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The first results of siliconization on SWIP-RFP device

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Abstract

The first results of reversed field pinch (RFP) and ultra low safety factor (ULQ) plasma experiments with siliconization on SWIP-RFP device are presented in this paper. The siliconization decreases the impurity concentrations in the plasma and increases the configuration sustainment time. Ion temperature has been estimated with the CV line of the visible light spectra and the broadening of CIII lines in vacuum ultraviolet (VUV) region. The anomalous ion heating as well as the anomalous resistance were observed.

Keywords: Cladding materials; Coatings and coated particles; Experimental techniques; Silicon and silicon compounds; Surface effects

1. Introduction

A few methods of wall conditioning have been performed to improve the plasma properties in RFP devices [1-4]. The wall conditioning has been performed with moderate baking and glow discharge cleaning in the EXTRAT2 [5]. To reduce the carbon and oxygen content in the plasma, the first walls of the RFX [6], MST [7] and REPUTE-1 [8] devices have been boronized. A new coating technique of plasma facing surfaces of fusion devices, siliconization, has been developed and applied to the TEXTOR tokamak. Similar to carbonization and boronization, siliconization uses a radio-frequency assisted dc glow discharge in through flowing reactive gas (SiH_4-CH_4-H_2 mixture) [9]. The pulsed discharge cleaning, carbonization and titanium gettering have been carried out for wall conditioning on SWIP-RFP device [10,11]. The preliminary results of RFP and ULQ plasmas experiments with siliconization are given. The vacuum chamber of SWIP-RFP ($R/a = 0.48$ m/0.1 m) was made of stainless steel with 34 molybdenum limiters, it was welded with 8 bellows sections with 0.4 mm thickness and 8 straight sections with 1 mm thickness.

2. Experimental results

The inner surface of the chamber wall was covered with a thin silicon layer using in situ plasma assisted chemical vapor deposition, namely siliconization. Silicon and its compounds with carbon (i.e. SiC) are of interest to be used in the fusion devices because the siliconization restrains impurities more efficiently.

During siliconization, total gas pressure was $P_0 = 0.66$ Pa with the proportion of $(SiH_4 + He):H_2 = 3.5:3$, in which $SiH_4:He = 1:9$. The plasma power from capacity bank for every pulsed discharge was about 25 MW and lasted about 10 ms in total during siliconization.

The line of H_α and the line radiation intensities of the impurities (CIV, CIII, CII, CI, OV, OIV, etc.) and spectra were observed for RFP discharges at $P_0(H_2) = 0.54$-0.66 Pa and plasma current $I_p = 80$-120 kA. After siliconization, the plasma current duration increased. The analyses of the data obtained from the E-498 visible spectrometer and the VUV spectrometer showed that after siliconization, all impurities were reduced except silicon impurity. The radiation of impurities obtained from the VUV spectrometer was reduced. Mo was reduced by 20%, Fe, Ni, Cr, Cu, etc., were reduced by 60%, O and C were reduced by 22% and 20%, respectively, but silicon impurity was increased. The typical impurity concentrations obtained with visible

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light spectrometer typically are: carbon about 2–4%, oxygen about 1–2%, nitrogen about 0.5–1% and other light impurities less than about 0.5%. The heavy impurities were less than about 0.1%, normally. The wall carbonization was normally finished with the proportion of CH_4:H_2 = 5:1 and total gas pressure $P_0 = 0.45$ Pa, after carbonization, Mo was reduced by a factor of 30%, Fe, Ni, Cr, Cu, etc., were reduced by a factor of 12%, C and O were increased by the factors of 15% and 8%, respectively.

Fig. 1 shows the waveforms of an RFP discharge; (a) the plasma current I_p; (b) the plasma toroidal voltage V_ϕ, up to 200–400 V. The peak I_p is about 110 kA; (c) the toroidal flux, $\Phi = \int \langle B_\phi \rangle \mathrm{d}s$; (d) $B_{\phi w}$ the edge toroidal field; (e) $B_{\theta w}$ the edge poroidal field; (f) $\mathrm{d}I_p/\mathrm{d}t$ is time evolution.

Fig. 2 gives the line radiation intensities of H_α, CII, SiII, CIII, CrI and WI, which are decreased as the plasma current increase for a RFP configuration. The ion averaged temperature, $\langle T_i \rangle$, is about 85 eV, it was obtained from C III (97.7 nm) VUV spectra Doppler broadening. The electron temperature, T_e about 70 eV is obtained from the intensity ratio of adjacent ionized line radiation of the same element.

After siliconization, ULQ experiments were also performed with the initial toroidal field up to about 0.12 T with plasma current between 80 and 120 kA. Discharges were set up by a capacitor bank that produces a toroidal voltage up to about 400 V after pre-ionization discharge. A power crowbar was added sequentially to sustain the discharge. Stable discharges were obtained. The edge safety factor q_a is about 0.05 and 0.1. The q_a was sustained as long as the flat-top longer, i.e. the minimum of q_a sustained about 0.58 ms.

The effective resistance R_p is 2.16 mΩ instead of the plasma classical resistance R_s of 0.755 mΩ. This indicates the existence of a large anomalous resistance. The comparison of ion temperature T_i and electron temperature T_e measured with VUV spectrometer shows that T_i of ULQ plasma is higher than T_e because of the anomalous ion heating mechanism. T_i is driven to about 150 eV with $T_e \approx 65$ eV. After siliconization, the plasma resistance R_p decreased by 20% for the ULQ discharge. Here $R_p = V_\phi/I_p$, where I_p is the plasma current and V_ϕ is the single-turn loop voltage, the values are taken at the moment with maximum plasma current. The plasma toroidal voltage decreased from $V_{\phi\max} = 435$ V and $V_{\phi\min} = 300$ V to $V_{\phi\max} = 420$ V and $V_{\phi\min} = 170$ V. The increment of configuration (ULQ and RFP) sustainment time is about 200 μs.

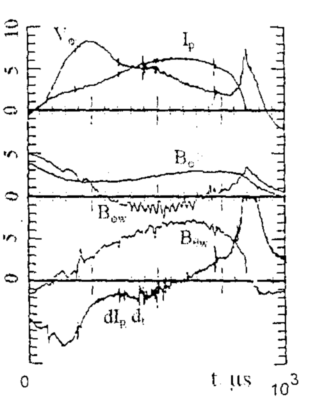

Fig. 1. RFP discharge waveforms after siliconization time evolution of V_ϕ, I_p, $\langle B_\phi \rangle$, $B_{\phi w}$, $B_{\theta w}$ and $\mathrm{d}I_p/\mathrm{d}t$. I_p: 15.8 kA/div, V_ϕ: 50 V/div, $\langle B_\phi \rangle$: 1.05×10^{-2} T/div, $B_{\phi w}$: 1.05×10^{-2} T/div, $B_{\theta w}$: 2.08×10^{-2} T/div and $\mathrm{d}I_p/\mathrm{d}t$: A.U.

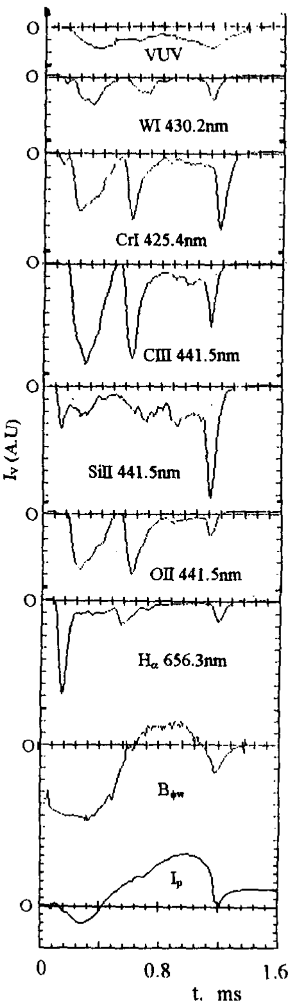

Fig. 2. WI, CrI, CIII, SiII, OII, H_α, $B_{\phi w}$, I_p and VUV waveforms under RFP configuration.

3. Discussion

The discharges after siliconization are characterized by significantly reduced oxygen and carbon impurities compared with the previous values obtained after carbonization which has been carried out in the last operating season. The reduction of the carbon impurity is due to the coverage of the surface by silicon. The bond energy per oxygen atom DG/O in SiO_2 is a enough figure of merit for the potential of silicon to getter oxygen plasma impurities. Oxygen plays an important role in carbon erosion via the formation of CO. Siliconization is expected to be a good getter for oxygen impurities and a course to reduce carbon. The method of siliconization is the qualification for their chemical and physical properties, chemical erosion and oxygen gettering capability.

The metal impurities are reduced simultaneously. The plasma current and sustainment time of configurations (RFP and ULQ) are increased. Plasma toroidal voltage and plasma effective resistance are decreased. Anomalous ion heating has been observed in ULQ plasma. The ion averaged temperature was increased from 30 eV to 120 eV, the electron temperature is also increased.

Acknowledgements

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