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Comparison of Boronization and Siliconization in ASDEX Upgrade

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The performance of a fusion device is limited by the impurity concentration, which is closely connected to the plasma wall interaction. Today the first wall of most tokamaks consists of graphite. For the control of the oxygen inventory additional coating by a thin layer of boron (boronization) is commonly used. Due to sputtering, however, the lifetime of this layer is restricted, i.e. the best performance lasts only a few high power discharges. In practice additional problems may appear due to toxical gases after venting of the vaccum vessel. To minimize the sputtering one has to use high Z rather than low Z material. On the other hand, contamination of the plasma with high Z material may lead to serious radiation losses. Based on the good experience at TEXTOR [1] we use for the first time in a divertor tokamak silicon for coating of the vessel walls. These experiments were also a pre investigation to examine the capability of high-Z material in the main chamber of a reactor relevant tokamak. High-Z material would be preferable because of the codeposition of hydrogen, carbon may have to be avoided in a fusion reactor [3].

Characteristics of the coating

The coating of ASDEX Upgrade is produced using a glow discharge with 90 % of He and 10 % of B_2D_6 respectively SiD_4. In contrast to most other experiments the film is deposited on a cold wall, which influences the deuterium contents of the coating [4]. During this procedure collection probes were exposed using a manipulator system. Surface analysing techniques show a typical thickness of 50 nm for the layer at the midplane and 0.2 nm in the divertor. Due to the small divertor slits the glow discharge does not reach the divertor plates. The boron layers consist up to 60 % of deuterium, the produced coating is soft and very reactive: after 24 h storage in air most of the deuterium is replaced by hydrogen. The silicon layer consists of 50 % deuterium, which is not replaced after 400 h at air. In contrast to the boronhydrid layer, hard and robust siliconhydrid layers were produced.

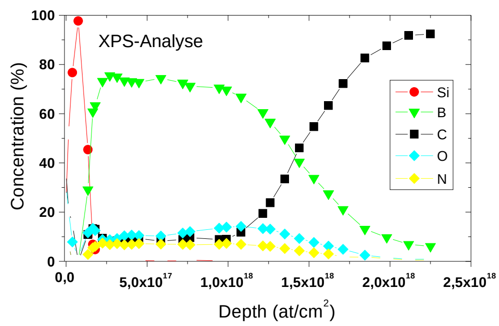

Fig.1: XPS depth profile of a tile showing 3 boronizations and one siliconization

Inspection of the vessel after venting shows a homogenous silicon layer at the outer wall. Erosion of the layer was only found at the ICRH protection limiter and the inner heat shield, which is used as limiter during current ramp up. One probe, which lasts for one experimental campain was analysed by X-ray photoelectron spectroscopy (XPS). This probe integrates the results of all coatings and the changes by the plasma discharges. The depth profile obtained is shown in Fig 1. The probe consists of graphite, on this we see a boron layer, which can be attributed to three consecutive boronizations. A constant fraction of oxygen, carbon and nitrogen is found throughout the whole boron layer, whereas no statement can be made on the deuterium content, because XPS is not capable to measure deuterium. At the surface we find the result of the siliconization. Although this layer is not as thick as one boronization, we find a region which consists only of silicon. At the surface carbon and oxygen are deposited. Because of the stability of this layer it was possible to reactivate it by glow discharge even after 4 months of venting and a start up without new coating was possible. This is very important for the test of tungsten tiles for the inner heat shield during the new experimental campain, which should be done without prior surface coating.

Plasma performance

For evaluation of the torus conditioning we use a ohmic density limit discharge which is performed at the beginning of each experimental day. This discharge consists of three phases: First a medium density phase, followed by a phase without gas inlet, to evaluate the pumping of the wall and finally a increase of the density to measure the density limit. Results showing the first discharge with a fresh boronization, a fresh siliconization and an old boronization are presented in Fig.2. The line averaged plasma density till t=2 s, the end of the first phase, is identical in all three cases, except limiter phase with higher radiation in the case of siliconization. With respect to the old boronization the density without gas inlet is 20% higher for a fresh boronization and 30% for the siliconzation, showing the strong decrease of the wall pumping for the siliconzation. This result is confirmed by the measured gas flux: to reach the same plasma density only 40% of deuterium flux is necessary for a fresh boronization and only 20% for a siliconzation.

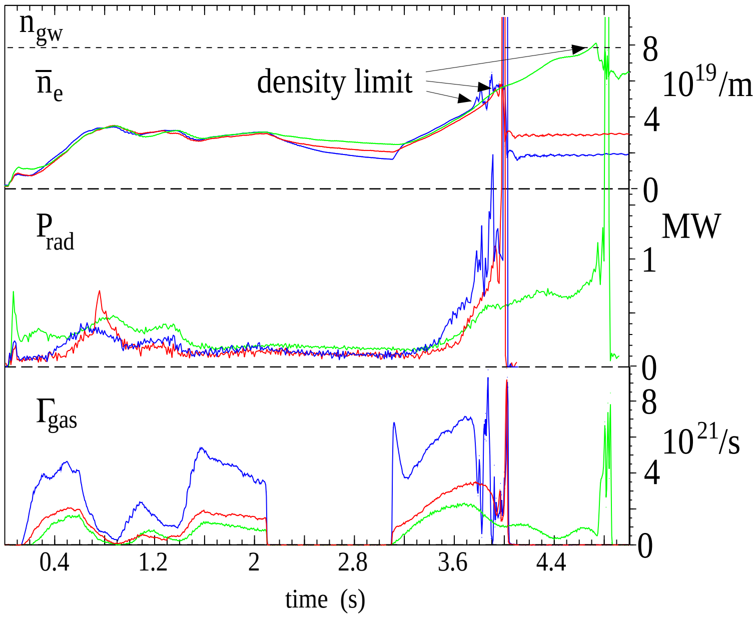

Fig.2: Ohmic discharge showing the difference of old boronization (blue), new boronization(red) and siliconization(green).

As found in TEXTOR [2] the density limit is strongly enhanced for a siliconization. For a fresh siliconization we find the highest ohmic density limit, normalized to the Greenwald limit, ever measured in ASDEX Upgrade. The density reaches the Greenwald limit, i.e. a factor 2 higher than for an old and 50% higher than a new boronization. This enhanced density limit lasted for 200 discharges in contrast to a fresh boronization, which lasts effect only 50 discharges.

Although these results are very promising, the coating must also be applicable to more reactor relevent scenarios. Silicon, as a mid-Z material, has the disadvantage of a higher radiation power, i.e. enhanced energy losses from the core plasma. As a possible side effect of this fact, siliconization was introduced in TEXTOR to enable an radiation improved mode plasma without adding impurities [2]. In contrast to this behavior the total radiation in ASDEX Upgrade is only slightly changed with siliconization as show in in Fig. 3.

Even for heating power up to 15 MW we find no differences for a boronization and the siliconization. This indicates that the siliconization enables the same performance as boronization. This is due to the fact, that the radiation of the silicon is negligible in spite of the radiation of carbon, with typical central concentration in the percent range. In contrast to TEXTOR, where up to 90 % of the input power is radiated after a siliconization, the maximal radiated power in ASDEX Upgrade is below 30 %. The profiles of the electron temperature and -density are not changed significantly after siliconization.

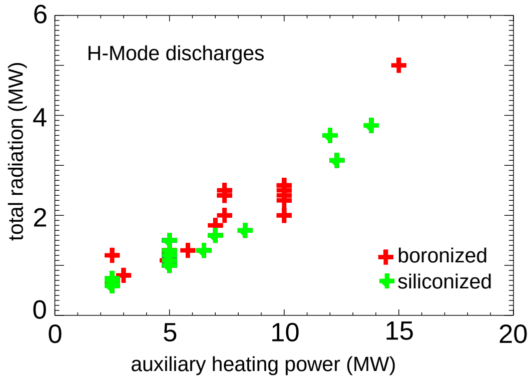

Fig.3: Radiated power for auxilar heated H-mode discharges

Impurity concentrations

During the first discharges after siliconization there was a strong reduction of the carbon content, which indeed was very transient. It is assumed that the rather fast increase of the carbon concentrations after siliconization was due to a strong carbon source at the ICRH protection limiters, where obviously high power loads were present and the silicon layer was removed very fast. Oxygen is removed very efficiently from the discharges. The effect is somewhat longer lasting than for a boronization.

The silicon fluxes into the plasma discharges were monitored spectroscopically at the inner heat shield and in the divertor in the visible spectral range. They were strongly density dependent and decreased for comparable discharges with the temporal distance to the siliconization. The influxes show a smooth variation across the inner heat shield with broad maximum in the equatorial plain and a strong increase towards the upper divertor region. During limiter operation the silicon concentration was found to be up to a factor 10 higher than during divertor operation with comparable discharge parameters (Fig. 4). During limiter operation the inner heat shield is exposed to a plasma of much higher temperatures compared to the divertor, which leads to larger erosion yields due to physical sputtering through deuterium. This observation is also in line with the

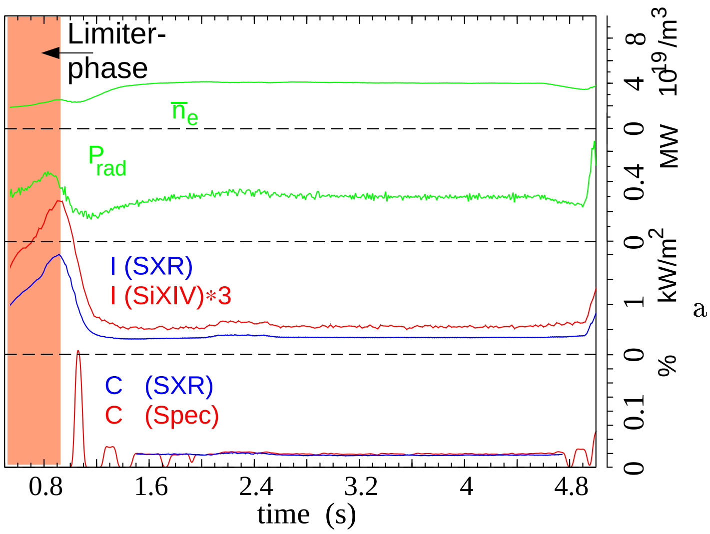

Fig.4: Silicon concentration for limiter and divertor configuration.

pronounced density dependence of the silicon fluxes, found in divertor operation, because higher plasma densities generally lead to lower edge temperatures and therefore to lower sputtering yields.

The silicon concentrations in the central plasma were also deduced spectroscopically, by measurement of the intensity of the Lyman-α line emission of H-like silicon and from Soft X-ray radiation profiles. In Fig. 4 the results of both methods are indicated as SXR for Soft X-ray and Spec for Lyman-α. The agreement of this independed methods is excellent. Again a strong decrease of the central concentration with increasing plasma density was observed. The concentration varied from about 2×10^{-3} in low density H-modes down to $\approx 10^{-4}$ for higher densities (see Fig. 5). In ohmic discharges the Si concentrations were even lower. The contribution of silicon to Z_{eff} is comparable to that of oxygen for a well conditioned wall. No accumulation of Si in the core plasma was observed and even for ITB discharges without sawteeth only slightly peaked concentration profiles were found. The generally low concentrations of silicon in the discharges explains the absence of any negative effect on the overall plasma performance as stated earlier, although during plasma startup, which is performed in limiter configuration the radiation was somewhat higher than for a boronized machine and consequently the loop voltage necessary for the current ramp was also increased, there were no problems with break down.

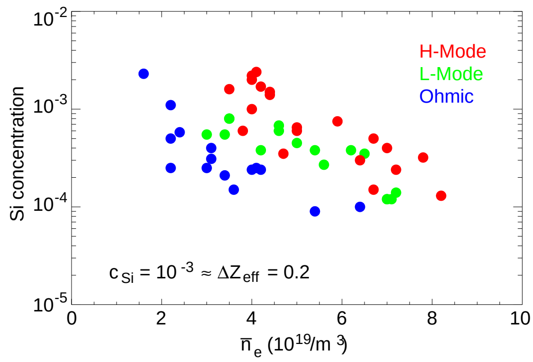

Fig.5: Core plasma silicon concentration for various discharges

An estimate shows that the observed silicon flux could not be explained by charge exchange atoms only. This is in agreement with the observed local erosion of the silicon layer. By optimizing the shape of these surfaces the silicon flux might be minimized further.

Summary and conclusions

In the divertor tokamak ASDEX Upgrade siliconization is a good alternative for boronization. The main advantages, beside the better performance in ohmic discharges, are the longer conditioning effect and less toxicidicy. Because of the low silicon core density observed, we find no significant increase of the total radiation or change in the plasma profile shapes. A reduction of the carbon influx was only temporary possible. The performance for high power discharges was not different from that after boronization. This enables the possiblity to use mid-Z and eventually high-Z materials, because of the lower sputtering rate in the main chamber of a divertor tokamak. Due to this graphite tiles of the inner heat shield of ASDEX Upgrade will be replaced by tungsten coated tiles in the near future. The possiblity to start the plasma after venting without a new coating will support these investigations.

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