DEPOSITION AND EROSION OF SILICON IN STRONGLY HEATED DISCHARGES AT TEXTOR-94

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1. Introduction

The problem of power and particle handling will be a critical issue in future fusion devices. During the last years much effort has been put on finding solutions for reducing the pollution from erosion of plasma facing components and handling high heat loads. The control of the residual oxygen concentration seems to be essential to achieve fusion plasmas with high performance. Efficient ways to control impurities are different coating techniques like carbonization, boronization, and siliconization [1], which have been applied at TEXTOR. In this paper we propose to use the possibilities of additional coating onto wall, limiter, and divertors by an ”online” coating, which can be done during a discharge. Therefore, it should be suitable to employ this method in stellarators and long pulse tokamaks. If non recycling material like silicon is introduced into a discharge to coat exposed surfaces, radiation from this material will also occur, which can reduce the peak power flow. This can be even adjusted to improve the concept of a ”cold radiative mantle” [2] which has been demonstrated successfully at many fusion devices [3]. Besides special siliconization techniques [4,5], gas puffing through limiters has been practised to introduce silicon, mostly as silane (SiH_4). The local deposition efficiency of silicon is in the order of 5 – 10 %, however, as the remaining material is deposited elsewhere it reduces the amount of other impurities, mostly metallic, from the wall components [5,6]. Local as well as global effects of an ”online” or ”in-situ” techniques have to be considered. The different effects of the introduction of silane into a tokamak discharge under ohmic, additionally heated, and I-mode [7] conditions have been studied and the application of such a method will be discussed.

2. Experiment

The experimental conditions for the silane gas-puffing experiments are chosen in such a way that the conditions can be compared with most of the TEXTOR discharges. TEXTOR-94 is a medium size (R=1.75 m, a=0.46 m) tokamak. The standard value of the toroidal magnetic field is 2.25 T and the plasma current in ohmic discharges is usually 350 kA. In I-mode or RI-mode discharges [7] the current is often increased to 520 kA, in this experiment we apply 400 kA. The toroidal belt limiter ALT-II [8] is located 45^{o} below the horizontal midplane and consists of eight discrete blades covered with graphite tiles. One of the eight limiter blades has been equipped with gas injection tubes feeding 10 injecting nozzles located at the toroidal leading edge [5]. Usually the gas-injection starts at the beginning of the steady state phase of the current and after the start of the additional heating. The amount of injected silane depends on the plasma parameters. In case of ohmic discharges about 15 to 20 mbar l are introduced in

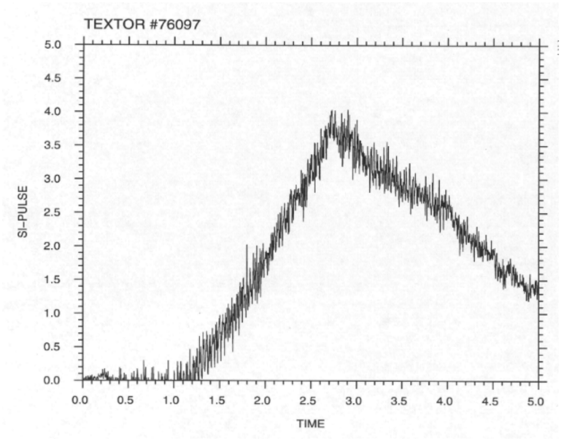

Figure 2: Typical silane puff into the TEXTOR-94 plasma as determined by the SiII line radiation.

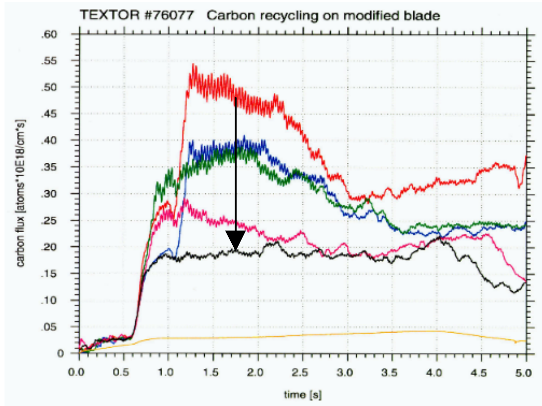

Figure 1: Reduction of the carbon flux recycling at the ALT-II limiter due to multiple injection of silane in subsequent discharges.

ca. 1.5 s. For heated and I-mode discharges the amount of silane could be increased to 60 mbar l. The pumping duct of the ALT-limiter blades have been equipped with 8 decomposers and Penning ion-gauges to handle the requirements of reactive gas operation. The front tiles of the modified blade as well as the centre of the blade are spectroscopically observed. The Si-XII emission light is monitored by a VUV-spectrometer.

3. Deposition and erosion under heat high fluxes

3.1. Variation of local plasma parameters

In a previous paper the main results of an ”in-situ” coating in TEXTOR during ohmic discharges have been compiled [5]. The deposition of silicon on plasma facing components (PFC) during tokamak discharges produces a hard, robust coating with the potential to protect the surface against erosion. Since the deposition efficiency of silicon on one modified limiter blade is of the order of only 5 – 10 %, the majority of silicon is deposited elsewhere, i.e. on the wall components and the other 7 limiter blades. This leads to a reduction of metallic impurities in the plasma as well. The erosion time, here defined as the time when the carbon flux at the local deposition point decreases exponentially to level as observed before deposition, extends to 5 – 10 seconds under these conditions. For the operation of TEXTOR-94 new limiter tiles with a thickness of up to 20 mm compared to previously 17 mm have been installed. Additionally the shaping of the tiles has been modified [9] in order to handle higher heat fluxes. The front limiter tiles include a toroidal taper to spread out the heat load that flows into the gap that exists between each blade. However, the previous results are confirmed with the new tiles. To increase the heat flux the plasma was slightly repositioned resulting in an erosion time of 3.5-4.5 seconds if all ALT-II blades are positioned at minor radius of 0.46 m. The electron temperature and density at this radius as measured by the He-beam diagnostic are 40 eV and 2 x 10^{12} cm^{-3} respectively. After two discharges of depositing silicon, two further discharges are performed to study the erosion process. The heat flux onto the modified limiter blade is increased up to a factor of 4 by inserting this blade into the discharge up to a minor plasma radius of 0.44 m. There the relative recycling carbon flux normalised to the deuterium flux increases locally by the same factors, whereas the local normalised silicon flux as determined by the Si-II emission light increases only by a factor of two. This reflects the mechanism of codeposited carbon onto the silicon layer [10]. The particle confinement time expressed by [11] $\tau_p = \lambda_{eff}\ a/2D_r$ (λ: effective average radial penetration depth ca. 4 mm [2], D_r: radial anomalous particle diffusion coefficient) is much shorter compared to the decay times measured during the experiment, the decrease of Si-XII mirror the erosion of silicon including possible codeposition processes. As only several percent of silicon are locally deposited the erosion time mostly reflects the reduction of silicon on the wall and other limiters (ca. 90% of the surface). The reduction in the Si-XII line emission can be described by an exponential decay, defining the erosion time. This decay time increases from 4. to about 5.5 s if the modified blade is inserted, as the heat flux onto the other components is reduced. The local erosion time of the primarily deposited silicon can be only determined with a high error and is reduced to 2.5 to 3 s.

3.2. Deposition and erosion in strongly heated discharges

A series of discharges with strongly heated plasma conditions has been performed. The silane is injected either in a separate ohmic discharge before the neutral beam heated discharge or in the same discharge during the heating phase. The erosion of silane is e.g. monitored by the change of the Si-XII intensity in the plasma. The Si-XII intensity rises strongly when the neutral beams are turned on. After this increase the line intensity decreases exponentially with a time constant of several seconds, depending on the heating power and electron density. By increasing the heating power from 1.3 MW to 2.6 MW the erosion time decreased from 3. s to 2.1 s. These results are higher as previously [5] because newly shaped limiter edge tiles have been introduced in TEXTOR-94 which should hold higher heat fluxes. As the erosion time of silicon amounts to several seconds, it seems possible to use this type of injection of additional impurities for simultaneous reduction of intrinsic impurities and plasma edge cooling. A series of discharges was performed with the same tokamak discharges parameters as for I and RI-mode conditions. Instead of neon, a puff of silane was introduced into the discharge. The gas pulse was spectroscopically monitored by the intensity of the Si-II light emission (Fig. 1). The line averaged density increases from 5 x 10^{13} cm^{-3} to 6.5 x 10^{13} cm^{-3} after the injection and stays constant. The carbon fluxes at the local point of injection as well as the carbon flux in the middle of the limiter blade are reduced by about a factor of more than two (Fig. 2). Also the oxygen flux is reduced when silane is injected. Simultaneously with the injection and deposition of silicon erosion takes place as it is reflected in the Si-XII light emission. In the following discharges the amount of silicon is reduced with a half time of about 2.4 s. After performing several NBI and ICRH heated discharges (P_{tot} = 2.6 MW) (Fig. 3) and injecting a total amount of ca. 800 mbar L silane (about 1.3 x 10^{22} Si atoms) into the

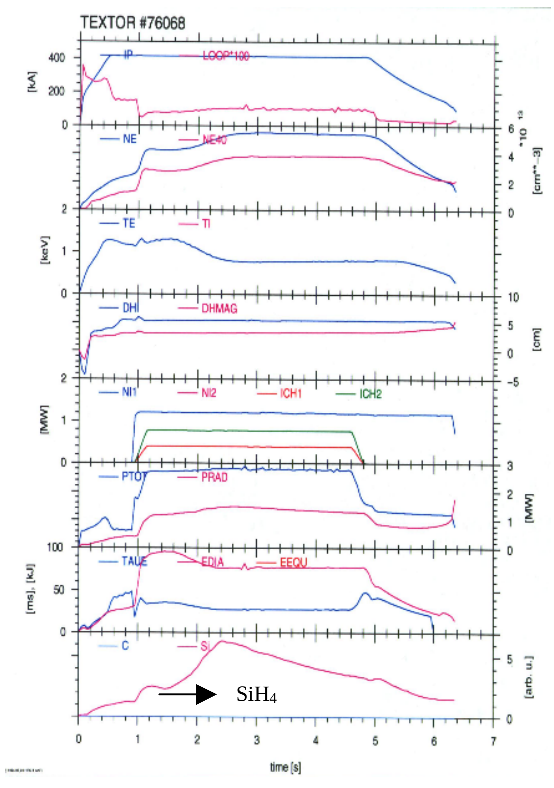

Figure 3: Global plasma parameters under I-mode conditions during injection of silane.

discharge the ratio of radiated power versus the total heating power increased from previously 0.35 to 0.55 (Fig. 4). Simultaneously the radiation is more uniformly distributed. However, the radiation decreases when the silane puffing is turned off and the total amount of silicon in the discharge decreases. The flux of recycling carbon increases together with the reduction of silicon. The Z_{eff} as determined from the conductivity and by charge exchange resonance spectroscopy [12] decreases from about 2.5 to 2.0. When silane is injected the diamagnetic energy content of the plasma is reduced from ca. 95 kJ to 75 kJ, and the improvement factor f_H is degraded from 0.8 to 0.6. One possible reason for the reduction is the release of H from the decomposition of SiH_4 during the discharge. This would be in agreement with the general observation that strong localised gas puffing is determinational for the confinement in the I-mode [13]. Even after the siliconization discharges the confinement is still degraded as no deuterated silane is used and the wall is loaded with hydrogen.

4. Discussion and outlook

Silane "in-situ" deposition could be used even under strongly heated discharge conditions to build up a radiative boundary and reduce the recycling flux of carbon, oxygen, and metallic impurities. However, it should be noted that as only one out of eight limiter blades was modified, carbon still dominates the radiation in the discharge. The lifetime of the deposition as determined by the reduction of silicon in the plasma is about 2 seconds for a total heating power of 2.8 MW. For steady state operation the accumulation of Si as well as on the wall as in the plasma core [14] has to be considered.

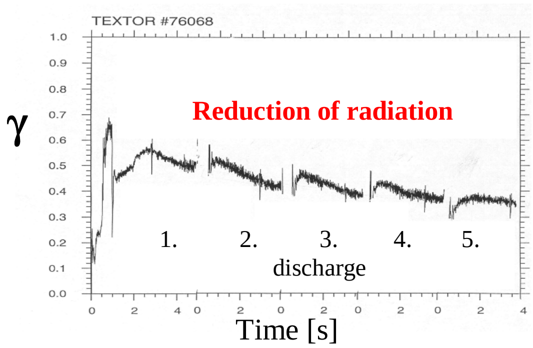

Figure 4: Reduction of the fraction γ of radiated power vs. total heating power after the turn off of the silane injection. (Several discharges are compiled in one figure.)

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