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Effects of wall titanium coating on FTU plasma operations

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Introduction

The first walls of the vacuum chamber of the FTU tokamak are made of high Z materials. Stainless Steal is used for the vacuum chamber, Molybdenum (TZM) for the internal toroidal limiter and Inconel for the poloidal limiter. Their behaviour as plasma facing components has been quite well characterized on FTU in the past [1] and compared with that of a low Z material as silicon [2]. The main result was that for well conditioned discharges high density plasmas ($\bar{n}_e \geq 2.0\times10^{20} m^{-3}$) with $Z_{eff} \approx 1$ can only be achived with fully metallic plasma facing material. At lower densities, however, it is impossible to work with clean plasmas, as instead required by some experimental programs, like Lower Hybrid Currend Drive and Ion Bernstein heating.

To optimize the operations of FTU in the whole range of density $0.3 \leq \bar{n}_e \leq 3.0\times10^{20} m^{-3}$, (up to 6×10^{20} m^{-3} with pellet), and also to complete the study of the plasma properties in presence of different plasma facing materials, film deposition of titanium and boron on the FTU first walls has been planned. These materials in fact are very suitable for their chemical property to form tight bonds with oxygen and carbon which constitute the main contaminants on FTU. It is to point out that Ti oxide is less reduced in hydrogen than the other oxides which can be present on our machine. The standard free energy ΔG_0 for the reaction $TiO+H_2 \rightarrow Ti+H_2O\uparrow$ is in fact 2.4 eV against 1.3 eV relative to the reduction of Cr_2O_3 which is a metal oxide more stable than NiO FeO and MoO [3].

An important factor for the quality of the deposited films, and hence for the effects on both the scrape off layer (SOL) and the core plasma, is the need to maintain the FTU walls temperature at ≈77 …K. Indeed it is well known that the Ti film properties of pumping hydrogen particles and ligth Z impurities (C,O) are strongly nnaffected at cryogenic temperatures.

In this paper, the effects of ÒtitanisationÓ on the plasma properties will be shown after a brief description of the experimental apparatus and the Ti deposition procedure. At the end the conclusions will be drawn.

Experimental Apparatus and Deposition Procedure

The titanium deposition on the FTU first walls is performed by using two Ti sources mounted on a Conflat flange equipped with three sublimation filaments which can be inserted up to the centre of the vacuum chamber from two ports toroidally displaced by 120¡. With this geometrical configuration a fraction of about 85% of the vacuum vessel area is covered by titanium. From other experiments, a significant decrease in the oxygen impurity content up to a factor 2 was already obtained with no more of 50% of the surface area covered by titanium [3].

A high pumping speed is foreseen when the titanium deposition and subsequent operations are performed at cryogenic temperature [4] and very good adhesion to the substrate is obtained. Typical pumping speed ranging from 6 to 14 l $s^{-1}cm^{-2}$ have been measured for H_2, N_2, O_2, CO, CO_2, H_2O. It appears that the effect is due to the

microscopic crystalline form of the titanium film formed at low temperature, which presents a greater sorption area and capacity. An other important feature of cold titanium layers is the saturation which corresponds to a capacity of about 10^{16} molecules/cm^2 or a few monolayers. However, in the case of hydrogen, if the flux is maintained sufficiently low (<3×10^{-2} Torr l sec^{-1}) or with pulsed flow separated by long enough time intervals, the titanium film is able to absorb higher amount of H_2.
On these bases, to limit the hydrogen absorption, frequent and very short titanisations are performed during experimental campaigns with the wall temperature ranging between -185¡C and -160¡C. Typically about 10 in 10 min are deposited on the walls after 5-10 pulses.
The pumping effect of Ti is clearly shown in fig.1 where the temporal evolution of pressure inside the machine is plotted during the time interval between pulses. The ON—OFF arrows indicate the beginning and the end of the 2 titanium depositions applied for 20 min and 5 min respectively. The pumping effect is evidenced only after the first one indicating that the fraction of vacuum chamber exposed to titanium has been fully covered. On the mass spectrometer only hydrogen is visible because all the other gases are normally condensed on the cryogenic walls.
The estimated value of pumping speed for H_2 is about 1.0×10^5 l/s against 5300 l/s of the turbomolecular pumps.

Plasma Results

To evaluate the effects of titanisation we have compared the results obtained before, immediately after and further after the Ti film deposition for plasma discharges characterized by a medium electron density (0.7×10^{20}m^{-3}), plasma current of 0.5 MA and magnetic field of 6 T.
The first indication of the very good properties of titanium as getter for oxygen and as a protection against sputtering of metals from the limiters is the strong reduction of about a factor 2 of the impurity concentrations inside the plasma as measured by UV spectroscopy (see Table 1). The decrease of low Z impurity content is also supported by the evolution of the visible spectra, which show that both fluxes of O and C are drastically reduced (up to a factor 4), whereas the Ti lines are very well observed. With titanium on the walls a strong variation of the plasma radiation properties are observed. The radiated power fraction decreases from about 90% to 65% and also the radial profile of the radiation losses changes according to the impurity modifications. In fig. 2 the emissivity drops more than a factor 3 at the edge which is consistent with the strong reduction of the light impurities, which radiate preferentially in the plasma periphery.
According to these observations also a remarkable reduction of Z_{eff} from 3.5 to 1.6 is measured from the intensity of bremsstrahlung radiation in the visible range.
Another interesting effect following titanization is the larger electron density (up to a factor 4) which is measured in the SOL by Langmuir probes located in different poloidal positions (fig. 3).
This last effect has a strong impact on impurity production because it leads to a reduction of the physical sputtering yield for metals thus reducing the impurity flux into

Table 1 Impurity concentration before and after titanisation

Concentration	Before titanisation	After titanisation
Oxygen	1.5×10^{18}	9.5×10^{17}
Iron	2.0×10^{16}	1.0×10^{16}
Nickel	3.5×10^{16}	2.0×10^{16}
Molybdenum	2.0×10^{16}	9.0×10^{15}

the plasma. The Z_{eff} value is systematically lower after titanisation over the whole density range explored. This result is also explained combining the two actions of the Ti film: first it changes the atomic number Z of the main impurity from 42 (Mo) to 22 (Ti), second it acts as an efficient getter for oxygen and carbon, which can increase the sputtering yield.

With regard to the density limit we find it to occur at very similar values before and after titanisation if we look at the central chord average density. However, after titanisation the density profile is systematically broader than before, expecially in the vicinity of the density limit. This is clear if we compare the ratio of densities measured by DCN interferometer on the central chord and on the more peripheral chord (at the relative radial position r/a=0.82) respectively. This value changes from 2.5 to 1.5 after titanisation confirming that the edge density more than the central chord average density is important for the density limit. This interpretation has been already supported in the past on FTU to explain the apparent lack of dependence of the density limit on the plasma current [5].

The main evidence of the pumping effect following titanisation is the higher amount of gas (about a factor 2) required to reach and to maintain the preprogammed plasma density. A flux of 5.3×10^{20} part/s for 1.5 s of plasma duration is required to have $\bar{n}_e=0.7\times10^{20}m^{-3}$. On the contrary before titanisation a very low particle flux of $2.6x10^{20}$ part/s is necessary to maintain the same density indicating a wall status closed to the saturation.

During all the series of discharges after titanisation a progressive reduction of the Ti pumping effect is observed. It is evidenced from the time evolution of the H_α emission close to the walls for subsequent plasma discharges. H_α signals are a measure of the neutral gas which is released by the surface of the titanium film and they show a very steep increase at times which become progressively closer to the beginning of the discharges. This phenomenology is a clear indication of a gradual saturation of the Ti layer which pumps hydrogen until all the available absorption sites have been filled. For these shots a progressive increase of the electron density at the boundary plasma and a broadening of the density profile (see fig. 4) is observed. In particular a strong increase of H_α emission at about 0.4 s occurs for the last shot and a Marfe develops at the high field side of the tokamak. At the same time the CIII and OII visible lines increase again up to levels which are very similar to those existing before titanisation. However, for all these shots no variation of bremsstrahlung emission from the central plasma is observed and also the Z_{eff} value does not change. This fact is probably due to the screening effect of the dense boundary plasma which limits the impurity influx into the plasma centre.

For this series of shots after titanisation only a small fraction of the input gas is found in the discharge as plasma, i.e. the ratio between the total particle content and the time integral of the injected gas is sensibly smaller than unity. The lowest value of 9% is found immediately after titanization due to the strong wall pumping effect and the highest of 13% in the last shot where the saturation of the titanium layer is reached. This last value is lower than that obtained before titanization (20%) because of the reduced SOL trasparency, caused by the higher edge density.

Conclusions

Titanium layers deposited on the first wall of FTU efficiently reduce the oxygen concentration inside the plasma of a factor 1.6 starting from 1.5×10^{18} m^{-3}. The Z_{eff} value decreases from 3.5 to 1.6 at $\bar{n}_e= 0.7\times10^{20}m^{-3}$ and it is systematically lower after titanisation over the whole density range explored; for $\bar{n}_e\leq0.5\times10^{20}m^{-3}$ where the release of metals by physical sputtering is the dominant process, two actions of the Ti film must be considered: first it changes the atomic number Z of the main impurity from 42 (Mo) to 22 (Ti), second it reduces the temperature at the plasma edge thus reducing the sputtering yield of metals. For $\bar{n}_e \geq 0.5\times10^{20} m^{-3}$, where the release of light impurities is the dominant process, the main feature of Ti of gettering oxygen and carbon becomes effective.

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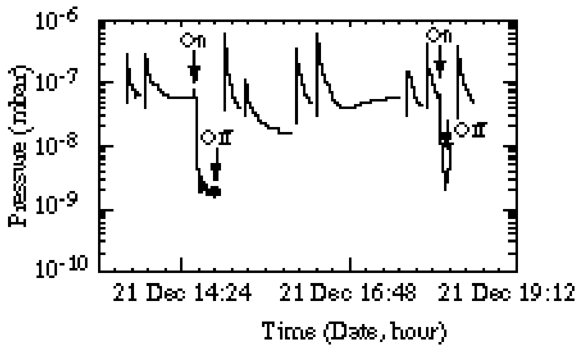

Fig. 1. Temporal evolution of pressure inside the machine during the time interval between pulses.

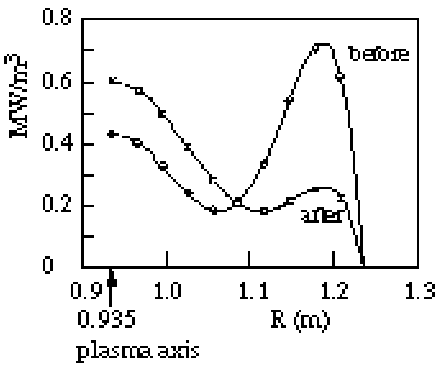

Fig. 2 Radial distribution of the radiated power before and after titanisation.

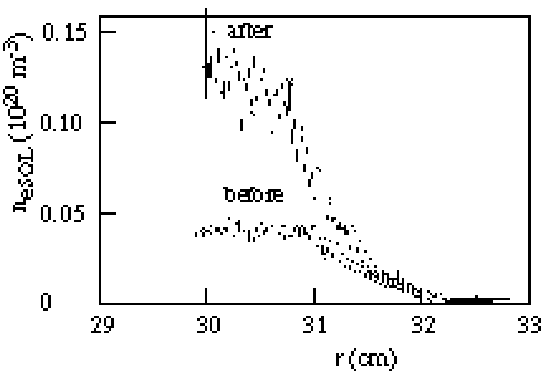

Fig. 3 Experimental profile of electron density in the SOL as a function of the minor radius before and after titanisation.

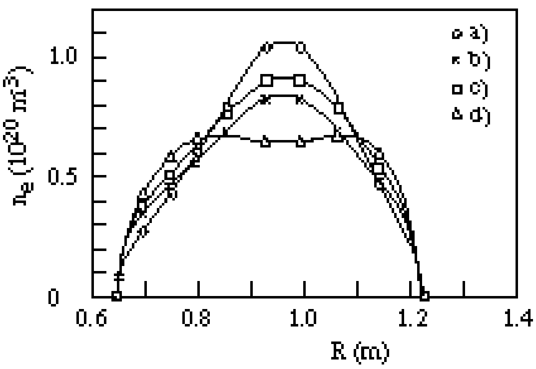

Fig. 4 Time evolution of the electron density profile starting from: a) before titanisation, b) just after titanisation, c) after 8 shots, d) after 11 shots when Ti film is fully H-saturated.