Improved Plasma Performance in TEXTOR with Silicon Coated Surfaces

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Coating of the walls of TEXTOR with silicon has led to improved tokamak plasma performance. Very low concentrations of C, B, and O are measured. Radiation from silicon is located at the plasma periphery at $r/a \gtrsim 0.75$ and decreases with increasing plasma density. Density limits are enhanced by 30% as compared to boronized conditions; large density gradients and low electron temperatures at the edge (< 10 eV) are obtained. The improved confinement regimes observed earlier at low densities [$\tau_E = 1.7\times$ITER L 89-P (International Thermonuclear Experimental Reactor)] were extended to significantly higher densities in spite of a high radiative power fraction.

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Silicon and its compounds with carbon are of interest for use in present and future fusion devices. SiC is regarded as a candidate wall material in reactors particularly because of its rapidly decaying radioactivity after 14 MeV neutron irradiation [1]. Silicon atoms ($Z=14$) may also be effective in establishing a radiative plasma boundary. The largest power is expected to be emitted from the Li-like ionization level (Si XII), radiating at an electron temperature of about 250–300 eV, which is near the plasma edge in TEXTOR. Silicon atoms have a large sticking probability on the wall surfaces and are practically nonrecycling.

The bond energy per oxygen atom $\Delta G/O$ in SiO_2 is a rough figure of merit for the potential of silicon to getter oxygen plasma impurities. Its value of $\Delta G/O = 428$ kJ/mole is between that of beryllium (581 kJ/mole) and that of boron (397 kJ/mole) [2], which have both demonstrated their high gettering efficiency in tokamak devices: Be evaporation in JET [3] and boronization in TEXTOR and other machines [4]. Thus silicon is expected to provide good control of oxygen plasma impurities, which is regarded as essential for high performance discharges.

The viability of using Si as a medium-Z wall material in fusion devices will, among other factors, depend on the quantity and location of radiated power fraction, plasma impurity production, and plasma dilution during quasistationary discharges. To address these questions, initial experiments have been performed in TEXTOR with silicon covered inner wall surfaces.

A new plasma assisted coating procedure was developed (*siliconization*). The process is similar to carbonization [5] and boronization [6] and uses a radio frequency assisted dc glow discharge [7] in a throughflowing SiH_4-He gas mixture. The deposition method is described elsewhere in detail as are the qualification of the films with respect to their chemical and physical properties, chemical erosion, and oxygen gettering capacity [8]. Depth profiles of the film composition on specimens exposed in TEXTOR during siliconization show that they consist of pure silicon and hydrogen.

Ohmic and neutral beam heated tokamak discharges (1.5 MW hydrogen coinjection, if not otherwise stated) with hydrogen and deuterium gas fueling have been analyzed. The values of plasma current I_p and toroidal field B_t have been 360 kA and 2.25 T, respectively. The TEXTOR device and its in-vessel components are described in detail elsewhere [9]. The major radius of TEXTOR is 1.75 m. The minor plasma radius $a=0.46$ m was defined by the pumped toroidal belt limiter ALT-II, equipped with graphite tiles.

Although the siliconization layer contains hydrogen due to its preparation from SiH_4, tokamak discharges with $D/H+D > 0.8$ have been readily obtained by gas puffing of D_2. Density control was easily achieved because of a pronounced wall pumping. The aspects of hydrogen recycling and isotope effects will be described separately in a forthcoming paper.

Tokamak discharges made after the siliconization are characterized by significantly reduced boron, oxygen, and carbon impurity levels as compared to the already low values of a well boronized TEXTOR wall. As an example, the flux ratio Γ_O/Γ_H of oxygen and hydrogen atoms at the ALT II limiter blade is shown for siliconized and boronized wall conditions in Fig. 1 as a function of the line averaged central density $\bar{n}_e$ for neutral beam heated plasmas. At $\bar{n}_e > 5\times10^{19}$ m^{-3} the value of $\Gamma_O/\Gamma_H = 0.75\%$ is well below that of boronization and only weakly dependent on density. This low yield is due to the high bond strength of O to Si and due to the low plasma edge temperatures at the high densities. The steep increase in oxygen at low $\bar{n}_e$ is induced by an increased sputtering of SiO from the surfaces (see below), which leads to increasing plasma dilution, further decreasing Γ_H. A similar trend is observed for the carbon fluxes at the limiter. The line intensities of O VI and C V measured in hotter plasma zones show reduction factors between

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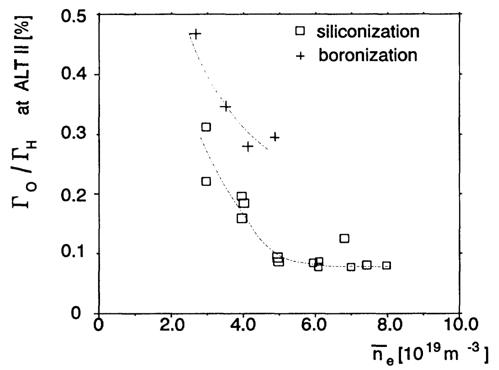

FIG. 1. Flux of oxygen atoms Γ_O normalized to that of hydrogen Γ_H as a function of line averaged central electron density for hydrogen discharges with 1.5 MW neutral beam heating under siliconized and boronized wall conditions.

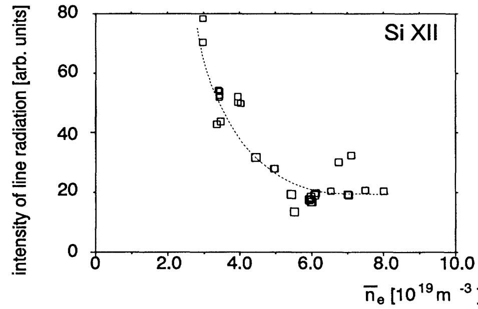

FIG. 2. Intensity of the Si XII line radiation as a function of line averaged central electron density for discharges with 1.5 MW neutral beam heating.

siliconization and boronization of 8 and 20, respectively. The reduction of the carbon impurity level is, on the one hand, due to the coverage of the surface by silicon and, on the other hand, due to the low oxygen concentration in the plasma.

The dominant plasma impurity is silicon. The density dependence of the Si XII line intensity (Fig. 2) suggests that Si is released from the limiter via sputtering processes. For a given heating power, the plasma edge temperature and thus the kinetic energy of incident particles increases as the density is decreased. The consequence is a strongly enhanced sputtering yield at low $\bar{n}_e$. Chemical erosion processes obviously do not play an important role. Their yields depend only little on energy. Chemical impurity production would increase with the hydrogen fluxes, i.e., with increasing plasma density which is not observed in our case.

Previously, the coupling of large ion cyclotron resonance heating (ICRH) powers into machines with metal surfaces of medium Z has been very difficult. With the availability of low Z wall surfaces by, e.g., boronization, the full available heating powers can be launched routinely into the plasma. In spite of the relatively high atomic number of silicon ($Z=14$) the operation of ICRH up to the highest available power levels in TEXTOR (4 MW) is comparable in ease and quality to that with boronized walls.

The above picture on impurity release is consistent with the radiation from the plasma. Figure 3 shows the fraction $\gamma = P_{rad}/P_{tot}$ of total radiated power P_{rad} related to the input power P_{tot} as a function of the line averaged density for beam heated hydrogen discharges. At low densities around 2×10^{19} m^{-3} the value of γ is of the order of 60%, decreasing to 30% at densities $>5\times10^{19}$ m^{-3}. The same trend is observed for Ohmic discharges. It has also been observed that the convected power flux to the limiters as measured by infrared thermography increases as the radiated fraction decreases. Usually P_{rad} is found to be proportional to $n_e n_{imp}$, where n_{imp} is the density of impurity atoms. The expected increase of P_{rad} with n_e is overcompensated in the case of siliconization by the strong decrease of silicon impurity release (see Fig. 2), leading to a net decrease of the radiation level.

The radial profile of P_{rad} is shown in Fig. 4 for a discharge heated by simultaneous co- and counter-neutral beam injection (1.5 MW each) and for an Ohmic discharge. The radiation is located at the plasma periphery and has, as expected, its maximum (in Ohmic discharges) at $r=0.35$ cm ($r/a=0.75$). In discharges with additional heating the maximum is shifted further outward because of the steeper temperature gradients. No trend towards centrally peaked radiation was observed even during long (2 s) neutral beam heated plasma phases. Assuming fully stripped Si atoms as the only central plasma impurities the measured enhancement of the soft x-ray continuum indicates central silicon concentrations of 0.1%. This is consistent with values of the central Z_{eff} (from conductivity) below 1.2 for $\bar{n}_e>5\times10^{19}$ m^{-3} for neutral beam heated discharges. These features of significant edge radiation, the absence of radiation from the plasma core, and very low central silicon concentrations render silicon an interesting candidate for the establishment of stationary radiative plasma edges.

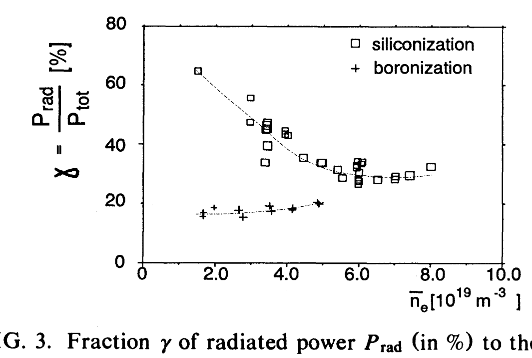

FIG. 3. Fraction γ of radiated power P_{rad} (in %) to the total input power P_{tot} as a function of the line averaged central electron density for 1.5 MW neutral beam heated discharges.

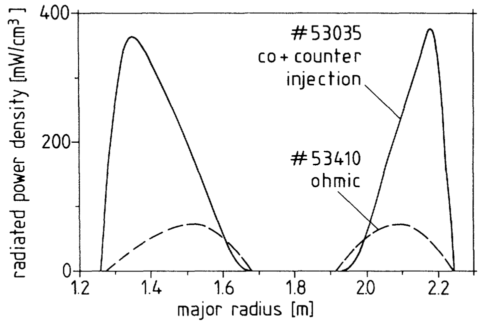

FIG. 4. Radial profile of the radiated power density for discharge No. 53035, heated by simultaneous co- and counter-injection of deuterium neutral beams (1.5 MW each), and for an Ohmic discharge, No. 53410, both during the current flat top phase at 1.4 s.

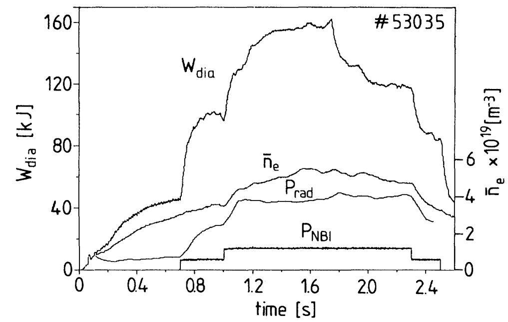

FIG. 5. Time traces of stored energy W_{dia}, line averaged central electron density $\bar{n}_e$, total radiated power P_{rad} and total injected neutral beam power P_{NBI} for discharge No. 53035 (see also Fig. 4). The radiated power fraction $P_{\mathrm{rad}}/P_{\mathrm{tot}}=0.6$ at $t=1.75$ s. A transition to a mode of increased confinement is seen around 1.14 s. The confinement relaxes again at 1.75 s and at 1.93 s.

After siliconization new increased density limits were observed. Line averaged densities of 8×10^{19} m^{-3} were reached for discharges with 1.5 MW neutral beam heating. This corresponds to a value of the Murakami parameter $\bar{n}_e R/B_t=6.2$ at $q=3.9$, which is an increase of almost 30% with respect to a boronized machine [4]. The low impurity level is probably responsible for this improvement. The attainable density appears to be limited rather by the available heating power than by MHD-like events. In almost all cases, also in Ohmic discharges, the occurrence of a poloidally asymmetric intense radiation zone on the high field side (MARFE) is observed at the highest densities while γ is still well below unity. This shows clearly that the density limit is not due to global plasma radiation exceeding the global input power but rather due to localized strong radiation (MARFE). Density profiles $n_e(r)$ were deduced from the nine channel HCN laser interferometer up to $r=0.4$ m and from the thermal He beam diagnostics [10] for 44.5 cm $< r <$ 49 cm. The profiles for beam heated plasmas in the L mode at $\bar{n}_e\sim(7\text{–}8)\times10^{19}$ m^{-3} were observed to be very flat in the center. The edge denisty gradients inside the last closed flux surface are steep. Values of $n_e(46)=1.6\times10^{19}$ m^{-3} were measured at the last closed flux surface at $r=0.46$ m. The electron temperatures $T_e(46)$ measured by the thermal He beam under these conditions are less than 10 eV, approaching the regime of a high recycling edge plasma.

Discharges with improved confinement (1.7×ITER L 89-P scaling) have been previously observed in TEXTOR [11,12]. The confinement deteriorated with increasing densities, however. Siliconization has significantly extended the density range at which high confinement discharges can be obtained towards higher values ($\bar{n}_e=5\times10^{19}$ m^{-3}). Peak densities $n_e(0)=1.4\times10^{20}$ m^{-3} have been obtained. Slow feedback controlled ramping of $\bar{n}_e$ by external gas puffing in the presence of neutral beam injection has proven to be important. Figure 5 shows the time traces of the stored plasma energy W_{dia} (from diamagnetic loop), of $\bar{n}_e$, and of the injected neutral beam power for a discharge with superimposed co- and counter-neutral beam injection (1.5 MW each). At $t=1.14$ s a change in slope of W_{dia} is observed, giving rise to a stored energy which is about 30% larger than previously observed for the same conditions (I_p, B_t, $\bar{n}_e$, P_{tot}) in a boronized environment. At $t=1.75$ s this high confinement regime relaxes to a regime in which τ_E is still well above L-mode scaling. A second relaxation of confinement occurs at about 1.93 s. As seen from the evolution of the density profiles in Fig. 6, a peaking of $n_e(r)$ is associated with the transition at 1.14 s. Beam fueling contributes to only about 10% of the total density increase, which is largely due to the continuous external gas puffing and due to increased particle confinement. The electron temperature profiles were measured by emission of electron cyclotron radiation. They are found to be peaked and essentially triangular in shape with a peak value $T_e(0)=2.3$ keV at 1.4 s. The corresponding cen-

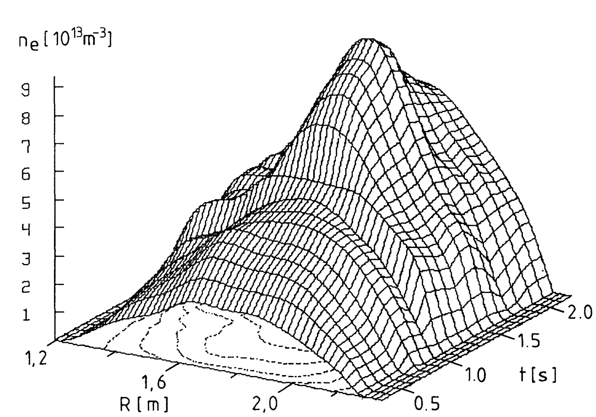

FIG. 6. Evolution of the electron density profile of discharge No. 53035.

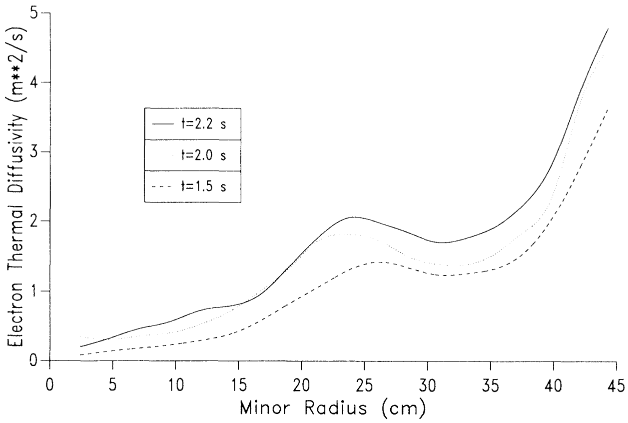

FIG. 7. Radial profiles of the electron heat conductivity $\chi_e(r)$ during three different confinement states of discharge No. 53035: $t=1.5$ s (high confinement phase), $t=2.0$ s (after the first relaxation), $t=2.2$ s (after the second relaxation).

tral ion temperature from charge exchange emission spectroscopy (CXES) is 2.7 keV. Complete stabilization of sawteeth occurs after $t=1.14$ s. The stable phase ends with the relaxation of confinement at 1.75 s, accompanied by a crash of the temperature. Radiation profiles during the high confinement phases (already shown in Fig. 4) do not exhibit centrally peaked features indicative of impurity accumulation. This is consistent with the measurement of the highest neutron yields ever observed on TEXTOR at these densities. The duration of the high confinement phase may still be too short, however, to give clear evidence for impurity accumulation. A first transport analysis using the transport code TRANSP [13] yields electron heat conductivity profiles $\chi_e(r)$ as shown in Fig. 7. In the high confinement phase (curve at $t=1.5$ s) χ_e gradually increases from the center to a minor radius of about 25 cm where it reaches a value of about 1 $m^2 s^{-1}$, exhibits a shoulder, and increases further towards the edge. After the first relaxation (trace at $t=2.0$ s), χ_e is increased by about a factor 1.5 almost everywhere, whereas the second relaxation (trace at 2.2 s) leads to enhanced electron heat transport mainly in the outer half of the plasma. It should be pointed out that the shape and absolute values of the χ_e profiles resemble very closely those of Tokamak Fusion Test Reactor (TFTR) supershots [14]. The value of the normalized β at the first relaxation in confinement is $\beta_n=(\beta_t a B_t/I_p)\lesssim 2.0$ (β_t is the toroidal β). This value is similar to the critical β_n in TFTR supershots [15]. Assuming that the ion heat conductivity χ_i equals χ_e, agreement within 10% is obtained for the measured energy content and the central ion temperature measured by CXES, indicating that ion and electron channel contribute in the same way to the energy transport. When comparing high confinement discharges with silicon edge radiation to those with smaller radiated power fraction (~25%) obtained in a boronized vessel, no significant difference of the current profiles could be identified within the accuracy of TRANSP calculations.

Because the density limits found with siliconization appear to be due to the finite power flux into the edge plasma, even higher densities might be obtained with larger heating power if one succeeds to burn out MARFES. The very high density plasmas with conditions close to those of a high recycling edge may provide power removal by low energy particles as an additional option compared to edge radiation. Very strong pumping of the ALT II pump limiter has been observed under these conditions. The improved confinement regimes at high densities were obtained in the presence of strong simultaneous gas puffing and edge radiation. This is contradictory to the notion that a low density of neutral particles in the edge and low radiation levels are a prerequisite for obtaining high confinement modes. Further experiments and analysis will be necessary in the future to reveal the driving mechanisms.

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