Control of Dust Flux in LHD and in a Divertor Simulator

Kazunori Koga¹, Katsushi Nishiyama¹, Yasuhiko Morita¹, Daisuke Yamashita¹, Kunihiro Kamataki¹, Giichiro Uchida¹, Hyunwoong Seo¹, Naho Itagaki¹,², Masaharu Shiratani¹, Naoko Ashikawa³, Suguru Masuzaki³, Kiyohiko Nishimura³, Akio Sagara³, and the LHD Experimental Group³

¹Kyushu University, 744 Motooka Nishi-ku, 819-0395 Fukuoka, Japan.
²PRESTO JST, 5 Sanban-cho Chiyoda-ku, 102-0075 Tokyo, Japan
³National Institute for Fusion Science, 322-6 Orooshi-cho, 509-5292 Toki, Japan

E-mail contact of main author: koga@ed.kyushu-u.ac.jp

Abstract. We have analyzed dust particles collected in the LHD and a divertor simulator by using the DC-bias substrates. The collection in the LHD was conducted in the 15th campaign on 11th and 12th August, 2011. In this campaign, spherical particles and flakes have been collected. The dependence of total flux of dust particles on the substrate bias voltage $V_{bias}$ showed that appropriate bias control can control the dust flux generated by applying a local bias and is useful for removing carbon and metal dust particles from the shadow area of fusion devices. While, for the flakes, the mass deposition rate and hydrogen atom accumulation rate deduced from the size distribution of the dust fluxes changed in the same manner as the total flux, those of mass deposition rate and H accumulation rate for spherical particles were different from that of the total flux. The reasons of the difference should be studied using laboratory plasmas. To confirm availability of study on the dust flux control using the divertor simulator, we have compared the total flux of dust collected in the divertor simulator with that in the LHD. The collected dust particles in the divertor simulator can be classified into three kinds: spherical particles, agglomerates, and flakes. The spherical dust flux increases exponentially with increasing the $V_{bias}$, while the fluxes of agglomerates and flakes are irrelevant to the bias voltages. The results suggest that the divertor simulator can be simulated the flux control of spherical particles in the LHD using DC-biased substrates.

1. Introduction

Much attention has directed to the study of dust in fusion devices mainly because dust can pose safety issue related to its chemical activity, tritium retention and radioactive content [1, 2]. The safety issue of accumulated dust particles was discussed from viewpoints of their mass [3, 4] and the amount of hydrogen retention in them. Accumulated dust particles and hydrogen can react with oxygen when the reactor is exposed to air after the operation, leading to an explosion hazard [5]. They are also known for penetrating to the core plasma, resulting in deterioration of plasma confinement [6]. Therefore, it is important to invent dust removal methods to overcome the safety issue.

So far, several methods have been proposed to remove the dust particles such as a liquid washing [7], vibratory conveyors [8], oxidation of dust particles [9], laser ablation and flush lamp irradiation cleaning [10-12], and an electrostatic method using two closely interlocking grids [13]. Recently, we have collected dust particles in the Large Helical Devices (LHD) in National Institute for Fusion Science using DC-biased substrates. The results suggested that the local bias is useful to remove carbon and metal dust particles at the shadow area in fusion devices using appropriate control of bias voltage [14]. For further discussion about the dust flux control using the local bias, laboratory experiments was required. Recently, we developed
a helicon discharge reactor. Using the reactor, we realized to simulate the generation of dust particles [15, 16] and studied effects of discharge power on the dust generation [17].

In this study, we evaluated the mass of dust particles collected in the LHD by using the DC-bias substrates and the amount of hydrogen retention in them. They were deduced from size distribution of collected dust flux. Then, we compared the flux of dust collected in the divertor simulator with that in the LHD to confirm availability of study on the dust flux control using the divertor simulator.

2. Experimental

Dust flux measurements were carried out using a substrate holder as shown in Fig. 1. The Si substrates of $15 \times 10 \text{ mm}^2$ were biased simultaneously. The bias voltage $V_{\text{bias}}$ was set at $-70$, 0, $+30$, and $+70 \text{ V}$ with respect to ground. For the LHD experiment, the holder was located at a bottom first wall position during a total discharging period of $920 \text{ s}$ of H$_2$ and He main discharges [14]. The holder was set on a movable sample stage at 4.5L port as shown in Fig. 2. The space potential of plasmas near the substrate and ion flux toward the wall was 0 V and $10^{18} \text{ m}^{-2}\text{s}^{-1}$, respectively. Using the movable stage, the holder was exposed during only discharge periods. After the collection, it was retracted inside the port and was separated from the main chamber by a gate valve. Therefore, the influence of dust accumulation from other place during the vacuum vent of the device is negligible. For the experiments in the divertor

FIG. 1. Substrate holder. Six silicon substrates are separated from the ground by ceramic insulators to apply DC voltages to the substrates.

FIG. 2. Position of the substrate holder in the LHD.
simulator, the substrate holder was set on the wall as shown in Fig. 3 [17]. The magnetic field was applied uniformly along the center axis of the discharge tube with the four magnetic coils. H₂ plasmas were generated by applying 13.56 MHz pulsed RF voltage to a helicon antenna. The discharging period was 0.25 s and the interval was 1.0 s to avoid overheating the quartz discharge tube. A graphite target of 35 mm in diameter and 8 mm thickness was placed as shown in Fig. 3 to produce dust particles due to interaction between the carbon wall and the plasmas. The ion density and electron temperature at the center of the discharge and 200 mm from the target was 2.5x10¹² cm⁻³ and 8 eV, respectively. The total discharging time was 600 s. The substrate holder was set below 110 mm from the target and on the wall.

![FIG. 3. Schematic of the divertor simulator. The substrate holder is set at 110 mm below graphite target and on the wall.](image)

The size and shape of the dust particles collected on the substrates were measured with a scanning electron microscope (SEM) and their composition was analyzed by energy dispersive X-ray analysis. For this SEM measurement, lower detection limit of size was 50 nm in this study. To measure an area density of collected dust particles, we have manually counted dust particles in the area of 1.67x10⁻², 1.67x10⁻², 6.79x10⁻³ and 2.07x10⁻² mm⁻² near the center of the substrates for \( V_{bias} = +70, +30, 0, \) and \(-70\) V, respectively. The flux of the collected dust particles into the substrates was obtained from their area density on the substrates and the discharging period.

3. Results and Discussion

The dust flux measurement in the LHD was conducted in the 15th campaign on 11th and 12th August, 2011. In this campaign, spherical particles and flakes have been collected [14]. In our previous dust collection, we have also found the agglomerates [15, 18] but the agglomerates in this collection were rare. In the present collection, spherical dust particles are below about 300 nm in size and flakes have the size below 1 μm and are irregular in shape. In this study, the longest line segment is drawn on each flake in SEM images to determine the size. The major composition of the dust particles is carbon, which is the primary component of the divertor plates in LHD (IG-430), whereas flakes contain Fe and Cr, which are the main components of its first wall (SS316). The shape of the flakes suggests that they are generated by peeling of the redeposited layer from the first wall. The shape of spherical particles suggests they grow in the gas phase.

Figure 4 shows size distribution of dust fluxes as a parameter of the \( V_{bias} \) [14]. The fluxes are obtained by dividing the area density by the collection time (920s). All spherical particles are smaller than 300 nm. Flakes have size between 100 nm and 900 nm. For the flakes, the size distribution is similar to the log-normal distribution for \( V_{bias}=0 \) V and +30 V. For \( V_{bias}=-70 \) V, the total number of particles is counted to be 80. The statistical error for \( V_{bias}=-70 \) V should
be larger than that for the other voltages. For $V_{\text{bias}} = +70\, \text{V}$, the evaluation of their shape around 100 nm might have ambiguity. The flux at the peak is almost independent of $V_{\text{bias}}$. The value of the flux at the peak position decreases with decreasing the $V_{\text{bias}}$. This result suggests the local bias potential has no effects on the generation of the flakes whereas it affects their transport towards the biased substrates. Figure 5 shows mass distribution of dust particles as a parameter of $V_{\text{bias}}$. For the flakes, they are assumed that thickness is 100 nm, the area is $d^2/2$ where $d$ is size of dust particles, and their mass density $\rho$ is same as stainless steel ($\rho = 7.98\, \text{g/cm}^3$). The $\rho$ of the spherical particles strongly depends on the conditions of plasma. The graphite which has $\rho = 1.8\, \text{g/cm}^3$ is employed for the divertor tile but the carbon layer redeposited at the divertor tile has $\rho = 0.91\, \text{g/cm}^3$ [19]. On the other hand, the carbon layer redeposited at remote area has $\rho = 1.8\, \text{g/cm}^3$ [19]. Previously, we have observed spherical carbon particles produced by a divertor simulator with a high resolution transmission electron microscope (TEM) [20]. Many particles had crystalline lattice indicating dense carbon. In the analogy from the result, the collected spherical particles are assumed to have graphite structure ($\rho = 1.8\, \text{g/cm}^3$). The mass of the spherical particles is below about $10^{-14}\, \text{g}$. The mass peak of about $4 \times 10^{-16}\, \text{g}$ is irrelevant to the $V_{\text{bias}}$. The mass of the flakes is in a range between $10^{-15}\, \text{g}$ and $10^{-12}\, \text{g}$. The mass at the peak of about $10^{-14}\, \text{g}$ is also irrelevant to the bias voltages.

**FIG. 4.** Size distribution of dust flux as a parameter of $V_{\text{bias}}$. Solid and dotted lines show the flux for spherical particles and that for flakes, respectively.

**FIG. 5.** Dust flux as a function of their estimated mass for $V_{\text{bias}} = (a) -70\, \text{V}, (b) 0\, \text{V}, (c) +30\, \text{V},$ and (d) $+70\, \text{V}$.

**FIG. 6.** Dust flux as a function of estimated number of H atoms in a particle for $V_{\text{bias}} = (a) -70\, \text{V}, (b) 0\, \text{V}, (c) +30\, \text{V},$ and (d) $+70\, \text{V}$.
From the mass of the dust particles, the amount of hydrogen retention was estimated. For the spherical particles, hydrogen atoms are combined carbon atoms inside the particles and their surface. The atomic ratio of hydrogen and carbon in the body and the surface is assumed to be 0.33 H/C [21] and 2 H/C [22], respectively. For the flakes, they produced by peeling of redeposited layer from the first wall. The hydrogen retention of redeposited stainless-steel layer at 110°C has been evaluated to be 1.5x10^{-3} mol/g (0.17 H/M) [23]. We have employed the value for evaluation of the hydrogen retention in flakes. Figure 6 shows dust flux as a function of estimated amount hydrogen retention in a dust particle as a parameter of $V_{bias}$. For the spherical particles and flakes, the H atom number is in almost same range between 10^6 and 10^8. The peak of the H atom number is about 1x10^7. Figure 7 shows $V_{bias}$ dependence of (a) a total flux integrated their size distribution between 50 nm and 1 μm, (b) a total mass deposition rate $R_{mass}$ and (c) a total H atom accumulation rate $R_H$. The total flux of the spherical particles increases exponentially by 1.5 orders of magnitude with increasing $V_{bias}$ from -70 V to +70 V. The total flux of flakes increases by 1 order of magnitude with increasing $V_{bias}$ from -70 V to +30 V and then it decreases with increasing $V_{bias}$ from +30 V to +70 V, as shown in Fig. 7(a). The transport mechanism of dust particles is currently unclear [14]. Pulsed discharges were applied in these experiments. If transport mainly occurs when the plasma is off, the electrostatic force will be the main transport force. However, if transport mainly occurs while the plasma is on, the transport mechanism will be complicated and will depend on plasma parameters and properties of dust particles. We intend to investigate the detailed transport mechanism in a future study. The present results suggest that flakes and spherical particles have different transport mechanisms. They also indicate that +30 V is a suitable potential since it attracts both spherical particles and flakes. On the other hand, a

FIG. 7. $V_{bias}$ dependence of (a) collected particle flux, (b) estimated mass deposition rate, and (c) estimated H atom accumulation rate. Solid circles and solid squares indicate spherical particles and flakes, respectively.
negative bias may repulse dust particles so that they may be deposited in undesirable places. These results suggest that the local bias potential is useful to remove carbon and metal dust particles at the shadow area in fusion devices. The $R_{\text{mass}}$ and $R_H$ of flakes change in the same manner as the total flux but those of spherical particles are different from the $V_{\text{bias}}$ dependence of the total flux as shown in Figs. 7(b) and 7(c). The $R_{\text{mass}}$ and $R_H$ have almost same value for $V_{\text{bias}}= 0, +30,$ and $+70 \, \text{V}$. The flux of the spherical particles in a size range between 100 nm and 300 nm for $V_{\text{bias}}= +30$ and $+70 \, \text{V}$ is much lower than that for $V_{\text{bias}}= 0 \, \text{V}$, and thus the $R_{\text{mass}}$ and $R_H$ for $V_{\text{bias}}= +30$ and $+70 \, \text{V}$ have lower values. There are two candidates for such difference between the $V_{\text{bias}}$ dependence of the flux and those of the $R_{\text{mass}}$ and $R_H$. One is that tails in large size of dust particles could not be counted due to the statistical error. The other is that the size distribution of flux is different for each $V_{\text{bias}}$ since the collection efficiency of dust particles depends on the $V_{\text{bias}}$. The reasons of the difference should be studied using laboratory plasmas. To employ the local bias potential to the dust removal method, the effects of the particle features such as the size, shape, and components on collection efficiency, the effective area for the dust removal in the fusion devices and influence of the sheath formed by the local bias potential to the core plasma. The influence of the plasma sheath potential is negligible because the sampling position in the LHD is far from the edge plasma. The effects of the particle features and the effective area for the dust removal are unclear. They should be revealed by using the laboratory plasmas.

The dust collection in the divertor simulator has been carried to confirm availability of study on the dust flux control using the DC-bias voltage. The collected dust particles can be classified into three kinds: spherical particles, agglomerates, and flakes. The major composition of the dust particles is carbon, which is the primary component of the graphite target. Spherical dust particles are below about 500 nm in size. Agglomerates are 50-600 nm in size and composed of small spherical primary particles of around 10 nm in size. Flakes have the size above 1 μm and are irregular in shape. Figure 8 shows the dependence of particle fluxes of dust towards the biased substrates on the $V_{\text{bias}}$. The spherical dust flux increases exponentially by 2 orders of magnitude with increasing the $V_{\text{bias}}$ from -50 V to +50 V, while the fluxes of agglomerates and flakes are irrelevant to the bias voltages. The results suggest that the divertor simulator can be simulated the flux control of spherical particles in the LHD using DC-biased substrates.
4. Conclusion

We have analyzed dust particles collected in the LHD and the divertor simulator. The collection in the LHD was conducted in the 15th campaign on 11th and 12th August, 2011. Following results were obtained. (1) Appropriate bias control can control the dust flux generated by applying a local bias and is useful for removing carbon and metal dust particles from the shadow area of fusion devices. For a positive bias of +30 V, attracts the dust particles. On the other hand, a negative bias may repulse dust particles so that they may be deposited in undesirable places. (2) The dependence of the dust flux on the $V_{\text{bias}}$ is different from those of the $R_{\text{mass}}$ and $R_{\text{H}}$ deduced form the size distribution. For the reason of the difference, there are two possibilities. One is that statistical error has been occurred in the particle counting. Other is that collection efficiency is different for each $V_{\text{bias}}$. The reasons of the difference should be studied using laboratory plasmas. (3) We have compared the flux of dust collected in the divertor simulator with that in the LHD to confirm availability of study on the dust flux control using the divertor simulator. The $V_{\text{bias}}$ dependence of flux of the dust particles suggests that the divertor simulator can be simulated the flux control of spherical particles in the LHD using DC-biased substrates.

Acknowledgements

This research was partly supported by a General Coordinated Research Grant from the National Institute for Fusion Science.

References


