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Journal of Nuclear Materials 241-243 (1997) 821-826

journal of nuclear materials

In-situ deposition of silicon on the leading edge of the ALT-II limiter in TEXTOR-94

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Abstract

Silane gas was injected through apertures in the leading edges of the ALT-II limiter in TEXTOR during tokamak discharges. The gas injection produces a hard, robust local coating which protects the exposed surfaces against erosion. As a byproduct, metallic impurities in the plasma are reduced, a radiation belt at the plasma periphery is generated and there is evidence that a major part of the wall is coated. For the given experimental condition the rise time until the carbon flux on a siliconized surface reaches the former level amounts to 5–10 s for ohmic discharges. For strongly heated discharges the deposited Si layer is eroded in about 1 s. The deposition technique has potential applications for in-situ protection/repair of divertor erosion in ITER.

Keywords: TEXTOR; Limiter; Wall conditioning; Wall coating; Erosion and particle deposition

1. Introduction

Wall coating of plasma facing components has led to an extension of the operational regime of tokamaks. Especially low Z materials (C, B, Be) as well as Si have valuable influence on the plasma operation, e.g. as oxygen getter [1,2]. In addition, it has been shown that the introduction of medium Z elements like Ne, Ar and Si can form a radiative layer to distribute the heat load rather uniformly [3,4]. An in-situ deposition method provides a potential for forthcoming fusion-reactors, where no glow-discharges are possible, but the deposition can be done during the discharge [5]. Different methods of silicon coating have been applied successfully on TEXTOR: full coating in a special glow discharge before plasma operation [6], gas puffing through a gas-inlet into the torus, see e.g. [4], and puffing of silane through a hole in a special test limiter [5]. The third method provides a local coating on specified positions. Intensive studies have been undertaken at TEXTOR for all these methods, and in particular for the test limiter the pattern of deposition could be well described by the ERO-TEXTOR deposition code [7]. In this study we extend the use of local deposition on highly exposed surfaces, namely on the ALT-II pump limiter. The influence of silane injection onto the impurity release will be discussed in the following sections.

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1 On leave at Forschungszentrum Jülich.

2. Experimental

The experiment is performed at TEXTOR-94 in ohmic and strongly heated discharges with deuterium gas fueling ($B_T = 2.25$ T, $R = 1.75$ m, $a_0 = 0.46$ m), with a discharge current of $I_p = 350$ kA and a pulse duration of 5.5 s. The toroidal belt limiter ALT-II is located 45° below the horizontal midplane at the low field side and consists of eight discrete blades covered with graphite tiles [8]. The gas is injected through 10 openings placed on the leading edges of the first two tiles of blade #5. The modified tiles face the electron drift direction. Only this limiter blade out of eight is modified. The holes with a diameter of 1 mm are drilled at the area of highest heat flux 1 cm behind the

PII S0022-3115(96)00613-7

last close flux surface. The poloidal separation of the holes amounts to 2.5 cm. The location of the holes can be seen in Fig. 1 (location indicated by arrows) where the deposition pattern of the silicon is shown from a colorimetric fringe analysis [9]. The gas feed lines have a diameter of 1 mm and a length of several meters, so the viscous flow allows only moderate gas flow changes. The shape of the silane gas pulse is indicated in Fig. 4. A total amount of up to 16 mbar l is introduced into the discharge.

2.1. Deposition under ohmic heating conditions

The line averaged density for all ohmic discharges is programmed to $2 \cdot 10^{13}$ cm^{-3} by using a feed-back control of the main gas injection system. After the ignition of the discharge and the ramp-up phase of the current, a steady state condition is kept for about one second. During this time the influence of layers deposited during previous discharges is studied. The relative fluxes of carbon, oxygen, deuterium/hydrogen, and silicon on the leading edge of the ALT-II toroidal belt limiter blade #5 are measured using spectroscopy. After injection of silane at 2 s, the density increases and stays constant at $3 \cdot 10^{13}$ cm^{-3}, as pumping is restricted due to technical reasons related to the safety of silane operation. At 4 seconds the plasma is moved away from the belt limiter, to prevent a further direct deposition of injected silicon or its erosion; then the current is ramped down and the discharge ends at 5.5 s.

In a first series of discharges, the amount of injected silane is increased from 2.8 mbar l to 14.1 mbar l. It is observed that the carbon flux (CI) as measured on the leading edge of the limiter blade was progressively reduced with increasing silane amounts up to 14 mbar l. At higher gas injection rates no further decrease is observed. To establish a stationary reference scenario for systematic studies all following experiments are done with a slightly higher amount of SiH_4 between 15.1 mbar l and 16 mbar l. Emphasis is placed on the reduction of the impurity content of medium Z (Ni, Fe, Cr) impurities in the plasma core and carbon as the major impurity at the plasma edge. Fig. 2a–c compares discharges with (No. 25–29, 35–41) and without (No. 24, 30–32) silane injection. In Fig. 2a the ratio of the CI to deuterium/hydrogen fluxes near the silane injection hole at the limiter edge is given. The dashed line shows the reduction during silane injection. The normalized carbon flux is reduced by a factor of five. The solid curve indicates that after a silane injection — i.e. at the beginning of the next discharge — the normalized carbon flux is reduced by about 15% due to the deposition of silicon at the leading edge. It is not understood up till now why this reduction is strongest after the first deposition (No. 26, 35). A second spectroscopic observation (Fig. 2b) performed 75 cm away from the injection shows a carbon flux (CI) reduction during the SiH_4 injection (dashed line) but not after the deposition (full line). This is consistent with the colorimetric fringe analysis, where it is found that predominantly the first 30 cm of the limiter blade are coated. During silane injection the CV line intensity normalized to the electron density decreases by about a factor two (Fig. 2c, dashed line), but no influence of the coating in subsequent discharges can be noticed (full line). It should be noted that the intensity of CV decreased by 7–10% after silicon deposition. The amount of medium Z components in the plasma (Cr, Fe, and Ni) as measured by SXR-spectroscopy was reduced by 60% after 11 depositions of silane. Nevertheless the total radiation increases probably due to silicon radiation. The bolometric analysis shows that a radiating mantle is built up at the plasma edge and that the highest amount of radiation comes from the region of the limiter blades.

After a series of 12 ohmic discharges with a total time of 24 s of deposition the tiles have been taken out and have been analyzed. Colorimetric fringe analysis [9] is used to determine the deposition pattern and the thickness of the layer as shown in Fig. 1. A detectable coverage above 20 nm which is about the limit of the colorimetric fringe analysis is found for the first four tiles of the limiter blade. The maximum thickness amounts to 800 nm near the point of gas injection. The layer-thickness decreases to about 100 nm within a toroidal distance of about 30 mm. The average thickness of the layer was ca. 160 nm in the observed area. A toroidal cut of the thickness of the layer along a line as marked in Fig. 1 is given in Fig. 3 and compared with the electron probe micro analysis (EPMA). According to the EPMA measurement around 50% of the layer consists of silicon. Following the analysis in [5] and [10], an average density of $5.4 \cdot 10^{15}$ cm^{-2} nm^{-1} can be used. Thus a total amount of about $2.8 \cdot 10^{20}$ silicon atoms are deposited at the first four tiles on an area of 660 cm^2 representing 15% of the total area of one blade. The amount of deposited Si has to be compared to 3.2×10^{21} silicon atoms injected during the deposition time, so that a deposition efficiency of about 8.7% onto the first four tiles of the limiter blade has been reached. This is comparable to previous depositions on a test-limiter [11]. The subsequent decrease of metallic impurities is most likely due to the deposition of a thin silicon layer onto the inconel liner in TEXTOR. A further part of the silicon is either pumped or forms thin layers on the other limiter blades.

After 5 discharges with silane injection three discharges without silane injection have been made. During these discharges, the carbon line intensity (CI) near the injection hole increases again. The rise time for reaching the level of the carbon line intensity before siliconization amounts to about 6 s. This may reflect an increase of the surface coverage of carbon as well as an increase of the carbon concentration in the near surface layer [12].

During the deposition discharges the amount of the TEXTOR external gas fuelling before silane gas injection is reduced from 14 mbar l to 4 mbar l; thus most of the fuelling comes from the wall, which is loaded due to the density increase during injection. The H/D ratio at the

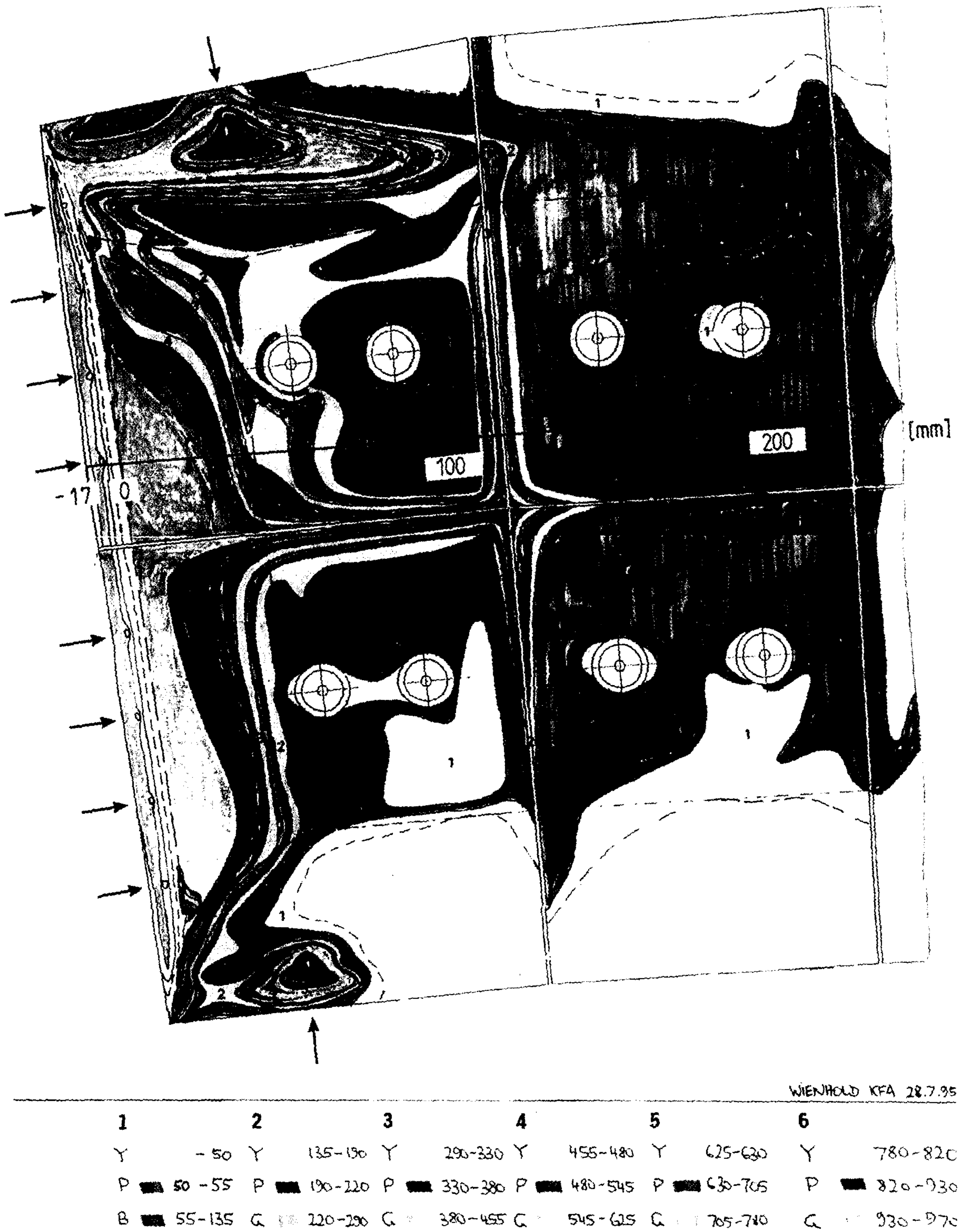
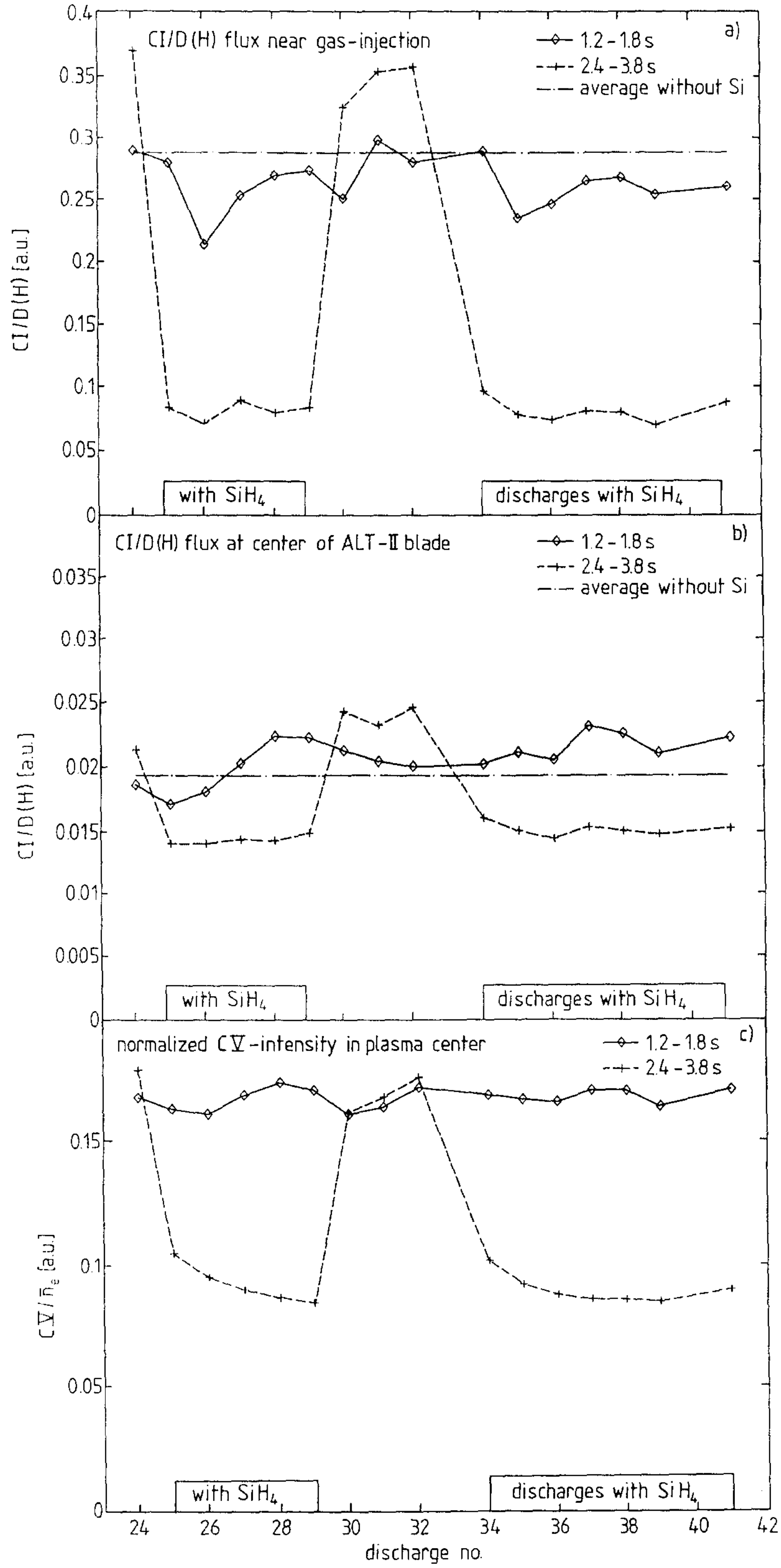


Fig. 1. Deposition pattern in false colors at the first four tiles facing the electron drift direction. The location of the gas injection holes is marked. Following the colorimetric fringe analysis layers of up to 900 nm are formed (refractive constant 2.0, absorption constant 0.15, incident angle 70°; numbers 1–6 are orders of interference, the colors correspond to the layer-thickness (nm)).


CI/D(H) flux near gas-injection
1.2 - 1.8 s
2.4 - 3.8 s
average without Si
a)
CI/D(H) [a.u.]
with SiH4
discharges with SiH4
CI/D(H) flux at center of ALT-II blade
b)
normalized CV-intensity in plasma center
c)
CV/n_e [a.u.]
discharge no.

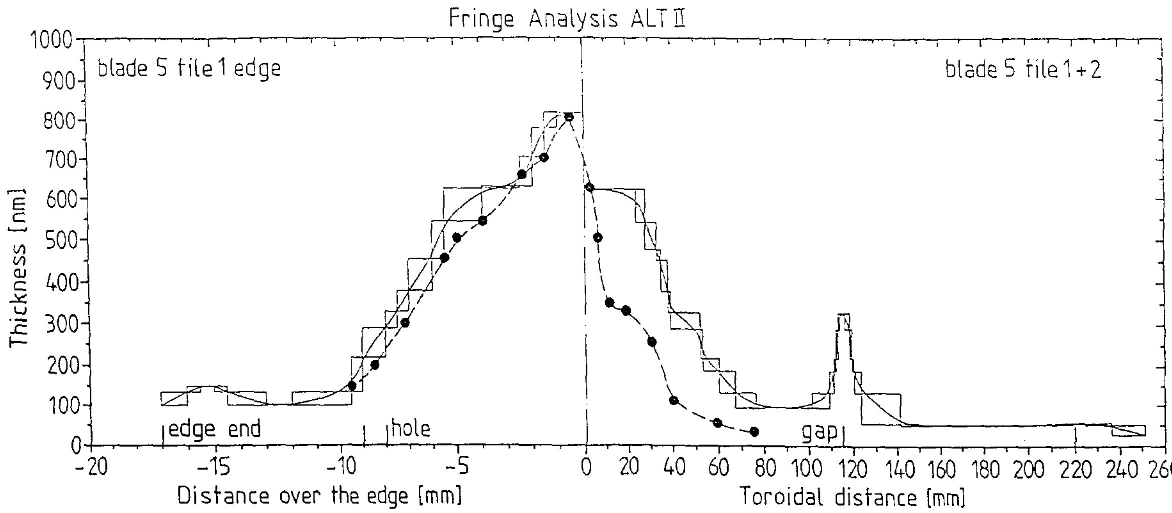


Fig. 3. Comparison of the deposition pattern as measured by colorimetric fringe analysis and electron probe micro analysis (EPMA) (full circles) along the line marked in Fig. 1. About 50% of the deposited layer consists of carbon.

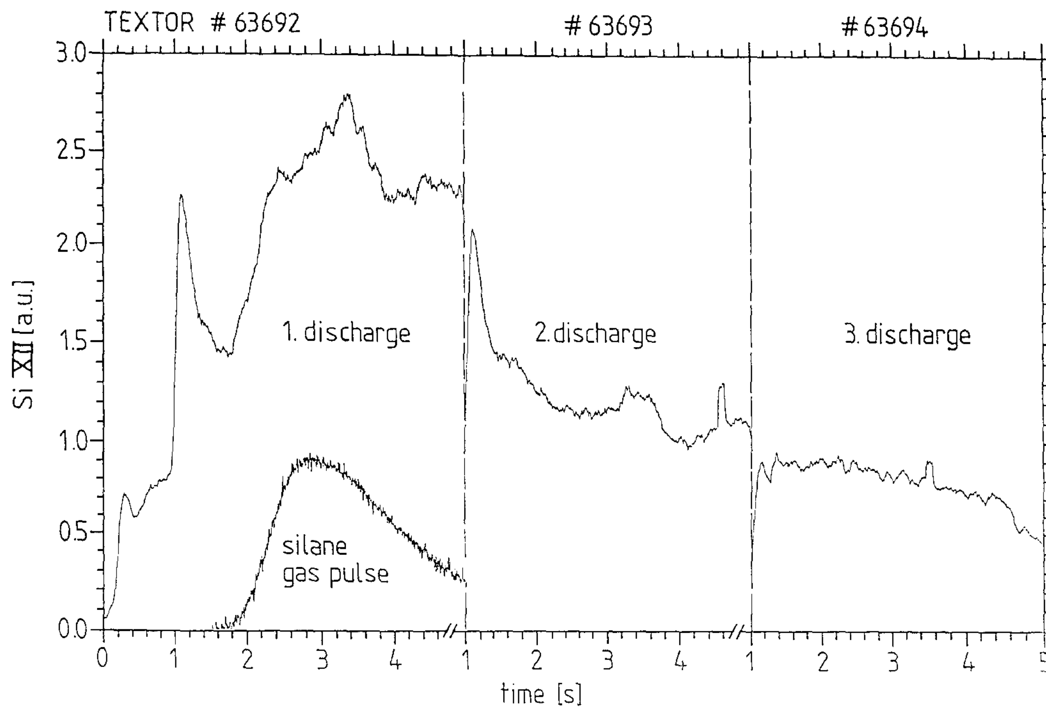


Fig. 4. Time development for the Si XII line intensity under neutral beam heated discharge conditions. The neutral beam is turned on at 1 s, thus resulting in a high Si erosion. At 2 s a silane pulse is injected. The pulse shape is shown as in the insert. The two following discharges lead to a reduction of Si XII to the level before deposition.

Fig. 2. Comparison of discharges with (62225–62229, 62234–62241) and without (62224,62230–62232) silane injection. Dashed lines with crosses: during silane injection; full line: steady state discharge conditions. (a) Relative CI to H, D flux at the limiter edge where silane is injected. (The dot–dashed line gives the average level without silicon layer.) (b) Relative CI to H, D flux about 75 cm away from the silane injection. (c) Relative CV line intensity normalized to the line averaged electron density.

edge increases from 7.8% to 30.0% as hydrogenated silane is used.

2.2. Deposition under strongly heated conditions

A series of silane injection with strongly heated conditions is performed. Before the first discharges two ohmic discharges with silane injection are made. According to the ohmic results presented in Section 2.1, about 70 nm of silicon layer should be deposited near the gas injection holes and about 15 nm in the average on the first four tiles of the limiter blade. The neutral beam co-injector is turned on at 1 s with a heating power of 1.4 MW. Fig. 4 shows the time evolution for the Si XII line intensity under neutral beam heated discharge conditions. The silicon XII line increases strongly when the neutral beam is turned on and falls off with a time constant of 0.8 ± 0.2 s. This suggests that the Si-layer is quickly eroded. At 2 s silane is injected during NBI heating conditions. The signal increases again and stays constant until the end of the heating period at 5 s. The next two discharges without silane are added in Fig. 4 on the same timescale. In discharge # 63693 the Si XII line again falls off with a time constant of about 0.8 s. The CV intensity reduction is about 6% as the reduction in ohmic conditions. After two NBI-heated discharges without silane-injection, the Si XII level is as low as before the first gas injection.

In the NBI and ICRH heated discharge (total heating power: 2.85 MW) the CV light intensity is slightly (about 3%) reduced. The Si XII intensity decreases with a time constant of 1.0 ± 0.2 s. As in the previous case the energy confinement time and the diamagnetic energy does not change within the error for conditions with and without silane deposition. The relative silicon content normalized to the line averaged density during NBI and ICRH heated discharges compared to only NBI heated discharges is about 15% higher. However, during silane injection this ratio varies around one.

For the co- and counter NBI heated discharges ($P_{tot} =$ 3.1 MW) only one discharge is made with silane injection. The line averaged density increases to $7 \cdot 10^{13}$ cm^{-3}. No significant increase of τ_E and E_{Dia} compared to the discharge without silane has been noticed. The additional heated discharges show some reduction in impurities.

3. Conclusion

In this study the edge of one of the toroidal belt limiter elements at TEXTOR-94 is covered by a silicon-layer on an area of 660 cm^2. The depositioning efficiency of silicon on this area is about 8.7%. In ohmic discharges there is a clear reduction of carbon light emission at the point of silane injection. The plasma contents of carbon, iron, chromium, and nickel are reduced due to the deposited layer. A rise time of about 6 s is deduced from the rise of the carbon I line intensity. This increase is not due to a strong erosion of silicon at the leading edge, but to redeposition of carbon impurities from the background plasma ions which impinge on the limiter [11]. The discharges are still dominated by carbon-impurities, as only one edge of one limiter blade out of eight limiter blades is modified. During the silane injection the CV intensity and the intensity of radiation from medium Z elements is strongly reduced as a radiating layer of silicon is built up. In strongly heated discharges the impurity content decreases. For steady state operation the amount of accumulated silicon has to be considered; however, this technique has potential applications for in-situ protection/repair of divertor erosion in ITER.

Acknowledgements

The authors would like to thank Dr. E. Graffmann, and Dr. G. Telesca for providing data and A. Hiller for technical assistance.

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