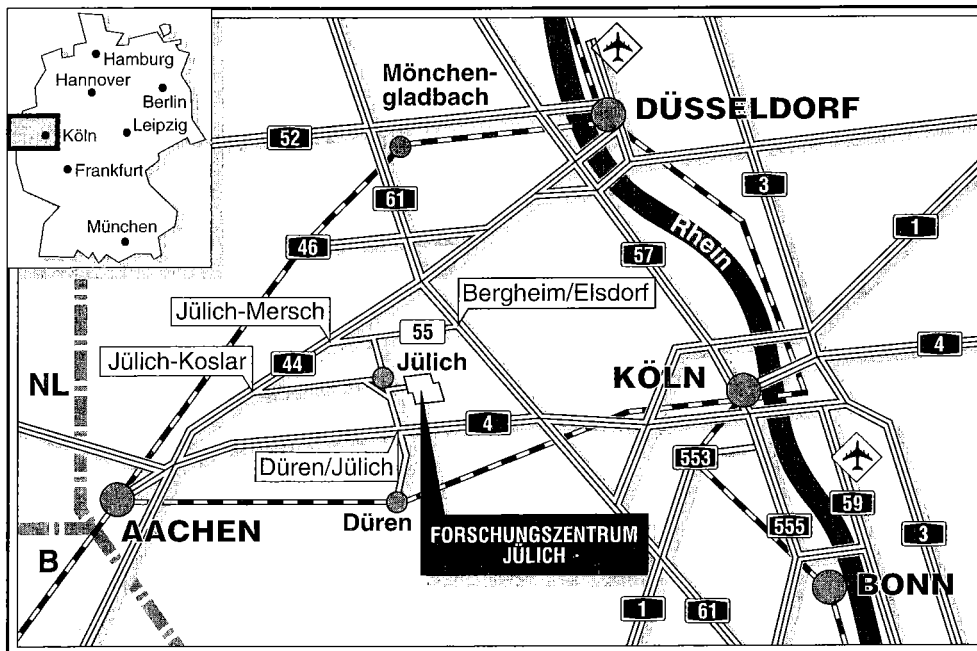


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**Control of Plasma-Surface-
Interactions by Thin Films**

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J. Winter

ABSTRACT

Changing composition and structure of the near surface region of wall materials in fusion devices can modify substantially the plasma-surface interaction and hence influence the performance of fusion plasmas. Main aspects are the control of the plasma impurity production and of hydrogen recycling. Important mechanisms are reviewed and examples from major fusion devices are discussed.

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1. INTRODUCTION

The interaction between the plasma in fusion devices and components of the first wall occurs in a shallow near-surface region. Ionized deuterons or tritons impinge on the surface with energies of a few eV up to several 100 eV, according to the ion temperature profile $T_i(r)$. The latter depends on the plasma regime chosen, magnetic configuration (divertor or limiter) and location of plasma impact (divertor plate or vessel wall). The impact energy of ions is further increased by their acceleration in the sheath potential $U_s \approx 3.6 kT_e$ which forms in front of any surface immersed into a plasma [1]. T_e is the temperature of the plasma electrons in contact with the surface.

Neutral atoms, created by charge exchange processes, can escape the magnetic confinement and may have higher impact energies, representative of the hotter plasma zones in which they were generated.

Atoms and ions from the plasma have a strong interaction with matter. Their range is limited to typically several 10 nm from the surface even in low-Z target materials (Be or C) with small stopping powers¹. It is this thin layer, the near-surface region, where plasma-surface interactions take place and where all the basic processes like sputtering, chemical erosion, trapping, reflection etc. occur. These processes may induce the release of wall material and thus introduce plasma impurities or have an effect on the hydrogenic particle balance (hydrogen recycling).

It is obvious, that a modification of this near surface region e.g. by depositing thin films of appropriate chemical composition and physical structure will bring about major changes in the plasma-surface-interaction (PSI-) processes and may thus allow an active control of phenomena critical to the plasma and its performance. It is important to realize that a strong non-linear interrelation exists between PSI- processes and $T_i(r)$, $T_e(r)$, the power flow in the plasma edge and its radiated fraction (radiative edge), and the concentration of neutral hydrogen atoms in the scrape-off-layer (SOL). Via complex mechanisms they modify energy and particle transport, the plasma confinement, and thus the performance of the discharge.

¹ We do not consider here the case of neutrons or runaway electrons which deposit their energies well below the surface of the material.

For experimental fusion devices of the present generation, thin film deposition is an inexpensive and flexible tool to change the material in contact with the plasma and to study the related effects. Deposition of thin layers also allows to decouple the requirement of plasma compatibility of a plasma facing material from that of desirable bulk properties like mechanical strength, thermal conductivity, ductility, weldability, etc.

Of course, thin films are less tolerant to erosion than bulk materials. It has to be considered, however, that erosion of the highly exposed limiters or divertor plates in long pulse devices will probably be very substantial /2/. An efficient local redeposition (>98%) of material has to be achieved in order to ensure an adequate lifetime. In situ coating and surface repair techniques will have to be developed. Thin film deposition during existing plasma discharges may become one of the future options here /3/.

Another option may be the use of high Z wall materials (tungsten) in conjunction with a cold plasma edge. Tungsten has a high threshold energy for sputtering, such that erosion is essentially suppressed under these conditions. Attempts to realize such scenarios in fusion devices have not been successful to date. The main reason has been the excessive radiation due to impurity ions (see chapter 2). Forthcoming high density divertor experiments like ALCATOR C-Mod with all wall elements made from molybdenum may be in the position to test the feasibility of this concept.

Another source for plasma impurity generation equally important as the high heat flux components, is the large wall area which is exposed to neutral particles from charge exchange and Frank-Condon atoms. Here, thin films will survive and maintain their influence on PSI for a much longer period.

2. THE ROLE OF PLASMA IMPURITIES

The attempts to produce thermonuclear plasmas have always been plagued by the occurrence of plasma impurities. They are generated by plasma-surface-interaction processes which have been reviewed previously e.g. by McCracken and Stott /4/. Detailed descriptions of various mechanisms and diagnostic aspects can be found in ref /5/.

Plasma impurities cause essentially two effects: radiation of power, and dilution of the hydrogenic species. According to their atomic number Z and their various ionization and excitation potentials, different impurity atoms will radiate in different plasma regions according to the electron temperature profile $T_e(r)$. Under the simplifying assumptions of coronal equilibrium (neglecting transport effects), the radiation from a transition with ionization potential E_i occurs from a plasma shell located at r with $T_e(r) \sim 2/3 E_i$. The radiated power is also a strong function of the atomic number Z , see fig. 1. In addition to line radiation, plasma impurities increase the energy loss by Bremsstrahlung, which is proportional to Z^2 .

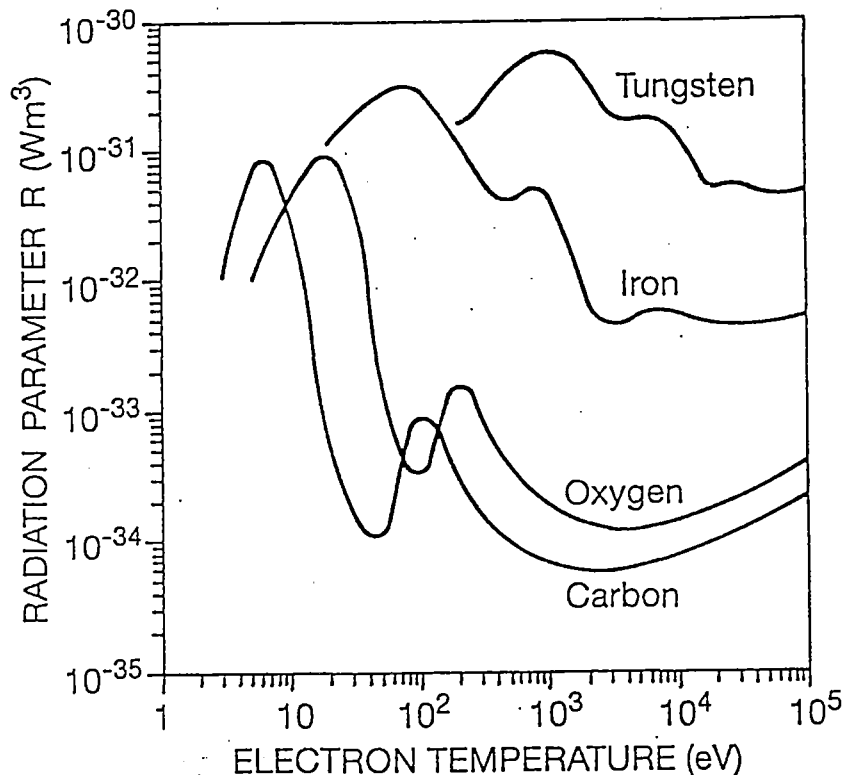


Figure 1 Radiation parameter R of various plasma impurities as a function of electron temperature T_e . The radiated power density P_{rad} is given by $P_{rad} = R \cdot n_e \cdot n_i$ where n_e and n_i are the electron and impurity density, respectively (after J. Wesson "Tokamaks" Clarendon Press, Oxford, 1987).

Cooling of peripheral plasma zones by radiation may be a desired effect in order to reduce the convective power flow to the limiters or divertor plates of a tokamak along magnetic field lines and distribute it over a large surface area /6/. It must be taken care, however, that the energy loss by radiation does not cool the hot plasma core. The correct impurity species has to be selected.

Plasma impurities also lead to a dilution of the hydrogenic fuel. Electrons and the nucleus of impurity atoms take the place of those from deuterons and tritons. Assuming $n_D = n_T = n$ and $n_e = 2n$ the fusion power density f_0 is $f_0 \propto n^2$. At full ionization, the concentration $c_z = n_z/2n_e$ of impurity atoms with atomic number Z leads to a decrease of f by

$$[1 - c_z(Z+1)]^2 .$$

For $c_z = 3\%$, this reduction is 17% for He, 28% for Be, 33% for B and 38% for C. The dilution cannot be counteracted by simply increasing n_D and n_T . In a given device the maximum achievable density is limited due to the critical plasma pressure $nk(T_i + T_e)$ (β -limit) whereby T has to remain between 10-20 keV for a thermonuclear plasma.

Plasmas once contaminated tend to be further polluted at an enhanced rate. If plasma impurities return to the wall, they are in general multiply ionized (charge q). Upon approach to the surface, they are accelerated to a total impact energy E of

$$E \sim qU_s + 2kT_i \quad // .$$

These multiply charged impurity ions will lead to enhanced erosion by sputtering. In the case of TEXTOR, the mean charge state of carbon ions hitting the limiter is $q=4$ ///. For a typical value of $T_e = 25$ eV at the limiter, the additional energy gain in the sheath is 360 eV, increasing the carbon self sputter yield on graphite wall components from about 1×10^{-2} to 2×10^{-1} .

From these basic consideration one concludes that the impurity release has to be reduced to a low level from the very beginning of the discharge. The tolerable amount depends on the type of impurity atoms. The value of Z and the sticking probability to the surface are important as is their shielding from penetration through the SOL. The steady state concentration of impurity atoms in the plasma is determined by the balance between influx and outflux rates. The latter is inversely proportional to the particle containment time τ_p of the species which is intimately coupled to the

transport properties. Therefore, an evaluation of acceptable primary impurity release rates and influx rates has to take the confinement of the respective plasma regime into account. Good particle confinement requires small primary erosion rates.

It has been recognized early in controlled nuclear fusion research that oxygen plays a special role in the plasma impurity generation. In situ evaporation of thin metallic films, in particular of Ti and Cr, onto the interior vessel surfaces were successfully used to bind oxygen atoms (gettering) and prevent them from recycling back to the plasma. Ti and Cr gettering has been reviewed e.g. by Dylla /8/ by Cecchi and Knize /9/ and by Winter /10/. Titanium turned out to be problematic because thick layers flaked off and gave rise to plasma disruptions and because of the very large hydrogen storage. The latter is particularly critical in view of the use of tritium. In addition, with strong plasma heating and intense PSI the high Z of these metal atoms became increasingly problematic and layers of beryllium, boron or carbon with a low value of Z turned out to be advantageous. The discussion in this distribution will concentrate on the recently developed low- Z film deposition techniques like evaporation of Beryllium /11/, the deposition of pure carbon layers (Carbonization) /12/, and of Boron or Boron/Carbon- (Boronization) /13/. The ability of these films to getter oxygen is very important for reducing the oxygen impurity level of the plasma and consequently for increasing its performance. The aspects of hydrogen recycling are not discussed in detail here.

3. DEPOSITION OF THIN FILMS AND FILM PROPERTIES

3.1. Oxygen Gettering

The ability of a material to getter (bind) oxygen plasma impurities may be assessed in a first approximation by its oxygen affinity as well as by the desorption temperatures and desorption rates of the oxides.

The oxygen affinity can be expressed in terms of the formation enthalpy of the oxides, normalized to the number of oxygen atoms $\Delta G/O$ (as listed in table 1). According to this figure of merit, Beryllium (Z=4) and Boron (Z=5) are good low-Z getters, Silicon (Z=14) is a good medium-Z getter and Titanium and Chromium are good high Z getter materials.

Nickel and Iron on the other hand, the main constituents of stainless steel and Inconel, respectively, are bad getters. Their oxides are readily reduced by a hydrogen plasma. The atomic

hydrogen species react to produce water vapour which is released from the surface into the tokamak plasma. This is probably the main oxygen source in fusion devices with walls from stainless steel or Inconel /14/.

Z	atom	oxide	$-\Delta G[\text{kJ/mole}]$	$-\Delta G/\text{O}[\text{kJ/mole}]$
low - Z - getters				
4	Be	BeO	581	581
5	B	B ₂ O ₃	1194	397
medium - Z - getters				
12	Mg	MgO	569	569
13	Al	Al ₂ O ₃	1582	527
14	Si	SiO ₂	857	428
high - Z- getters				
22	Ti	TiO ₂	889	444
73	Ta	Ta ₂ O ₅	1911	382
24	Cr	Cr ₂ O ₃	1058	352
bad getters				
74	W	WO ₃	764	254
26	Fe	Fe ₂ O ₃	742	247
28	Ni	NiO	212	212
reference molecules				
1	H	H ₂ O	228	228
6	C	CO ₂	394	197
		CO	137	137

Table 1: Free enthalpy of formation ΔG and free enthalpy of formation per oxygen atom $\Delta G/\text{O}$ for various oxides.

Under the non equilibrium conditions of a plasma-exposed tokamak surface the formation of non stoichiometric hydroxides and radicals is likely. They can have vastly differing volatilities and it is thus difficult to provide a simple figure of merit for their release. In the case of Carbon the release of CO and CO₂ during oxygen-ion bombardment has been measured /15/. Oxygen is retained up to a concentration of about 0.25 oxygen/per carbon atom within the implantation zone, before it is reemitted in the form of CO and CO₂ with a yield close to unity even at room temperature. After dissociation and ionization, CO and CO₂ are sources for both carbon and oxygen plasma impurities (see below). The yield of unity implies that oxygen recycles in the tokamak (see also chapter 4.1).

The reemission of CO, CO₂ and of boron oxides from different B/C compounds during oxygen-ion exposure has also been measured /15/. The most prominent boron oxide species is BO. The maximum of the desorption rate is observed around 1200 - 1400 K. It has been found that B/C materials retain (getter) significantly more oxygen than pure carbon does. Moreover their retention is increasing with the boron content. CO and CO₂ reemission from these materials occurs at significantly lower yields than in graphite and at higher desorption temperatures. The reduction in yield depends on the boron concentration and is of the order of 5-8 for boronization films with B/C=0.8.

No comparable measurements of the release rates are known to the author for beryllium-oxides and -hydroxides. It has been reported that, at temperatures above about 280 °C, Beryllium metal diffuses through a surface oxide layer and thus replenishes the surface with active Beryllium atoms /16/.

3.2. FILM DEPOSITION TECHNIQUES

3.2.1 Carbonization and Boronization

Film deposition by Carbonization and Boronization is accomplished by the same technique, namely a glow discharge in a throughflow of reactive gases. The basic equipment needed is that normally used for glow discharge cleaning /17/: one or more anodes in the tokamak vessel, a continuous gas feed and the torus pumping system.

A typical composition of the working gas is 0.25 Methane + 0.75 Hydrogen (or Helium) for Carbonization, 0.2 Diboran + 0.8 He for Boronization (or appropriate CH₄ and B₂H₆ mixtures for B/C films). The deuterated gases may be used when a very high isotopic fraction of deuterons in the fusion plasma is aimed at. All gases are used in a flow through situation.

In a simplified picture of the film deposition mechanism the molecules are partly ionized in the glow plasma and are accelerated in the cathode sheath onto wall and limiters or divertor plates which are the discharge cathode (see fig. 2).

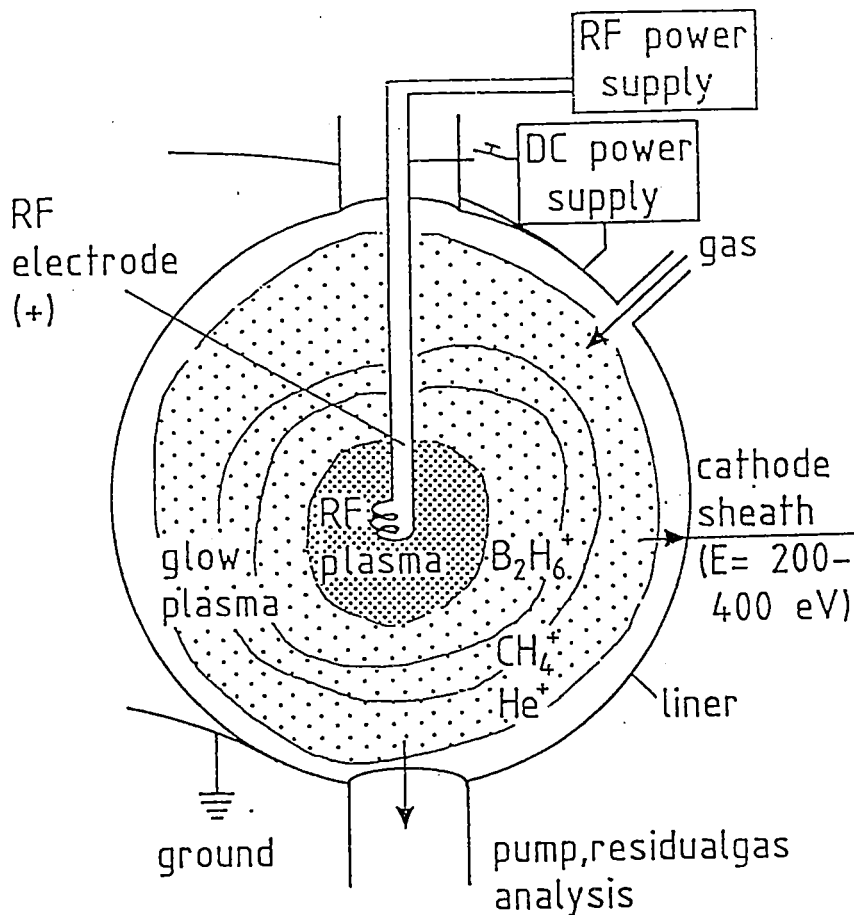


Fig. 2 Sketch of the glow discharge arrangement used for Carbonization and Boronization

They desintegrate upon impact and the amorphous films grow from individual C, B, and H atoms. He is not incorporated. Neutral radicals may contribute significantly to the film growth, depending on the gas mixture and pressures used.

In order to produce hard carbonaceous films with as little as possible gas incorporation, a high impact energy of the ions appears to be advantageous /18/.

In the case of Boronization the use of the toxic and highly explosive B_2H_6 (diborane) gas necessitates special components, lay out and operation of gas injection and pumping systems to

ensure safe handling /19/. We have successfully used at TEXTOR /20/ and in other tokamaks /21-23/ the less hazardous substitute (trimethylboron $B(CH_3)_3$) for diborane. It is not possible to deposit films with an atom ratio $B/C > 0.3$, however. Since the initial introduction of Boronization less hazardous precursors have been used : Decaborane ($B_{10}H_{14}$) in JT 60- U /24/, and carboranes ($C_2B_{10}H_{12}$) /25/ in the Russian tokamaks T-3M and T-11M.

It is important to note that unlike beryllium the deposited boron films are not hazardous compounds. Access to the machine is as uncomplicated as before the coating. In TEXTOR, films have been produced at wall temperatures of 150 °C and 350-300 °C, as was the case in D III-D, whereas ASDEX, ASDEX-Upgrade, TCA, TFTR and most other machines deposit at room temperature. The wall temperature does not seem to be of decisive importance. However, it has been shown in laboratory studies, that films grown at high temperature tend to absorb less water vapour when stored in air for a long time /26/, indicating that the microstructure might indeed be affected by the deposition temperature.

The coverage of the tokamak surface may be inhomogeneous due to the depletion of the reactive gas by the glow discharge close to the point of gas injection. The homogeneity can be significantly improved when toroidally distributed multiple gas injection ports are used /27,28/.

Recently, boron containing bulk materials have been used successfully in TEXTOR /29/ and other devices /22/ as limiters or plasma exposed probes with the aim to provide an in situ source of boron. In the case of graphite doped with 3 % boron, it has been observed that significant thermal sublimation of boron is observed when the limiter surface reaches about 1600 °C. The rate increases exponentially with temperature while the carbon sublimation is still small at temperatures below about 2200 °C /29/. Rapid migration of boron out of the bulk to the surface occurs leading the near-surface depletion /30/

3.2.2 Beryllium Coating

In JET, a resistively heated meander from CFC materials was used to heat a hollow Beryllium half sphere from the inside up to the sublimation temperature / 11/. Four such evaporators were equipped around the midplane of the machine. The typical thickness of the layers evaporated onto the graphite wall armour and divertor plates and on the inconel vessel was 30 nm, corresponding to about 10 g Beryllium per evaporation. Good vacuum conditions are required before Beryllium can

be evaporated. At surface temperatures of about 900 °C a reaction with CO and CO₂ in the residual gas occurs, leading to the formation of BeO. The oxide impedes the further evaporation and, in addition, changes surface emissivity and makes the temperature control of the evaporator difficult.

JET has also used limiters and divertor plates from bulk beryllium. Thermal overloading during tokamak discharges has led to melting and to in situ beryllium evaporation from these surfaces.

Beryllium dust is highly toxic. The access to the interior of a device in which Beryllium evaporation or wall components from Beryllium have been used is thus very much restricted. In-vessel work requires full biological protection. This impacts on the flexibility of the device.

3.3 Film Properties

The Carbonization process produces amorphous, hydrogen rich carbon films a-C:H with a ratio H/C of about 0.4. The film is transparent, hard, and homogeneous down to a microscopic scale /17/. Experiments using the annihilation of positrons revealed, that at least 3% of the total volume is occupied by micropores with a diameter of about 0.5 nm /31, 32/. Auger Electron Spectroscopy

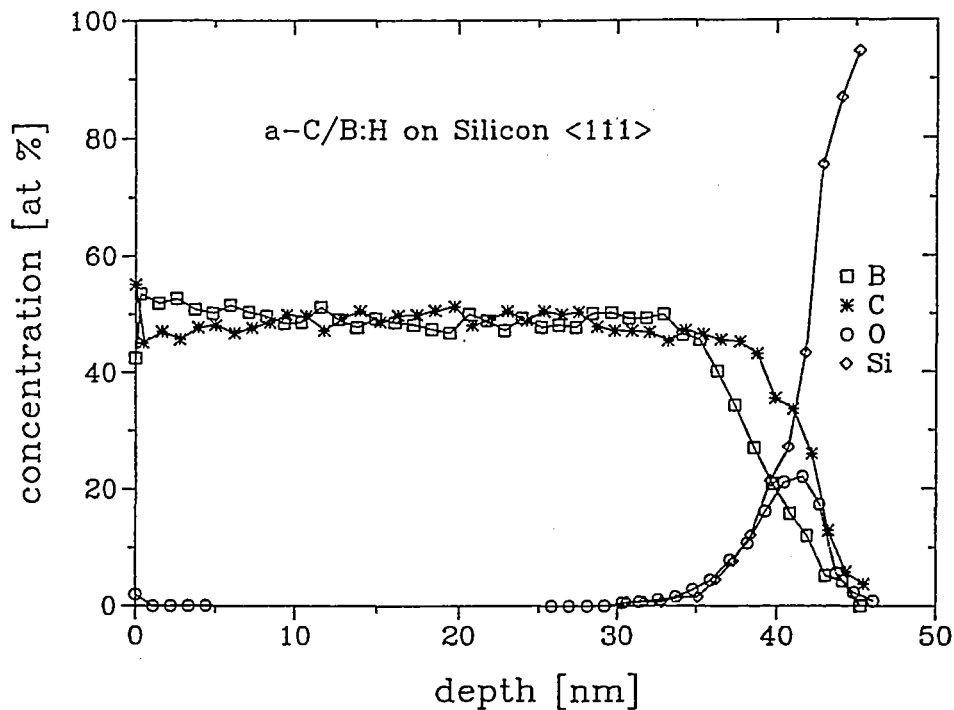


Fig. 3 AES depth profile of the atomic composition of a-C/B:H on Si-substrate as deposited in TEXTOR.

with sputter depth profiling (AES) shows that no (AES) impurities are incorporated. The film is inert to air exposure /17/. In steady state, oxygen recycles as CO with a yield close to unity from Carbonization layers already at room temperature (see chapter 3.1).

Boronization produces amorphous boron a-B:H or boron-carbon films a-C/B:H, depending on the gas mixture used. Boronization layers have a well defined composition which is homogeneous in depth, as can be seen from the AES depth profile of a film deposited in TEXTOR on Si substrate (fig 3). The ratio B/C is $\sim 1/1$ for this particular film. The bulk oxygen concentration is almost at the detection limit (1 at%). X-ray induced Photoelectron Spectroscopy (XPS) reveals that the B-C bonds in a-C/B:H have a carbidic character /32/. This is probably the reason for the chemical inertness and the improved thermal stability compared to a-C:H.

Depending on temperature, the erosion yields by atomic hydrogen exposure are lower by a factor up to 10^{-20} compared to a-C:H or irradiated graphite, see fig. 4. Radiation enhanced

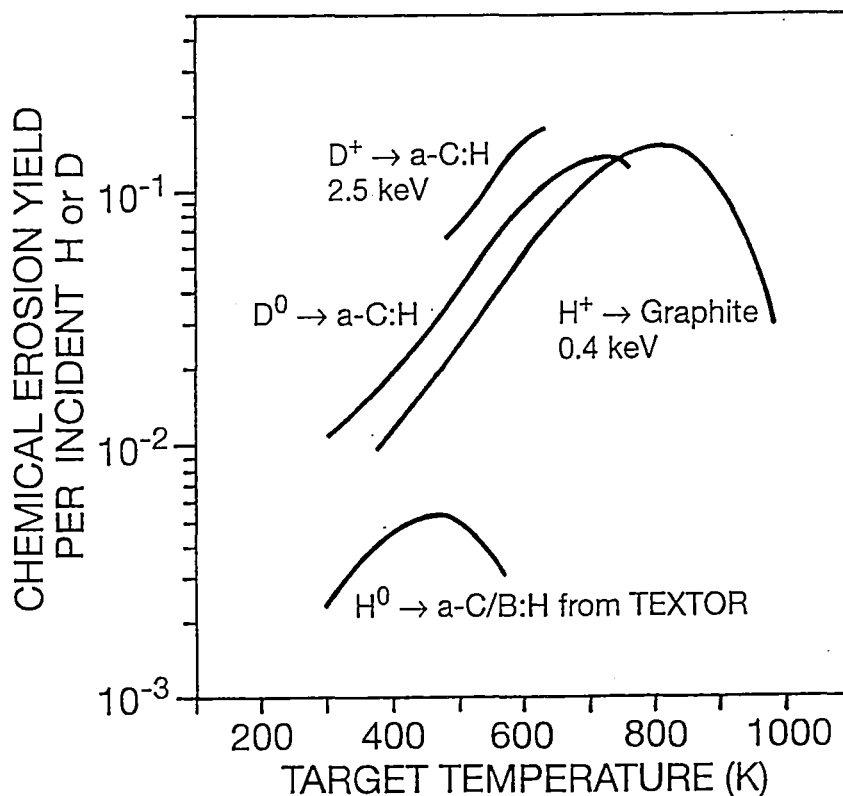


Fig. 4 Total chemical erosion yield (C atoms per incident H) for graphite at an impact of energy 0.4 keV H^+ ions, for a-C:H and a-C/B:H at thermal atomic hydrogen exposure.

sublimation is not significantly suppressed in a-C/B:H, although a shift of the onset temperature towards higher values exists as compared to pure carbon /34/. Thermal desorption spectrosc., nuclear reaction, and ion beam analysis all indicate a concentration of $H/B+C = 0.3 - 0.4$, a little less than the value for H/C in a-C:H /33/. The amorphous structure has been proven by x-ray and electron beam diffraction. First experiments with slow positron beams /35/ indicate a considerable microporosity with a mean pore size of about 1 nm diameter, which is larger than in a-C:H. The films are chemically inert and show no progressive oxidation. Whereas O-gettering is observed when boron containing surfaces of a-C/B:H are exposed to energetic O particles /35/, B/C surfaces appear to be chemically stable when exposed to thermal oxygen molecules /32, 36/.

Another effect, called "reactive gas gettering", also contributes to the control of oxygen impurities. It has been identified in TEXTOR that adsorbed (molecular) diborane gas acts as a getter /10/. Figure 5 shows the partial pressures of B_2H_6 , CH_4 and He as measured by quadrupole mass spectroscopy (QMS) as a function of time when the working gas for the Boronization has been let into the torus and all pumps were valved off. The glow discharge is off. In contrast to CH_4 and He which remain constant, the B_2H_6 pressure falls exponentially, indicating a first order reaction with

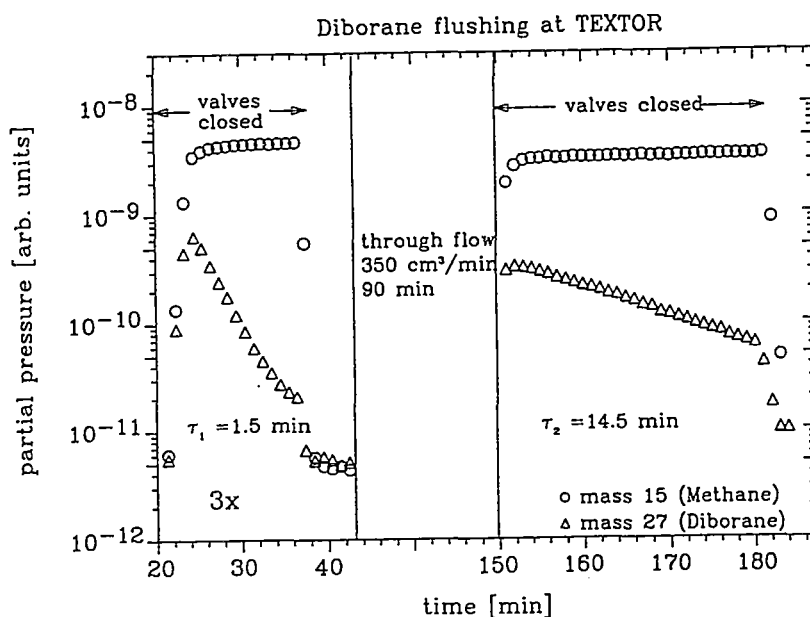
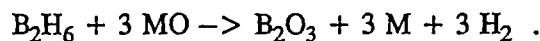


Fig. 5 Variation of the partial pressures of methane (circles) and diborane (triangles) after their introduction into the unpumped TEXTOR vessel. The diborane pressure decreases by reactions of the gas with oxidized vessel surfaces. Progressive flushing leads to a smaller reaction rate (longer time constants), indicating saturation of the surface reaction.

the surface of the system. Successive runs show a gradual saturation of the reaction rates. It is assumed that B_2H_6 reduces residual metal oxides (MO) to bare metal (M) on the untreated surfaces predominantly on the backside of the liner and on the vacuum vessel according to the following schematic reaction:



This diminishes the release of water vapour in reactions with scattered hydrogen plasma particles and easily reducible metal oxides (NiO, Fe_2O_3 etc) and thus decreases the primary oxygen source in the tokamak /14/. A corresponding reduction of oxygen impurities in tokamak plasmas following "reactive gas gettering" has been observed /10/.

Berylliumcarbide formation must be considered when beryllium evaporation is used in machines with graphite wall components, as is the case in JET. Beryllium carbide (Be_2C) has an enthalpy of formation of only -28 kcal/mole /37/. It is brittle and hygroscopic. The formation of Berylliumcarbide has indeed been observed in JET when Be and C atoms are co-deposited by the tokamak plasma on a collector sample /37/.

3.4 Hydrogen Storage and Release

The thermal desorption of hydrogen from a-C/B:H is different compared to that from a-C/H. Whereas a broad release pattern, extending from about 250 °C to 1000 °C is found in a-C/H /17/, a well defined release around 570 °C is measured for a-C/B:H /13/. The type of H bonding seems to be better defined in a-C/B:H. Measurements using the "Wall Pump and Release Effect" /38, 39/ indicate a pronounced transient hydrogen pumping of a-C/B:H during the first exposure to a hydrogen plasma, in particular when He was used in the working gas for film deposition. The subsequent exposures exhibit much less pumping with long time constants. Such an evolution is also observed during tokamak operation. Whereas pure a-C:H layers tend to be saturated with hydrogen rapidly, some reproducible hydrogen pumping is observed with a-C/B:H. The behaviour suggests a slow degassing of H_2 from the films at $T \geq 150$ °C after tokamak plasma exposure.

During impact of energetic particles, the release of hydrogen from the carbonaceous films is dominated by particle induced desorption of H, its recombination into H_2 within the bulk of the layer and the subsequent diffusion of H_2 to the surface /40/. Enhanced mobility of H_2 is found during particle impact /40/.

With respect to the hydrogen pumping and recycling properties, Beryllium behaves like stainless steels, Inconel and other non hydride forming metals. Measurements using the "Wall Pump and Release Effect" give values for the recycling constant $R = D/2\sigma k_r$ (D = hydrogen diffusivity, σ = surface roughness, k_r = surface recombination rate constant for hydrogen) of $R = 8 - 9 \times 10^{15} \text{ cm}^{-2}$ with a small activation energy of 0.03 eV in the temperature range between ambient and 300 °C /41/. Transient flux dependent hydrogen pumping is expected for a tokamak with Beryllium layers similar to that of a well discharge cleaned metallic machine. Indeed, the time history of the density evolution tokamak discharges in JET could be well described on this basis /41/.

4. INFLUENCE OF THIN SURFACE LAYERS ON FUSION PLASMAS

4.1 Carbonization

Carbonization, leading to an "all carbon" inner surface coating, was first applied late 1984 in TEXTOR /12/ and has since been used in many other devices like ASDEX /42/, JET /43/, JIPP T II-U /44/, D III-D /45/, Heliotron - E /46/, etc. The effects have been discussed in a comprehensive manner in /17/.

The common observation is the almost complete suppression of metal impurity atoms in the plasma since the entire wall surface is covered with the clean carbonaceous film. This has led to a breakthrough in heating fusion plasmas by electromagnetic waves /47/ and to a general improvement in plasma performance. This became manifest by low values of Z_{eff} and a low fraction of $P_{\text{rad}}/P_{\text{heat}} = 0.2-0.4$ of total radiated power P_{rad} to that of the total heating power P_{heat} . The value of $Z_{\text{eff}} = \Sigma\{Z_i^2 n_i/(N_e/V)\}$ is a figure of merit for plasma purity (Z_i is the atomic number of impurity i , n_i is its density, N_e is the total number of plasma electrons and V is the plasma volume). An ideally pure hydrogen-plasma has $Z_{\text{eff}} = 1$, that of a pure carbon plasma is $Z_{\text{eff}} = 6$. Values close to $Z_{\text{eff}} = 1$ were obtained shortly after a fresh Carbonization.

Oxygen as a plasma impurity is reduced by Carbonization (factor of about 5 - 8) compared to the well discharge cleaned metallic surfaces. This strong reduction is transient (over about 20 discharges) however, and a gradual increase of oxygen, saturating at about a factor of 2 - 3 net reduction is observed. The reason is the complex cycle of oxygen in an all carbon machine. A schematic representation of this cycle is shown in fig. 6 /48/. When quasi stationary impurity concentrations are reached, the oxygen atoms enter the plasma mainly via particle induced desorption of

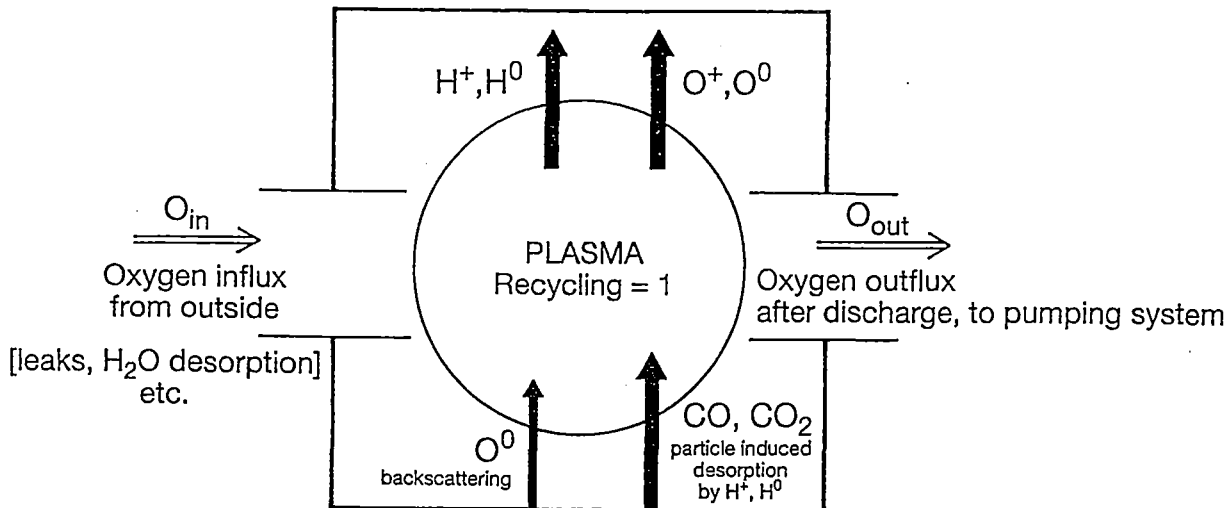


Fig. 6 Schematic diagram of the oxygen impurity cycle in a tokamak with all carbon walls.

CO and CO₂ from the near surface layers of the film in which oxygen is stored again by implantation during the termination of the discharge. Within this picture, the oxygen level never changes. It can be decreased by depletion of the wall from oxygen by glow discharges in He /17/ or by a fresh Carbonization. After such procedures the oxygen recovers to the previous values in subsequent discharges, a fact which points to the influx of oxygen from additional sources (water vapour, as discussed in section 3.3) because some oxygen atoms are evacuated from the system between discharges. As already mentioned, each CO molecule also carries a carbon impurity atom into the plasma and gives rise to a synergism in impurity production.

The hydrogen recycling /49-52/ and impurity release mechanisms on carbon differ very much from those in metallic machines, requiring wall conditioning techniques relying on particle induced and/or thermal desorption as described e.g. by Dylla /53/, Wienhold /54/ and Jackson /55/.

4.2. Comparison of Boronization and Be operation in JET

The first paper on the Boronization of tokamak walls has been published from TEXTOR in 1989 /13/. In the following chapter, new data from TEXTOR together with information meanwhile available from Boronization in ASDEX /56/, TCA /57/, TFTR /58/, D III-D /28/, JT-60 /59/, TORE SUPRA /60/ and other machines will be compared to the results of operation in JET with beryllium coated walls.

This approach appears to be justified in view of the similar mechanisms for oxygen impurity control by Beryllium and Boronization films and in view of the very similar significant improvements in tokamak plasma performance.

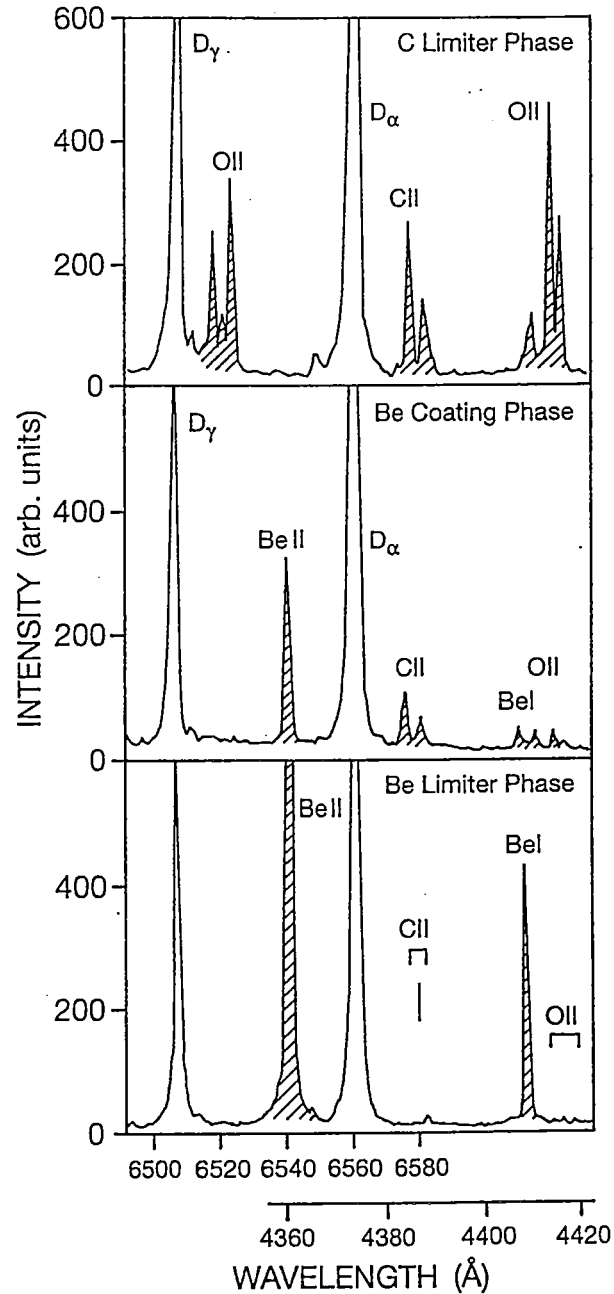


Fig. 7 Survey of spectral lines in the visible region in JET for three operating phases: all carbon phase (top), Be coating phase with Be evaporation and C limiter (middle), and the Be limiter phase with Be evaporation and belt limiters from Beryllium tiles (bottom).

Beryllium limiters have been tested first in the small tokamak UNITOR /61/ and in ISX-B /62/ before beryllium was introduced into JET in 1989 /63, 64/. The results from these early experiments already indicated an effective control of plasma impurities but they also revealed the problems associated with overheating high heat load components from beryllium. Melting and resolidification introduced irregular surface shapes. Large beryllium influxes were then observed already in discharges with low heating powers when beryllium protrusions were evaporated. This is not the case for graphite elements which do not melt but sublime when they are overloaded.

The reduction of oxygen as a plasma impurity after the first beryllium evaporation in JET can be seen from the intensities of various spectral lines in the visible region, see fig 7. Here three phases are compared, namely the all carbon-phase (graphite, Carbonization), beryllium evaporation onto graphite wall components and beryllium evaporation with limiters from bulk beryllium. The O-II signal is decreased by a factor > 20 , that of C-II by a factor of about 2 with beryllium evaporation. In the Be-limiter phase, beryllium is the dominant plasma impurity.

A similar survey was measured on ASDEX after Boronization and is shown in fig. 8. The decrease in oxygen is obvious. In the case of ASDEX the Boronization also suppressed the metal

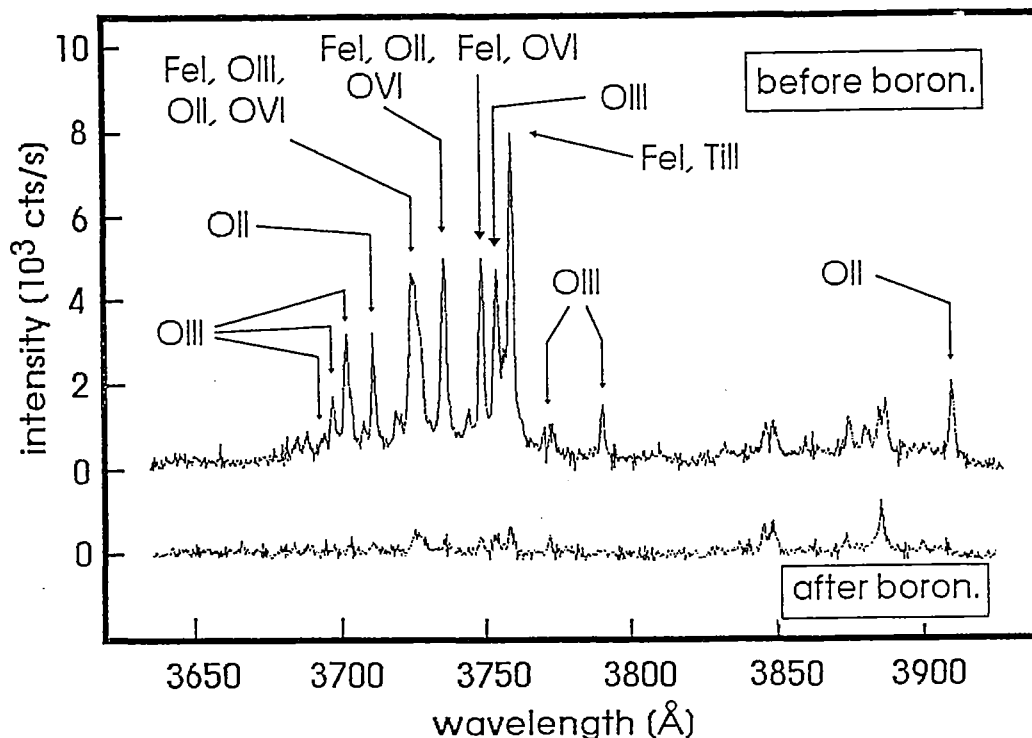


Fig. 8 Survey of spectral lines in the visible region in ASDEX before and after Boronization.

contamination by covering the metallic vessel with a-C/B:H. Due to the carbon wall, metals were unimportant in JET.

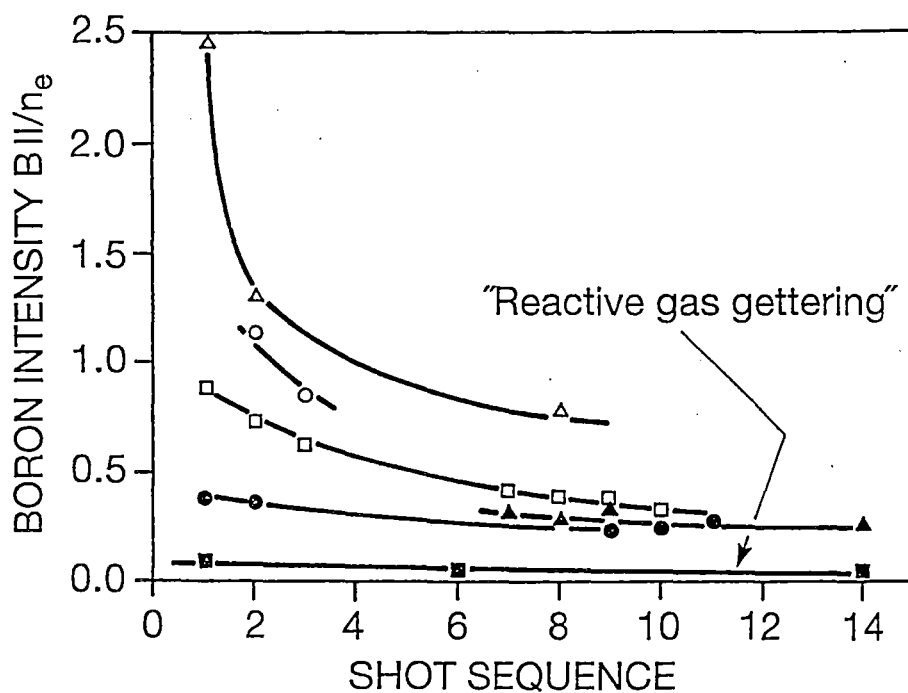
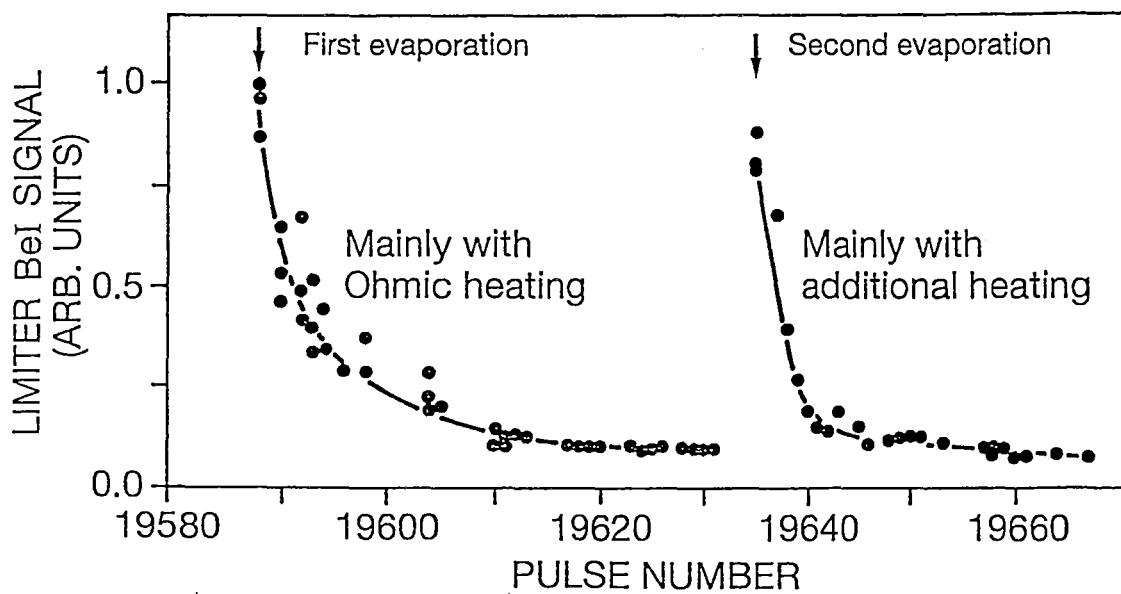


Fig. 9 a) Erosion of a-C/B:H films on the ALT-II limiter in TEXTOR as indicated by the BII emission as a function of the discharge number for consecutive operation days.



b) Erosion of beryllium films evaporated on the JET carbon limiters as indicated by the Be I intensity as a function of the discharge number.

Both in the JET with evaporated beryllium layers and in the case of the Boronization in TEXTOR the films are eroded rapidly from the limiters. This is evident from the a transient appearance of the Be I intensity and the B-II intensity, respectively, measured at the limiters as a function of discharge number. Figs. 9 a and b show that the films erode in a few discharges but also indicate that an erosion/redeposition equilibrium is established. Beryllium and Boron atoms are probably released from the wall and transported in smaller quantities back to the limiter and form mixed Be/C or B/C compounds. The carbon gradually dominates due to the preferential erosion of carbon from the virtually unexhaustable supply of the graphite limiters.

The very small level of B-I intensity after the diborane "reactive gas gettering" experiment should be noted in figure 9b, indicative of only a minute boron concentration on the plasma exposed surfaces (see chapter 3.3).

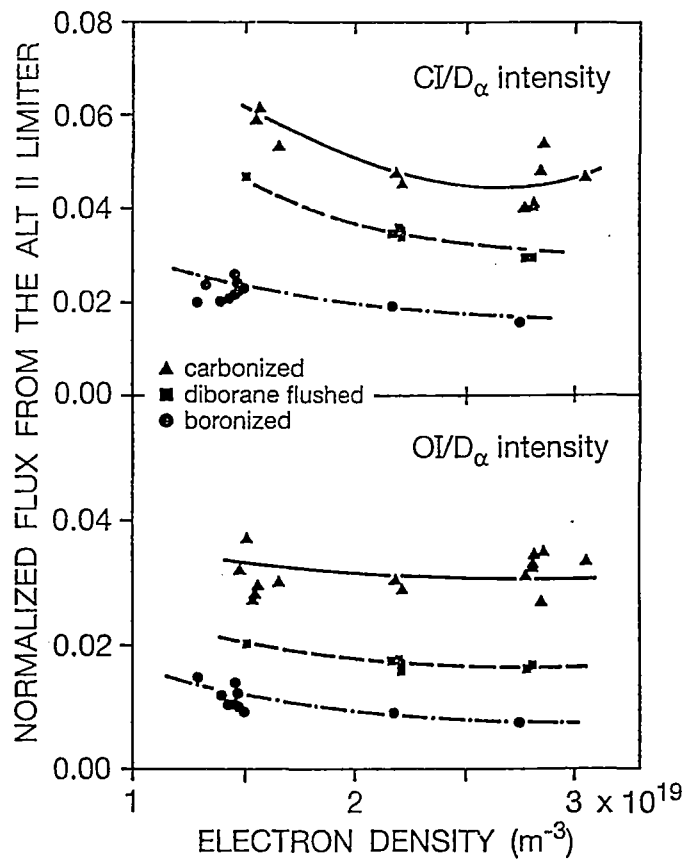


Fig.10 Ratio of the carbon flux and the deuterium flux CI/D_{α} and ratio of the oxygen flux and the deuterium flux OI/D_{α} measured at the toroidal pump limiter in TEXTOR for ohmic discharges as a function of the line averaged density after Carbonization (triangles), Reactive Gas Gettering (squares) and Boronization (points).

The effect of the Boronization on the carbon and the oxygen fluxes at the TEXTOR limiters is best evident from the spectroscopically measured ratio of the C-I/H α and O-I/H α intensities for similar ohmic discharges, see fig. 10. Here three cases are compared: the carbonized "all carbon machine" as a reference, the fluxes after "reactive gas gettering" by diborane and after a regular Boronization. The reduction in the oxygen flux is evident. It is worth noting the pronounced effect of the "reactive gas gettering" experiment on the oxygen level. A further significant reduction of the oxygen flux is found after the regular Boronization.

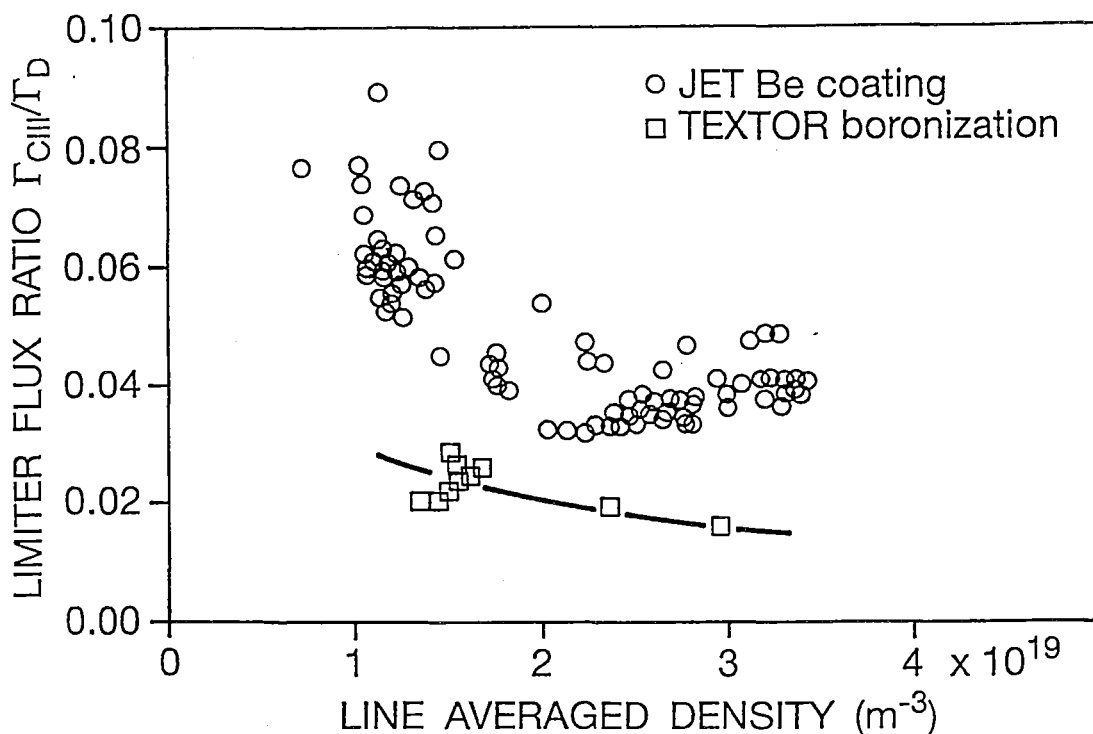


Fig. 11 *Ratio of the carbon and deuterium flux $CIII/D_{\alpha}$ at the limiter as a function of the line averaged density for ohmic discharges in JET with beryllium evaporation on the carbon limiters. The values measured at the toroidal limiter in TEXTOR after Boronization are shown for comparison, see fig. 10. Both data sets essentially agree within the ranges of systematic and statistical errors.*

A reduction similar to that of oxygen is found for the carbon fluxes. The data suggest a correlation between both fluxes. Since oxygen is known to recycle as CO in a carbon machine, this may not be too surprising. A decreased level of CO measured in the residual gas during and after the discharges has been observed both in TEXTOR and ASDEX. The smaller chemical erosion by hydrogen of a-C/B:H compared to a-C:H is masked by the oxygen effect. It may nevertheless be important in plasma regimes with low T_e and large particle fluxes to the wall.

The ratio of the CIII/H α intensities at the limiter have also been measured in JET after beryllium evaporation for ohmic discharges and are shown in fig 11. The above mentioned values for TEXTOR are included for comparison. Evaporation of Beryllium in JET reduces the carbon fluxes significantly compared to the "all carbon" case. The data are consistent with the assumption that the contribution of oxygen to the carbon removal from the limiters has been eliminated by the getter action of beryllium. Both conditioning techniques, Boronization and Beryllium evaporation, yield essentially the same effect.

In the case of TFTR /58/, the observed reduction of the carbon level appears to be more transient than in the case of the other machines using Boronization. The decrease is about a factor of 2 for the first few discharges after Boronization but increases again thereafter. A long lasting reduction of the oxygen level is clearly documented, however.

The reduction of the impurity concentration has a significant effect on the attainable values of Z_{eff} as shown for JET and TEXTOR in fig 12. In the case of JET, the Be- limiter phase is

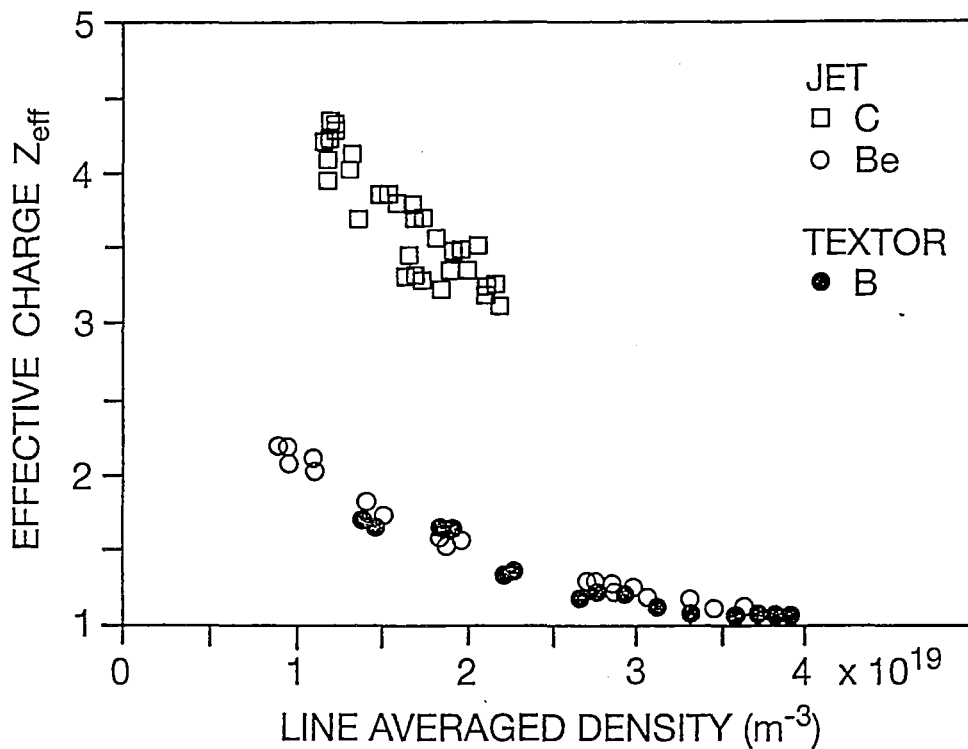


Fig. 12 Z_{eff} as a function of line averaged density in ohmic discharges for JET with all carbon limiters (open squares) and beryllium evaporation and beryllium belt limiters (open circles) and for TEXTOR after Boronization (full circles).

included also. The TEXTOR curve coincides with that of the Be-limiter phase in JET. Z_{eff} is not changed noticeably when additional beam heating at the level of 1.7 MW is applied in TEXTOR (co-injection). An increase of Z_{eff} by about 0.5 at densities $< 3 \times 10^{13} \text{ cm}^{-3}$ is observed for counter injection and by about 1.0 during ICRH at the level of 4 MW. This indicates that the dilution of the plasma in TEXTOR with additional heating is kept low. It should be mentioned, that the power flow out of the last closed flux surface is about the same for TEXTOR with 1.7 MW beam injection and for JET with about 10 MW additional heating.

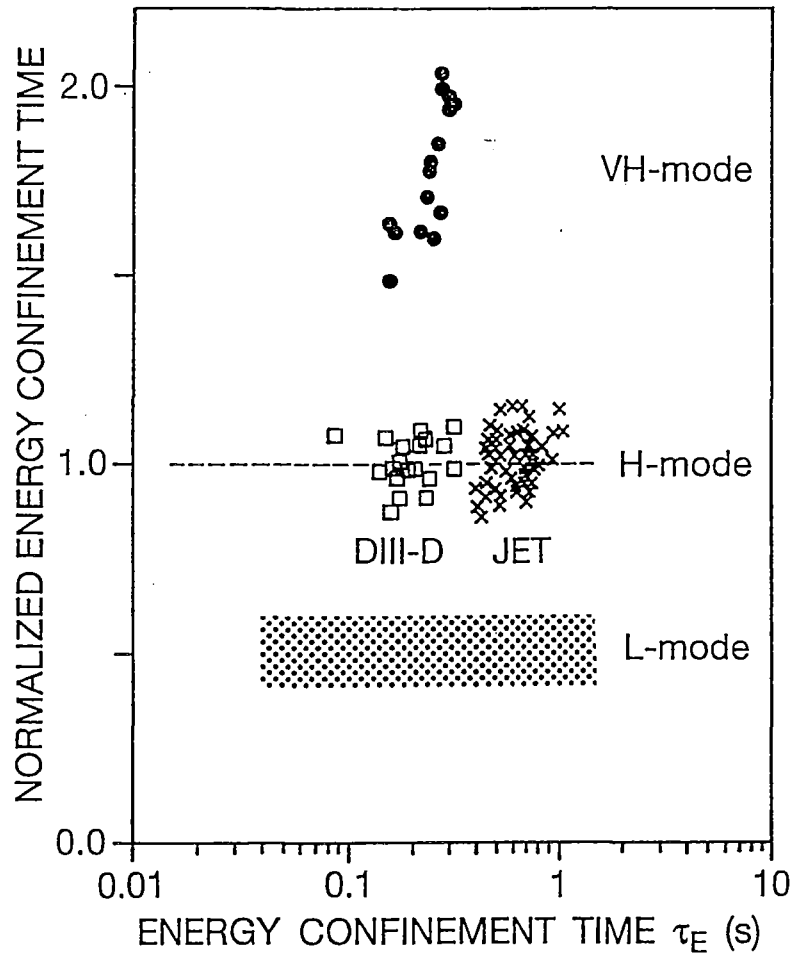


Fig. 13 *Energy confinement time, normalized to the JET-DIII-D scaling for H-mode. Confinement times measured in quiescent H-mode plasmas in JET and DIII-D and in VH-mode discharges in DIII-D after Boronization are shown. VH-mode confinement times are 1.5 - 2 times larger than these of quiescent H-modes.*

The best conditions ever obtained in the machines for wave heating have been observed for TEXTOR, ASDEX and in TCA, after Boronization. Boronization usually allowed the full installed

heating powers to be coupled into the plasma while maintaining a low degree of plasma contamination. In JET, a similarly beneficial influence is observed after beryllium evaporation, leading to RF-only H modes /64/. Both in TEXTOR and JET the combined heating by beam injection and ICRH has been successfully applied. A particularly interesting observation has been made at D III-D. After Boronization new plasma regimes were obtained with an energy confinement time τ_e about 1.8 times longer than the highest confinement times ever observed previously in ASDEX, JET and D-III-D /65, 66/ in H-mode, see fig. 13. This new regime has been called VH-mode (very high confinement mode). It has been discovered in JET during operation with beryllium covered surfaces /67/ and also in JT-60 U after Boronization /68/. Besides the low impurity content a low hydrogen recycling seems to be instrumental in providing the adequate conditions for the large confinement improvement. The details of how conditioning intervenes are not yet fully understood.

The total power radiated out of the plasmas is significantly decreased in all machines using Boronization. TCA reports that the radiated power fraction falls from 65-70% before to about 25 % after the Boronization /57/. The radiation profile indicates a factor of 3-4 less radiation from the plasma periphery. TFTR observes a decrease in the radiated power fraction by typically 25 % extending up to the density limit, which is attributed mostly to the reduction of oxygen. In TEXTOR the radiated power in ohmic discharges after Boronization is typically 15 - 20 % at densities in the range $0.5-3.5 \times 10^{13} \text{ cm}^{-3}$ and does not increase significantly with additional heating. A concomitant increase of the convective power flow to the limiters is measured. The radial profiles of radiated power as measured in ASDEX for a metallic, carbonized and boronized machine are shown in fig. 14. Carbonization already suppresses the central radiation from metals and Boronization further decreases the edge radiation. Also JET observes a reduction in radiation after beryllium evaporation but carbon still dominates in this phase. Only after the use of Be-limiters, and after a transient enhancement of chlorine impurities was overcome, did the radiation level decrease significantly.

An improvement of the density limit and the operation space has been reported from all machines using Boronization and from JET using beryllium. In TEXTOR the ohmic density limit is improved after Boronization by about 20%. The largest improvement is, however, observed with additional heating, which allows the density to be increased significantly. It has been observed that the signature of the density limit disruption in the boronized TEXTOR is different from the metallic or carbonized cases. Whereas strong MHD activity was usually a precursor to hard and rapid disruptions in the metallic and carbonized machine, a much softer limit is found in the boronized TEXTOR, often accompanied by poloidally localized highly radiative plasma zones of high density

and low temperature (MARFES). It appears that the maximum density is rather limited by the power

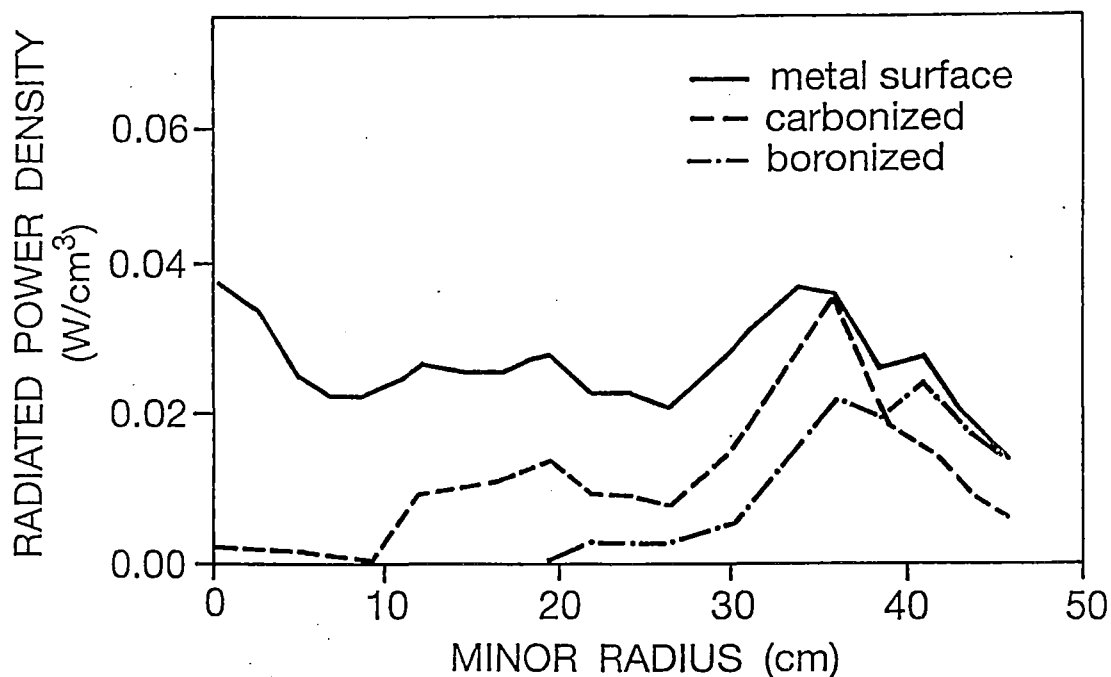


Fig. 14 Radial profile of the total radiated power in ASDEX for the metallic, carbonized and boronized machine.

flow into the SOL and not by the occurrence of instabilities under boronized wall conditions. The same observations are made for JET /64/, in which a power dependence for the maximum density of the type

$$n_e R/B_t = 3 (P_{tot})^{0.5}$$

has been found.

The recovery from disruptions has been a cumbersome matter in JET and TFTR before the new conditioning techniques were applied. The use of beryllium and Boronization lead to a rapid recovery. One or two discharges at maximum are required before high performance operation can be continued. In TFTR this is a reduction by a factor of 5 - 10 in the number of discharges required to reestablish low oxygen levels after a disruption, increasing the availability of the machine.

In TEXTOR and in JET with beryllium evaporation strong wall pumping of hydrogen is observed similar to the best He conditioned carbon operation /11/. In both cases the pumping action is retained for about 10 - 30 discharges with a gradual deterioration, which is more rapid when operation close to the density limit is made. The pumping action can be recovered in TEXTOR by

overnight baking to 350 C. In TFTR no significant difference was noted in the wall pumping characteristics between He-conditioned graphite and a-C/B:H /58/.

An even stronger pumping is found in JET when Be-limiters are used, which is comparable to that of a metallic machine (see chapter 3.3.). In TEXTOR and in JET low recycling allowed the attainment of the "hot ion mode" yielding very high ion temperatures and high values of the fusion product $nT\tau_E$. Large current drive effects are found in TEXTOR with combined heating by neutral beam injection and ICRH heating under these conditions /69/.

Many features of tokamak operation like the efficient control of plasma impurities, low Z_{eff} , higher attainable densities with "soft" limits etc. are very much the same for a boronized machine and a machine using beryllium on the first wall surface. The key element in the mechanisms underlying the effects are the efficient control of oxygen plasma impurities and low hydrogen recycling for improved confinement scenarios.

5. REDEPOSITION OF THIN FILMS

The fact that effective redeposition of carbon takes place within an all-carbon machine has been measured early in the carbonized TEXTOR /12, 17/. Using Laser-induced Resonance Fluorescence of iron atoms in front of a carbonized stainless steel limiter during ohmically heated discharges, the net erosion of a-C:H was measured at low plasma densities ($n_e = 2.5 \times 10^{13} \text{ cm}^{-3}$) whereas net deposition of carbon was observed at higher densities ($n_e = 3 \times 10^{13} \text{ cm}^{-3}$) on the same area of the limiter and under otherwise identical conditions. A high degree of redeposition ($> 99\%$) was held responsible for the surprisingly long lifetime of the thin a-C:H layers on the limiter.

Collector probe experiments in the SOL of TEXTOR /17/ and detailed analysis of the collected deposits by AES and nuclear reaction techniques revealed that a-C:H reforms in the SOL after transport in the plasma. As long as the temperature of the collecting surfaces does not increase beyond about 400 °C, the ratio H/C is close to 0.4. At higher temperatures desorption of H occurs leading to lower H/C ratios. The structure is amorphous and the refractive index of redeposited a-C:H is identical to that of a Carbonization film.

"Soft" a-C:H films with lower refractive indices and higher hydrogen concentrations are

deposited on surfaces which are exposed to particles with low kinetic energy. This may occur on remote surfaces like the backside of the liner or support structures for limiters onto which multiply reflected C atoms or thermal hydrocarbon radicals impinge.

Successive discharges lead to the buildup of stratified films /70/. The individual layers can be well distinguished and be attributed to single discharges, in particular when they incorporate small amounts of easily detected metallic plasma impurities. When large thicknesses ($> 1\mu\text{m}$) are accumulated the integrated stress may lead to delamination of the layered films..

In the case of Boronization the B/C concentration ratio of the redeposited material varies with the number of discharges made since the last Boronization. The AES depth profile of a layer deposited some 250 discharges after a Boronization on a collector in the limiter shadow of TEXTOR is shown in fig. 15.

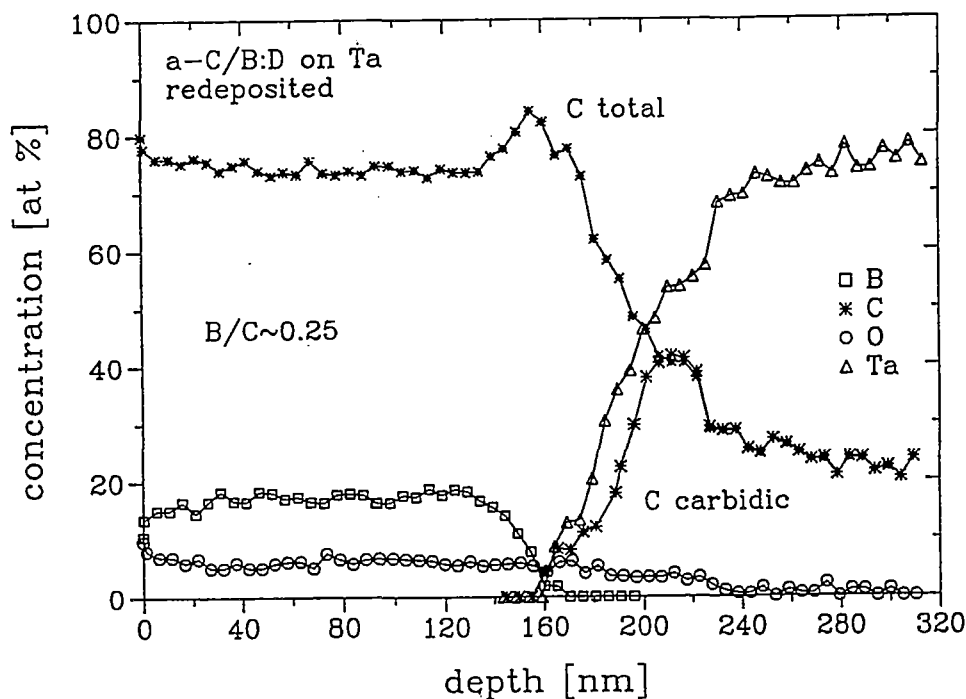


Fig. 15 AES depth profile of the atomic composition of material deposited in the scrape-off layer of TEXTOR, 250 discharges after the last Boronization.

As in the case of Carbonization, a reforming of a-C/B:H layer is observed. The ratio of B/C is about 0.25, however, which is considerably less than in the original film which had a composition of $B/C = 0.5-1$. The hydrogen (deuterium) content is $H/(B+C) = 0.3 - 0.5$, close to that of the Boronization film. The clearly visible oxygen level in the redeposited film is noteworthy. It is due

to the continuous gettering of oxygen in the growing film during plasma bombardment (no comparable oxygen incorporation is found in a-C:H). The smaller level of boron is obviously still sufficient to yield good control of the oxygen impurities over a long time. Nevertheless a gradual decrease of the oxygen getter potential is observed, requiring a fresh Boronization about every 400 - 500 discharges, which corresponds to about one month of operation in TEXTOR.

Collector probe experiments as a function of time following a fresh Boronization, i.e. at various boron fluxes in the SOL, have been carried out. The gettered amount of oxygen in the film was correlated with the spectroscopically observed intensity of the O-I line measured at the limiter /71/. The retained concentration of oxygen is proportional to the boron concentration in the film. XPS analysis confirms that, as expected, the oxygen is bound to boron in form of an oxidic bond. An inverse relation between the O-I intensity in the plasma and the gettered oxygen in the layer is found. On the average, one boron atom in the redeposited film retains about 0.7 oxygen atoms.

Analysis of redeposited Be-C layers in JET has shown the formation of berylliumcarbide by codeposition of beryllium and carbon atoms, as discussed already in section 3.3. Significant oxygen gettering was observed during plasma operation and oxygen was seen to accumulate within the beryllium layer deep in the SOL. However, closer to the plasma boundary, oxygen did not appear to penetrate through the plasma deposits, though these deposits themselves did incorporate some oxygen /37/.

It should be recalled here, that carbon layers can be easily etched away by plasmachemical processes involving oxygen atoms, e.g. by a glow discharge in He/O₂ mixtures /38/. The yield is about 1 C atom per arriving O atom. This fact has motivated a proposal in 1987 to control the thickness of redeposited carbon layers by e.g. glow discharges in oxygen and thereby control the inventory of tritium codeposited in the films /72/. It is now reconsidered in the frame of the TPX project.

6. CONCLUSIONS AND OUTLOOK

Gettering has had a renaissance for the conditioning of fusion devices. This is brought about by the development of techniques strictly optimizing the use of low-Z material as realized in the case of beryllium gettering and of Boronization. The dominant effect is the reduction of the oxygen impurity concentration. Large getter surfaces on the deposition dominated wall prevent the release

of oxygen-containing species by plasma-surface-interactions and are a sink for oxygen diffusing out of the plasma. The strong chemical binding of impurity atoms to the surface is essential. In this respect both Boronization and beryllium evaporation are essentially equivalent and superior to the use of pure carbon surfaces.

The use of a limiter of getter material alone, i.e. without sputtering, evaporating or sublimating material, does not lead to improvements. The surface composition changes by incorporation of oxygen up to saturation and the control of oxygen plasma impurities is lost.

A reduction of hydrogen recycling, has been found for beryllium and, to a lesser extent for Boronization. Beryllium surfaces seem to behave like a "normal" metal exhibiting transient flux dependent pumping and recombinative release of hydrogen. It is thus expected that pure beryllium will not retain large tritium inventories. The situation for boronized surfaces is still unclear, but they tend to behave like He-conditioned carbon, which provides pumping just for few discharges. Boronization and Carbonization layers trap hydrogen by codeposition processes. This may lead to large tritium inventories unless the thickness of the codeposited layers is kept low or the wall temperature is everywhere kept above about 600°C.

Another important aspect is the handling of the materials. Beryllium dust is hazardous and work in the machine requires permanent precautions which limit the flexibility and speed of in vessel modifications. This is not the case for the Boronization.

In view of future machines, which operate with long pulses, the effect of redeposition of wall material must carefully be considered. Injection of reactive gases may provide an elegant tool for local in situ repair of high heat flux components and also offer a method for active control of plasma-surface-interactions in continuously operating devices. First experiments using TMB and Silane in TEXTOR have been encouraging.

The compatibility with large neutron fluxes has to be examined. Also here, thin film concepts may offer advantages. By releasing the constraint of plasma compatibility from the bulk substrate, additional flexibility in the choice of first wall materials may be provided. Thus an optimized selection of bulk materials according to the integrity of mechanical and thermomechanical properties and neutron activation can be made.

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