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Characterization of Particle Growth and Enhancement of Sputtering Yields in a Co-generated Dusty Plasma

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ABSTRACT

A Direct Current glow discharge argon plasma is produced in between the graphite made cathode and the anode. Due to the ion bombardment, the carbon particles are eroded from cathode surface at a particular discharge condition. These carbon particles are then charged negatively by collecting more electrons than ions and levitated in the cathode sheath region by balancing electrostatic force with gravitational force. The experimental results showed that the more carbon particle erode if the experiments have performed for longer time and higher discharge voltage and background pressure. The sputtering even becomes more efficient when the cathode is biased with negative voltage. We believe, our experimental results will be helpful to fusion community to understand the sputtering from carbon walls of various tokamaks.

Keywords: plasma; sputtering; agglomeration; fusion

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 and acetylene [2]. A portion of the physical and chemical eroded material generates dust with a wide range of size and shape. In the micro-millimetre 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 [3-5]. In the micro to nanometre 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 [6] as this occurs in plasma processing [7-8]. These PPs result either from the condensation of the vaporized material or from the multiple collisions between atoms and molecules released by the PFCs.

The ITER program has initiated different studies on the dust formation mechanisms, the produced quantities and their effects in fusion devices [9-10]. 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. Arnas et al.; carried out laboratory experiments in a dc argon parallel electrode glow discharge [8,11-12] to understand the growth and charging mechanism of spheroid carbon dust grains observed in Tore Supra Tokamaks. In these experiments fine carbon particles formed in plasmas from sputtered carbon atoms of the graphite made cathode surface.

In Indian scenario, Sarkar et al.; produced cogenerated dusts in unmagnetized plasma through sputtering using a bipolar pulsed dc power supply [13]. In this experiment, the dust particles have been generated through sputtering of graphite cathode and were stratified between two electrodes. In these experiments, they observed the Taylor-like instability at the interface of two dusty clouds with different densities and also observed a self-excited dust density wave propagates towards the higher density dust fluid inside the system. In another experiment [14] they observed spatiotemporal evolution of dust density waves (DDWs) in cogenerated dusty plasma in the presence of modified field induced by glass plate. Various DDWs, such as vertical, oblique, and stationary, were detected simultaneously for the first time.

Thus, in order to perform successful fusion experiments it is important to assess and understand the processes by which dust is formed and by which it interacts with the fusion device and its plasma. Instead of understanding processes that exactly happen inside a fusion reactor, it is always better to match some aspects of graphite-hydrogen interaction in a plasma environment in small laboratory devices, and study the physical processes.

To address some of these issues, we have performed an experiment to examine the particle growth and sputtering yields in a DC glow discharge plasma in between the graphite electrodes. In the first set of experiments, it is shown that sputtered carbon particles density increases at a particular region in between electrodes with the increase of discharge voltage and /or background pressure. In the second set of experiments, it is found that the enhancement of sputtering yield from cathode surface and its variation over a wide range of discharge condition when the cathode is biased negatively with respect to the grounded chamber.

2. Experimental setup

The experiments are carried out in a cylindrical SS chamber as shown in Fig. 1(a), which has number of radial and axial ports for different purposes. The vacuum chamber is pumped down by a rotary pump (pumping speed = 250 lit/min and power 0.5 HP) and the ultimate base pressure is obtained as ~ 0.01 mbar. Argon gas is then introduced into the chamber through one of the radial ports using a Blazer made needle valve. The working pressure (P) is set in the range of 0.4 to 0.04 mbar by adjusting the gas leak rate and the pumping speed. The pressure inside the chamber is monitored using a Pirani gauge. Two disc shaped parallel plates made of graphite material of diameter 80 mm and thickness 6 mm are used as electrodes for the plasma production (see fig. 1(b)). The main reason to use graphite electrodes is to create carbon dust particles through sputtering process in the plasma environment akin to tokamak plasma at some extent. After filling the chamber with argon gas at the desired pressure, the DC voltage is applied to the anode (upper electrode) with respect to the grounded cathode (lower electrode) through a current limiting resister. The glow discharge argon plasma is produced in between two electrodes at a discharge voltage (V_d) of 250-350 volt at a discharge current of 30-100 mA.

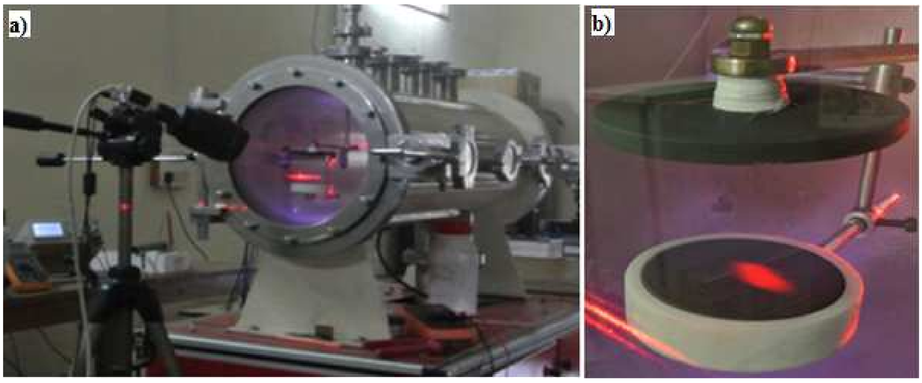

Figure 1: Picture of the argon plasma with carbon dust cloud in between two electrodes

2.1. Plasma parameters

To begin with, the plasma parameters such as electron temperature, plasma density, floating potential are measure using a single cylindrical Langmuir probe over a range of discharge voltages and neutral pressures and electrode distance. The typical measured values of electron temperature and plasma density are in the ranges (4-11) eV and 8x10^9 - 2x10^9 cm^{-3} respectively when the electrode separations are changed from 5.5 cm to 11.5 cm for a particular discharge condition (P = 0.09 mbar and V_d = 250 volt) as shown in table (I). As electrode separation increases for a given discharge voltage, plasma volume increases, as a result plasma density between electrodes decreases. In addition, collision frequency between electron and neutral decreases. Therefore, bulk electrons lose less energy and average temperature of the electrons increases between the electrodes. Whereas the plasma density and electron temperature change from 3x10^9 - 9x10^9 cm^{-3} and 2-5 eV over the range of discharge parameters for a particular electrode separation of 5.5 cm.

Table I:

Sl. No.	Electrode Seperation (cm)	Electron Tempreature (T_e) eV	Plasma Density (n_e) m^{-3}
1	5.5	4.11	7.42 x 10^{15}
2	8.5	5.99	4.10 x 10^{15}
3	11.5	11.52	1.89x 10^{15}

2.2. Experimental results

In the plasma environment, the carbon particles are sputtered from cathode surface due to ion bombardment at a discharge voltage, V_d = 255-265 volt and background pressure, P = 0.08-0.95 mbar. These carbon particles are then charged negatively by collecting more electrons than ions and levitated in the cathode sheath region by perfectly balancing the electrostatic force and the gravitational force. A red He – Ne laser is used to illuminate the levitated carbon particles near the cathode sheath region. The time evolution of scattered light from the growing carbon particles is captured using a CCD camera (with frame rate ~ 60 fps) and the still images are then stored in a high-speed computer for further analysis. An IDL based particle tracking code is used to extract the dynamics of dust particles from these images.

At first to investigate the structural morphology, these sputtered carbon particulates are collected on a rectangular glass plates, placed on the inner surface of the grounded chamber. Their shape, size and structure are analyzed by ex-situ diagnostics: Scanning Electron Microscopy (SEM). SEM images confirm that the cogenerated dust particles are nano-scaled flex like structures of graphite particles with irregular shapes and sizes. As shown in fig. 2, the flex width increases from 20 nm to 60 nm with the increase of discharge voltages at a particular background pressure. Similar observations are also made when the background pressures is increased at a given discharge voltage.

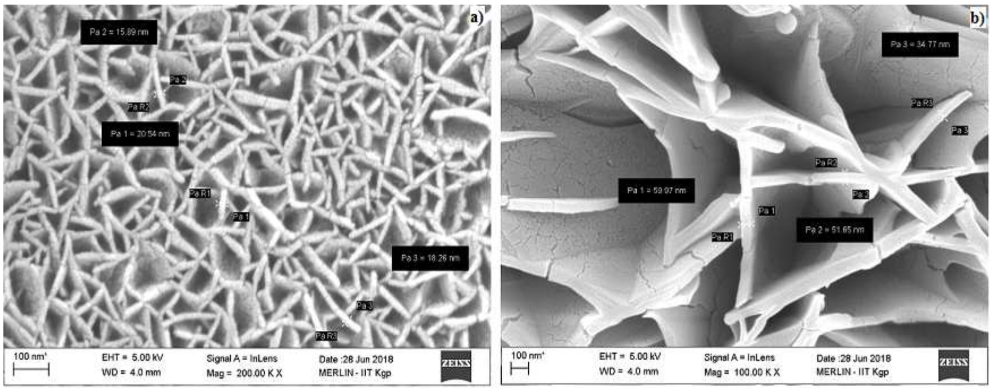

Figure 2: SEM Photograph of sputtered graphite cluster (a) at V_D = 270 Volts and P= 0.085 mbar b) V_D = 278 Volts and same neutral pressure.

In the first set of experiments, the pair correlation function (g(r)), defines the probability of finding a particle at a distance r from another particle [15-16], is calculated from the recorded still images. The location of first peak in g(r) vs r plot (as shown in figure 3) gives the inter-particle distance (d), which is used to calculate the particle density ($n_d = 3/4\pi d^3$) for a 3D dust cloud. Particle number density is calculated by considering only one particle inside a circle of radius equal to the inter particle distance. As time evolves, it is found that the peak in g(r) curve shifts towards left, which essentially implies that the decrease of inter-particle distance and hence increase of particle density. Using the above technique, the variation of dust density is estimated over a range of discharge parameters. The experimental results showed that with the increase of discharge voltage and/or background pressure the number density of carbon particles at a particular region increases.

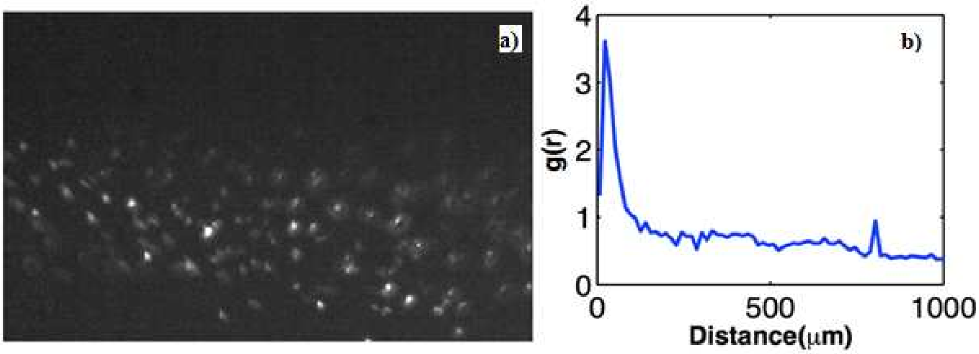

Figure 3: a) Image of dust cloud b) A plot of pair correlation function g(r) vs r for the eroded dust cloud of fig 3(a). The location of first peak gives the inter-particle distance.

It essentially signifies that with the increase of discharge voltage and pressure the ionization become more efficient and as a result the ion bombardment at cathode increases which causes more sputtering from the graphite cathode as a result carbon particle density increase. It is seen in fig. 4(a) that the density of eroded two dimensional carbon particles cloud increases with the increase of discharge voltage at a particular gas pressure. With the increase of discharge voltage, the plasma density increases which results in the increase of sputtering of ions on the surface of cathode. As a result the number density of eroded dust particles increases in the cathode sheath region. It is also found that the temperature of dust particles increases (see fig. 4(b)) with the increase of discharge voltage. It happens due to the increase of sheath electric field which helps the ions to reach towards the cathode with higher kinetic energy.

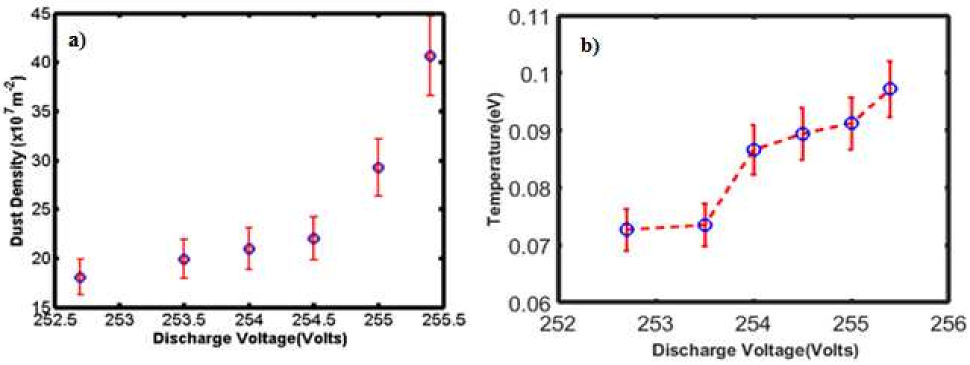

Figure 4: Dusty Plasma variation with discharge voltage at a fixed neutral pressure

Similar to discharge voltage, the density of two-dimensional dust particles also increases when the neutral gas pressure is increased at a constant discharge voltage as shown in fig 5(a). That is with the increase in pressure more sputtering occurs and hence more carbon particles are eroded out from the cathode graphite surface. The variation of temperature of dust particles with pressure also follows the same trend as shown in fig. 5(b).

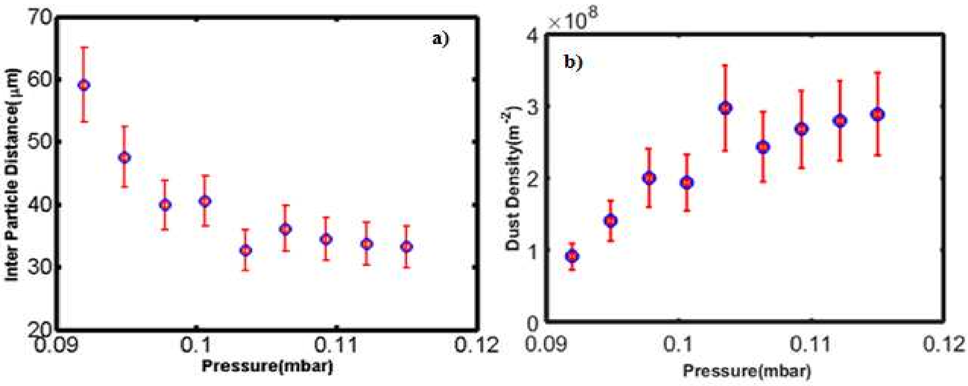

Figure 5: Dusty Plasma variation with neutral pressure at a fixed discharge voltage

In the second set of experiments, the enhancement of sputtering yields is studied with increase of cathode bias voltage systematically at a constant discharge parameters, V_d = 264 V and P = 0.085 mbar. In this set of experiments, the cathode is biased with a negative voltage with respect to the grounded chamber to increase the sputtering yields at a particular discharge voltage. The sequence of still images of the dust cloud at a particular location is shown in the fig. 6 when the bias voltage is increased in the step of 1 volt with respect to the grounded chamber.

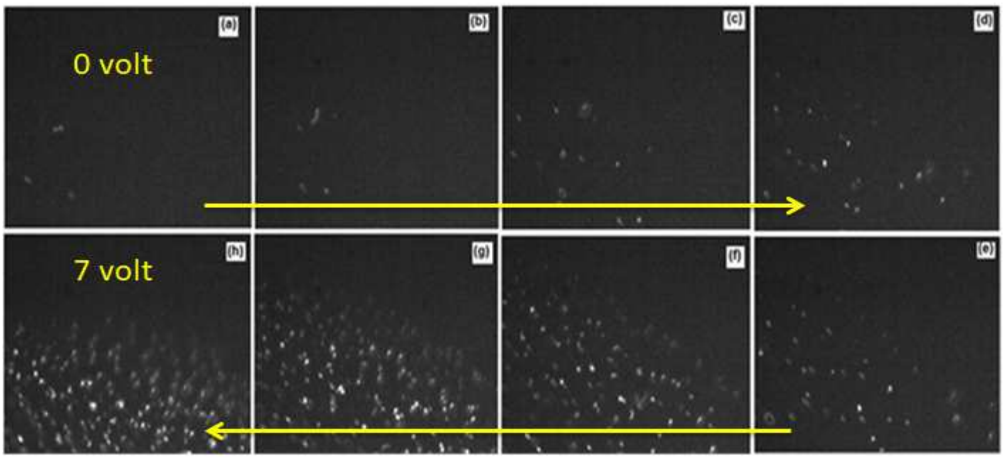

Figure 6: Stable carbon dust cloud of different cathode biasing voltages (a) 0 volt (b) 1.0 volt (c) 2.0 volt (d) 3.0 volt (e) 4.0 volt (f) 5.0 volt (g) 6.0 volt (h) 7.0 volt.

It is seen that carbon particle density increases with slight increase of bias voltage and gradually it reaches to a saturated state. The average distance between two particles for different cathode bias voltage over 100 still images is calculated from the still images of the stable dust cloud with the help of particle tracking code in IDL. The variation of average distance and corresponding particle density for different biasing voltages is plotted in fig. 7.

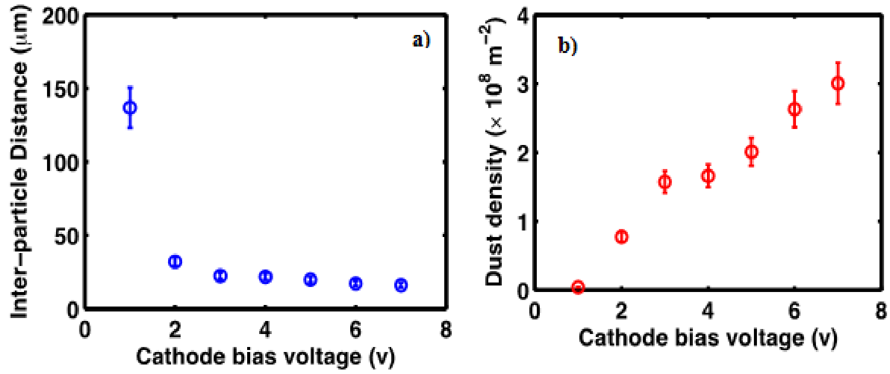

Figure 7: Variation of the mean distance and corresponding particle density with cathode bias voltage

With the increase of negative cathode bias voltage, the ion reaches to the graphite cathode surface with higher momentum and erode more carbon particles when the other discharge parameters are kept constant. It is to be noted that opposite trend in the dust density is observed when the cathode is biased with the positive voltage (not shown in figure).

3. Conclusion

An experiment has been carried out to study the particle growth in a DC glow discharge argon plasma with two parallel graphite electrodes. The experimental results showed that the more carbon particle erode if the experiments have performed for longer time and higher discharge voltage and background pressure. The sputtering process becomes more efficient when the cathode is biased with negative voltage. We believe, our experimental results will be helpful to fusion community to understand the sputtering from carbon walls of different tokamaks.

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