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Characterisation of carbon dust produced in sputtering discharges and in the Tore Supra tokamak

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Abstract

The sputtering of inside wall components of tokamaks can lead to the injection of supersaturated vapor in the edge plasmas. The resulting condensation favors the formation of clusters which can give rise to solid particulates by further accretion. Sputtering discharges are proposed to have highlight on the formation of carbonaceous dust observed in the tokamaks with graphite based wall components. The flux of the sputtered carbon atoms is evaluated in the conditions of our laboratory discharges as well as the evolution of their energy distribution. It is shown that a cooling mechanism occurs through collisions with the discharge argon atoms, leading to a nucleation phase. A comparison between the carbon structure of the resulting dust particles and a dust sample collected in the Tore Supra tokamak is proposed. The structural differences are discussed and can be correlated to specific plasma conditions.

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1. Introduction

In the tokamaks, plasma facing wall components (PFCs) are exposed to high particle fluxes which can induce high sputtering erosion. Off normal events like disruptions, arcing, instabilities can furthermore produce melting and/or evaporation of these PFCs [1]. Additional chemical erosion of the components in graphite based material releases hydrocarbon gases as methane, ethylene, acetylene [2]. A portion of the physical and chemical eroded material generates dust with a wide range of size and shape. In the micro-millimeter size range and more, one can observe small pieces and fragments coming from the walls [3], irregular grains coming from brittle redeposited layers, flat flakes from thin coatings and fibrous particles [3–6]. In the micro-nanometer scale, spherical primary particulates (PPs) are observed, piled up in macroscopic agglomerates in which the presence of nanotubes has also being evidenced [3]. The PPs can aggregate to form chains of particles and dense spheroids [7] as this occurs in

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plasma processing [8,9]. These PPs result either from the condensation of the vaporised material or from the multiple collisions between atoms and molecules released by the PFCs. In particular, radicals coming from hydrocarbon gases can polymerise to form macro-molecular precursors [10].

The ITER program has initiated different studies on the dust formation mechanisms, the produced quantities and their effects in fusion devices [11,12]. Among the used wall materials, the graphite has the largest capability to retain tritium. Carbonaceous dust is then considered as a safety hazard in the case of accidental device opening and a potential limit of the performances.

The results presented in this paper concern the carbonaceous particle formation from supersaturated carbon vapors coming from cathode sputtering in argon parallel electrode glow discharges. Conditions of supersaturation can be developed in tokamak plasma edge when arcs take place or when ions accelerated in sheaths, acquire energy higher than the sputtering threshold. In particular, this process is likely dominant in the Tore Supra (TS) tokamak [13], operating since 2000 with a toroidal wall component made in carbon fiber composite and so called: Toroidal Pumped Limiter (TPL).

The laboratory experimental conditions are presented in Section 2. In Section 3, a simple model is presented to estimate the carbon flux injected in these conditions from the cathode surface bombardment. Then, a numerical analysis showing the cooling of the sputtered atom during their collisions with argon atoms is proposed since it is assumed that the particulate precursors come from condensation. A better understanding of the dust formation can be provided by a correlation between the carbon structure in the atomic scale and the plasma characteristics. In Section 4, we propose structural analyses [9,14] of particles produced in our laboratory experiments and of a dust sample collected in January 2003 in a shadowed area of the TPL of TS, i.e. not directly exposed to high fluxes of the magnetized plasma. The differences are discussed in Section 5, according to specific conditions and plasma parameters of each case.

2. Experimental setup of sputtering discharges

Argon DC glow discharges are produced between two parallel electrodes separated by 5 cm. The lower one of 10 cm diameter is made in polycrystalline graphite and used as cathode. The upper one of 12 cm diameter, made of stainless steel, is grounded and used as anode. They are set in a cylindrical stainless steel vessel of 40 cm long and 30 cm diameter, equipped with four windows for optical diagnostics. Argon is admitted through a wall inlet and pumped at the bottom of the device by an oil diffusion pump, connected with a rotary pump. The residual pressure is lower than 10^{-6} mbar after several discharges. The experiments are performed at the argon pressure $P_{Ar} \sim 0.6$ mbar, without pumping flow. Rather low discharge currents of $I_0 \sim 70$ mA are used, resulting in discharge voltages of $V_K \sim -600$ V and providing current densities of ~ 9 A/m^2. These conditions allow carbon injection in the plasmas through cathode sputtering by ions and charge exchange (CX) neutrals.

The stability of the discharges is controlled through the spectral line evolution of C_2 dimer, one of the molecular precursors of solid particles, formed here. In our conditions, the intensity of the C_2 Swan band head (516.5 nm) remains constant during $\sim$20 min. We therefore, perform successive discharges of 10 min, separated by several minutes during which the pumping flow is restored. The mean cathode and anode temperature measurements by thermocouples are 120 °C and 60 °C, respectively. As a consequence, we assume that a gas temperature of $\sim$100 °C is reached during the discharges.

The presence of the atomic hydrogen line H_α in the successive plasmas is assigned to the water residual pressure and/or to the wall outgassing during the discharges. Oxygen or other impurities have not been observed by optical emission spectroscopy.

Nanoscaled particulates are collected on stainless steel foils, placed on the grounded anode surface. Their shape, size, microstructure and chemical composition are analyzed by ex situ diagnostics: Scanning Electron Microscopy (SEM), X-ray Absorption Near Edge Spectroscopy (XANES) and InfraRed (IR) absorption spectroscopy.

3. Flux and energy distribution of sputtered carbon atoms

3.1. Flux of sputtered carbon atoms

At the intermediate pressure of $P_{Ar} = 0.6$ mbar, several assumptions can be made: (i) the ionization within the cathode sheath is negligible, (ii) the sputtering comes from the bombardment of argon ions accelerated in the cathode sheath and of CX