in fusion devices is much smaller than calculated. In TEXTOR small puffs of methane and silane through testlimiters reveal about one order of magnitude less redeposition compared to the calculated.one[15] In JET and many other machines thick carbon deposits have been found on remote areas where no ion flux is expected. These findings are presently attributed to the fact that at first the sticking probability of the returning radicals to the surface can be smaller leading thus to many attempts of redeposition associated with large transport. In addition, the chemical re-erosion probability of the freshly deposited fragments is probably much higher than for normal graphite. As a result, carbon can be transported long distances leading to large net erosion and thick films on remote areas which store large amounts of the fuel. This property is of large importance for the future use of carbon materials in fusion devices since it is the main mechanism which determines the long term retention of tritium inside the vessel. Control and limitation of the radioactive T inventory is indispensable for fusion and may limit the possible use of graphite in future devices.

VI. HYDROGEN RECYCLING AND RETENTION

The particle confinement time in fusion plasmas is typically a factor of hundred or more smaller compared to the duration of the plasma pulse, meaning that the plasma fuel exchanges many times with the walls during one discharge. This process is called recycling and important for the control of the fuel inventory during the plasma but even more important for the inventory of the fuel in the walls. This inventory must be kept small due to safety

reasons with respect to the radioactive tritium in future devices. Recycling and retention in the walls can occur by three processes:

Implantation of hydrogen in the walls followed by thermally activated diffusion and recombination on the near surface

Implantation in the solid followed by diffusion and trapping on trapping sites. If the diffusion is very small trapping determines the process exclusively

Co-deposition of the fuel with eroded wall material forming a mixed material layer in which the fuel is stored.

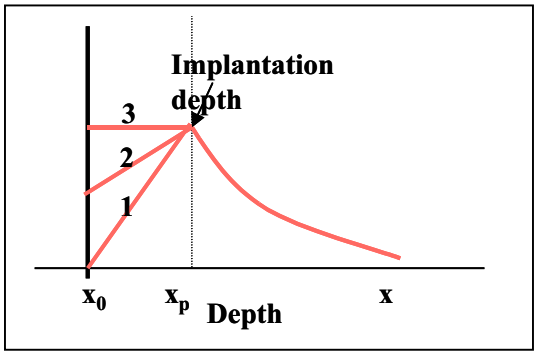

Fig 11: Schematic diagram of hydrogen concentration in the near surface region of wall materials. (1) diffusion determined process (1), (2) diffusion and recombination determined, (3) process fully determined by surface recombination.

Figure 11 shows the situation where diffusion and recombination are the rate determining steps for the fuel inventory, which is normally true for metallic walls. For non metallic walls or metals with low hydrogen diffusion, trapping can become the an important process for fuel retention. This is e.g. the case for graphitic materials but fuel retention by co-deposition is nevertheless the most important mechanism for fusion machines with graphitic walls. This is due to the fact that carbon suffers from high erosion rates even at low plasma temperatures by chemical erosion and that carbon can build up hydrogen rich layers with H/C ratios up to 1:1. Furthermore co-deposition is a process which is unlimited in time while all other retention mechanism will saturate.

VII. WALL CONDITIONING

The plasma wall interaction processes discussed here occur in a shallow near surface zone of typically a few tenths of nm. It is thus evident that the physical and chemical structure and composition of the near surface can have a significant influence on plasma wall interaction processes and thereby also on plasma performance. Techniques to coat the entire surfaces of fusion devices have been developed and are nowadays employed regularly on fusion experiments[16]. These methods have led to a significant improvement of plasma performance such as higher density limits, stored energy, etc.

The aim of surface and wall conditioning techniques can be divided in two main areas:

reduction of impurity influxes from the walls

control of hydrogen recycling

With respect to control the impurity influx the control of oxygen is the most important issue. Oxygen is present in all fusion devices and wall materials as metal oxide and hydroxides, water and various other components. It readily forms volatile gases such as CO, CO_2, H_2O (see chapter III) and can also be released by photon impact in form of CO_2 and CO as discussed in chapter IV. All of the wall conditioning techniques were developed primarily to passivate or remove the oxygen which is done by forming stable oxygen compounds which are not easily dissociated. The combination of the effect of oxygen gettering by stable compounds and the requirement of a low Z wall material did result in the use of boron and beryllium as the most promising wall coating. Siliconisation of the walls is another possibility which can provide both oxygen gettering but also radiation from silicon impurities in the plasma edge for power exhaust control, a behaviour which has been demonstrated in TEXTOR.

The technique used in TEXTOR (which in a similar manner is used world-wide in all tokamaks) is a rf supported DC glow discharge (RG discharge). The wall and the limiters act as cathode and the discharge is sustained by 4 antennas on which a positive bias voltage (typically 400 - 500 V) and a RF power (250 W) is simultaneously coupled. RF power helps to ignite and establish the discharge at lower pressures and to fill the volume with the glow plasma in a more homogenous manner, resulting in a more uniform film deposition.

A flow of gases is established, which e.g. in case of boronization, consists of 80 % He and 20% B_2D_6. When the ions approach the cathode region they are accelerated by the sheath, disintegrate by the collision at the surface and form an amorphous film on the substrate. The films are transparent, mechanically hard with a refractive index close to 2.2 and contain significant amounts of hydrogen depending mainly on the deposition temperature (0.4 H/B,C at RT, 0.1-0.2 H/B,C at 350 °C). After coating the

walls of fusion devices oxygen impurities are largely reduced by gettering. The effect is mainly not due to implantation of oxygen impurity atoms in the coatings nor by gettering molecular oxygen in the residual gas but due to film erosion and codeposition of eroded getter material along with oxygen impurities. Experiments have shown that after boronization of TEXTOR the oxygen content in the plasma decreased but the amount of oxygen found in deposition probes positioned in the SOL increased where the oxygen is bonded in form of stable oxides.

A similar effect is observed in JET by evaporation of Be onto the entire first wall. The data show that the reduction of oxygen impurity fluxes reduces also the carbon fluxes which is understandable in terms of CO formation of oxygen with carbon walls (see chapter III). The boronization films are eroded rather rapidly from the limiter. This results in a strong decrease of boron line radiation within the first 15 discharges after a fresh boronization followed by a stabilisation of the boron radiation. This is caused by the fast erosion of the deposited films from the high flux areas at the limiters, whereas a quasi -equilibrium is reached in which a small part of boron is released from the rest of the wall, where the reservoir is much larger. This leads to a nearly constant small boron flux in the SOL (5-10%) which is sufficient to control the oxygen. The beneficial effect of a reduced oxygen level remains thus for a comparable long time of several hundred of shots.

VII. SUMMARY AND OUTLOCK

A serious concern in magnetic fusion is the exhaust of power under steady state operation which easily can exceed the technical limit. Plasma scenarios with high radiation level are necessary which also have to fulfil the requirements of good energy confinement and helium exhaust.

Even more serious are the transient heat loads in disruptions or ELMs which easily can lead to sublimation or melt layer loss and determine seriously the lifetime of the target. Due to target sublimation, present type I ELM H-mode operation is most probably not allowed for ITER and melt layer loss in disruptions force to use graphite for the lower part of the divertor target.

For the problem of continuos steady state erosion of high heat flux components, redeposition of eroded material nearby its origin is essential and necessary. Here more work has to be done to analyse the basic processes of redeposition, proof the present models and investigate the properties of redeposited materials. However, recent data show a significant long range transport of carbon, probably associated with low sticking of radicals and high chemical erosion of freshly deposited films, leading to large net erosion and large storage of tritium by codeposition. The codeposited amorphous carbon material can store large amounts of tritium. Not enough data exist about the properties of mixed materials.

The needs for wall conditioning in future fusion devices with quasi steady state operation are not fully clear yet. Films on high heat flux areas will be fastly eroded away and impurity control and recycling control during the long stable flat top phase might not be possible. Start-up and ramp down phases as well as plasma operation after critical events like air or water leaks will be critical and will require the help of wall conditioning. The standard well proved techniques of RF-DC discharges can only be used in absence of a toroidal magnetic field which will be maintained for long times to avoid cycling the coils. Thus in addition ICR and ECR based condition techniques will be explored more in the future.

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