Characterization of heated dust particles using infrared and dynamic images in LHD

N Ashikawa 1), Y. Tomita 1), S. Masuzaki 1), A. Sagara 1), G. Kawamura 1), K. Nishimura 1), N. Ohno 2) and LHD experimental group 1)

1) National Institute for Fusion Science, Toki 509-5292, Japan
2) EcoTopia Science Institute, Nagoya University, Furo-cho, Chikusa-ku, Nagoya 464-8603, Japan
e-mail contact of main author : ashikawa@lhd.nifs.ac.jp

Abstract. To investigate the dust properties, their movements were observed by a high-speed (time resolution of 5.3 ms) infrared camera in the Large Helical Device (LHD). Heated dust velocities were estimated to be 1 – 15 m/s in this experiment. We propose a method for revealing the three-dimensional position of heated dust particles using real and reflected images on the wall observed by an infrared camera. A simple theoretical model shows that the sizes of dust particles have been estimated using experimental observations, such as change of dust velocity and the background plasma parameters.

1. Introduction

Investigation of the dust properties in fusion devices, such as their composition, sizes, mechanisms of their production and movement is one of the important issues in next step devices such as ITER from the view points of their impacts of the core plasma properties and safety issues [1]. From macro scale estimation in vessel phenomenon, erosion and re-deposition rates around divertor targets are measured and their modeling is also developed [2-3]. In the other hand, a dust movement for each dust particles is investigated for micro scale phenomena.

Typical investigation methods for various dust properties conducted in fusion devices experimentally are as follows: 1) postmortem dust collection to characterize remaining dusts in vacuum vessel [4-6], 2) observation with high-speed camera to analyze individual dust movements [7], 3) Rayleigh scattering measurement using Thomson scattering system to measure dust density and its spatial profile [8,9], and 4) weight measurement by quartz crystal unit to reveal the growth of the deposition layer [10]. For the safety issues, it is necessary to reveal where dust particles are produced and where they deposit mainly in fusion devices. A theoretical analysis for micron-size spherical shape dust dynamics shows that the velocity of dust particles can be very mobile (velocity of over ~ 10 m/s), and traverse the distances comparable to fusion device radii [11]. Therefore, to predict where dusts deposit, it is necessary to model the dust movement and to compare the model with experimental observations.

In the Large Helical Device (LHD), a large-scale superconducting heliotron–type device with a set of *l/m* = 2/10 helical coils [12], the postmortem dust collection using a vacuum pumping system with filters was conducted in 2001 [4], 2004 and 2005 [6]. The collected dusts were investigated by using the mass balance method to reveal total weight of dust particles, Energy Dispersive X-ray Spectroscopy (EDX) for analysis of the dust particles composition and Scanning Electron Microscopy (SEM) and Transmission Electron Microscopy (TEM) for analysis of dusts shapes and the size distribution of dust particles. The first wall is made of stainless steel-316L (SS 316L) and divertor plates are made of isotropic graphite (IG430U), respectively. Usually the wall temperature during plasma operation, GDC, and boronization is room temperature and it rises up to 368K when wall baking by hot water is conducted [13, 14]. Mainly two types of dust elements have been observed, and one is spherical-shaped and the other is irregular-shaped dusts. The dominant material of the former type dusts is carbon, and that for the later type is iron. The sizes of carbon and metal dusts are smaller and larger than 1 μm, respectively, and the density increases with decrease of the size. It should be noted that the size distribution is well expressed by an inverse power law size distribution function (Junge distribution [15]) [4]. Many dust movements have been observed during plasma operations by high-speed cameras for visible and infrared regions, respectively. An infrared camera measurement has an advantage of the good sensitivity to radiation over the visible camera, and thus the infrared camera could measure relatively low temperature dusts moving out of the plasma. This is very useful to reveal dust movements.

In this paper, the observations of the dust movements in LHD using high-speed infrared camera will be presented. A simple theoretical model will be introduced, and the experimental observation will be compared with the model.

2. Experimental setup

In LHD, the high-speed infrared camera, Phoenix in FLIR/Indigo was installed at a viewport which is located at torus outboard side, and its height from the equatorial plane was 0.5 m. The detector type of this infrared camera, is InSb which is sensitive wavelength of 3-5 μm. The camera frame rates depend on the pixel numbers, and 320x254 pixels with 5.3 ms of time resolution was used in this experiment. This time resolution includes an exposure time of 2.4 ms and a data transfer time to memory on the camera of 2.9 ms. Figure 1 shows a schematic drawing of the horizontal cross-section at the height of the camera in LHD, and the field of view of the camera is also shown (insertion). The camera mainly looked at the inner first wall (helical coil can). In the insertion, many tiles can be seen. They are first wall panels made of SS316L as mentioned above, and they are bolted (four bolts per a tile) to the vacuum vessel wall. The distance from the camera to the wall was about 5m.

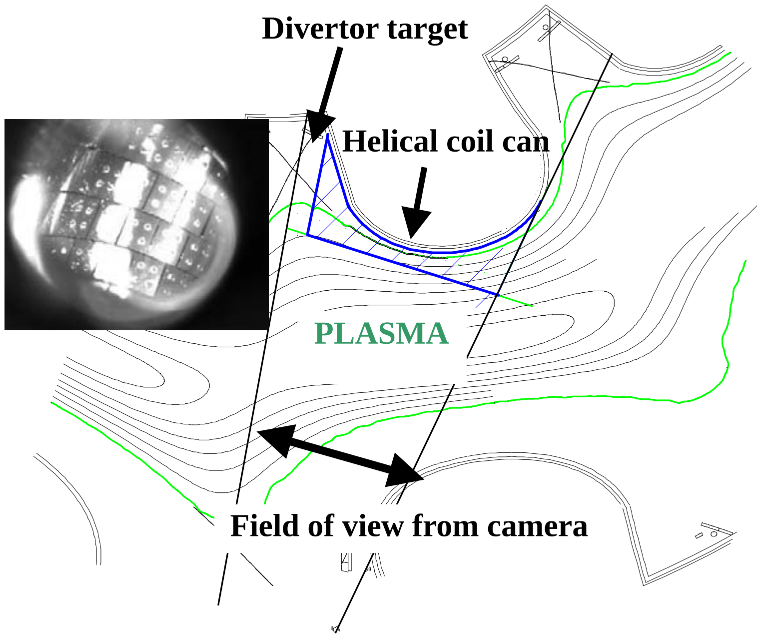

FIG.1 A schematic drawing of the LHD horizontal plane with field of view from infrared camera and a sample image of infrared camera from this field of view. The distance from the infrared camera to the inner wall is about 5m and dust location is estimated in hatched area near the inner wall.

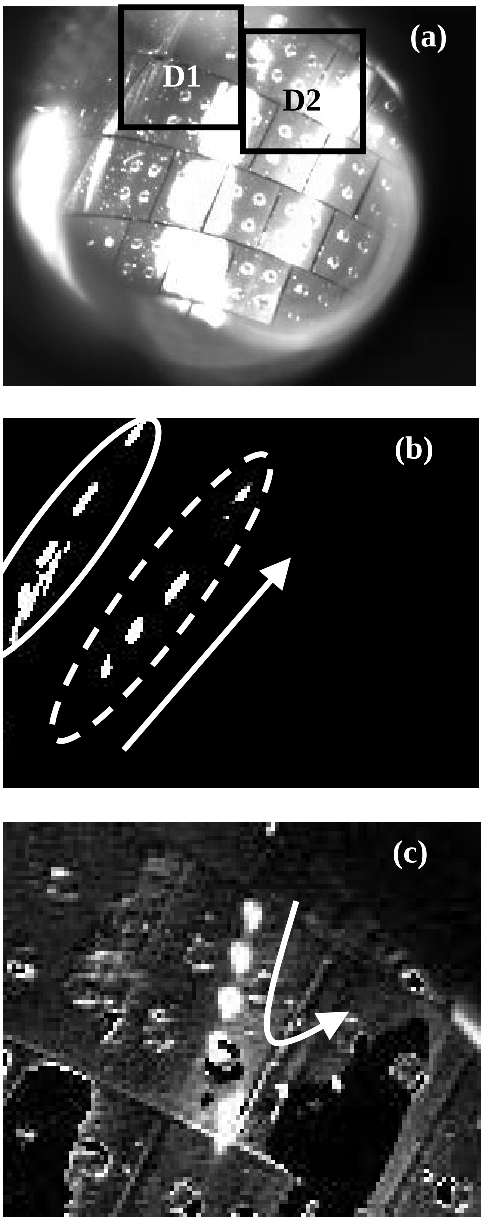

FIG.2 Movement of heated dust particles in after-glow of hydrogen plasma observed by infrared camera. (a) observed image by infrared camera. Observed areas for each dust, D1 and D2, are shown as squares (b) dust, D1, images located in ellipse by solid line and reflected images are shown by dotted line (c) dust, D2, images. Allows show moving directions.

3. Experimental results

The observation of dust particles using the high-speed infrared camera was conducted after the plasma temperature decrease for radiation collapse for many dusts has been observed during this phase. In this case, plasma was not fully collapsed, but neutral beam injection (NBI) heating sustains the low temperature plasma. Such situation can appear for the existence of steady state plasma confinement magnetic surfaces in the heliotron-type device. Dust particles were observed to move various directions, and it seems to be random. It should be noted that we have not detected above mentioned dusts movement by the camera during the glow discharge wall conditioning operation.

We focus on the two dusts, D1 and D2 in Fig. 2, to analyze their movement. Figure 2 shows their movements observed by an infrared camera. Several images are superimposed on these images to show dust trajectories. These two dusts are unique for that their reflection images can be seen on the first wall, and thus, they are considered to move near the inner wall, though the three-dimensional positions of the dusts are not obtained at this stage. Velocities of the dusts on the assumed plane neat the inner wall which is shown in Fig. 1 were estimated, and the time evolutions of

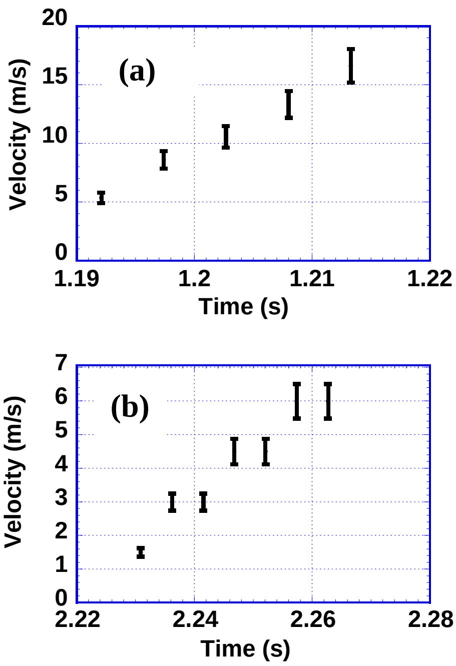

FIG.3 Time evolution of velocity of the dust particle, (a) D1, and (b) D2.

the velocity are depicted in Fig.3. As shown in Fig. 2 (b), D1 moved upward straightly, and it seems to move along the helical coil can on this assumed plane. The dust's velocity on the plane increased from 5 to 15 m/s during observed time, and it looks to be accelerated with 500m/s^2 in apparent.

In Fig.2 (c), the distance between real dusts and their reflection images were smaller than those in Fig. 2 (b). The real dust images are indicated at left side in the ellipse by solid line on this picture and their reflected images are shown in the ellipse by dotted line around center of this picture. Apparent velocity of D2 is about 1 to 6 m/s, and is slower than that of D1. Moving direction of D2 is almost vertically downward. After 2.263 s, D2 looks to collide with the wall and then its moving direction is changed clearly as shown in Fig.2 (c). This observation clearly indicates the importance of the dust reflection on the wall to reveal the dust movement.

4. Theoretical modeling

The dust dynamics is depending on background plasma parameters and the fields. To compare the experimental results and theoretical modeling, theoretical modeling for 1-D dust dynamics along the magnetic field is considered. If dust particles are located between the first wall and the confined plasma and moving direction is along the magnetic field lines with this edge connected to the wall, three kinds of force are considered to compare effective forces to dust movement [11, 16-18]. The dust particle is estimated as a spherical shape with diameter of few μm and negative charge. This diameter is reasonable in actual devices [4-6].

The drag force due to ion absorption can be obtained in the form

$$\boldsymbol{F}_{iab} = \pi R_d^2\, n m_i V^2 (1 - Q_d e / 2e\varepsilon_0 R_d m_i V^2) \tag{1}$$

where R_d is a diameter of dust, m_i is a mass of ion, n is a density, Q_d is a charge of dust, V is ion flow velocity along the magnetic field line. The drag force due to Coulomb scattering can be obtained in the form

$$\boldsymbol{F}_{isc} = n Q_d^2 e^2 \ln\Lambda / 4e\varepsilon_0^2 m_i V^2 \tag{2}$$

where $\ln\Lambda$ is the Coulomb logarithm for an attractive dust potential.

The electrostatic force can be obtained in the form

$$\boldsymbol{F}_E = Q_d\, E \tag{3}$$

A charge of dust particle is written from an equilibrium equation due to charging time faster than a time of dynamics of a dust and it can be obtained in the form

$$Z_d \;/\; R_d \;\; T_e \;=\; 1.06 \;\; \text{x} \;\; 10^{28} \tag{4}$$

where R_d is a diameter of dust particle. An ion flow along the magnetic field line is almost the same order of ion sound speed and then V_ξ can be obtained for the isothermal ion

$$V; c_s = \sqrt{(T_e + T_i)/m_i} = \sqrt{2T/m_i} \tag{5}$$

From substitute Eq. (4) for Eqs. (1), (2) and (3), each parameters are written as followings,

$$\boldsymbol{F_{iab}}=2.17 \text{ x } 10 \; nTR_d^2 \tag{6}$$

$$\boldsymbol{F_{isc}}= 1.14 \text{ x } 10^2 \; nTR_d^2 \tag{7}$$

$$\boldsymbol{F_E} = 1.70 \text{ x } 10^9 \; nTE \tag{8}$$

For Eqs. (6) –(8), plasma parameters are considered a low density plasma a order of 10^{17} m^{-3} as after-glow plasma and T_e and T_i are a few eV. From comparison of Eq. (6) – (8), dominant forces are the drag force due to ion absorption, Eq. (6), and Coulomb scattering, Eq. (7). Here electrostatic force is negligible small because a dust particle is located out of the Debye sheath, where the strong electrostatic field strongly affects dynamics of a dust particle. Therefore, a force dust particle F_ξ is written as following,

$$\boldsymbol{F_\xi} = \boldsymbol{F_{iab}} + \boldsymbol{F_{isc}} = 1.35 \text{ x } 10^2 \; nTR_d^2 \tag{9}$$

Using Eq. (9), an estimation of dust diameter can be done. An equation of motion for dust particles along the magnetic field line is

$$M_d \, dV_d/dt = \boldsymbol{F_\xi} = \boldsymbol{F_{iab}}+\boldsymbol{F_{isc}} = 1.35 \text{ x } 10^2 \; nTR_d^2 \tag{10}$$

$$M_d = 4\pi/3 \; R_d^3 \; \rho_d \tag{11}$$

where ρ_d is a density of dust particle and this is depending on a dust element. From the different dependences of the dust radius between the equation of motion, Eq. (10), and the dust mass, Eq. (11), experimental observations of acceleration or deceleration of a dust particle, an electron density, electron temperature and element of a dust, diameter of dust particle have been estimated. This estimating method is useful to understand moving mechanics of dust particles and expand these modeling.

It is needed more calibration to determine a dust position in Figs.3, but in near future both parameters from estimated diameter by theoretical modeling and observed dust particle diameters will be compared.

5. Summary

Using the high-speed infrared camera, dust movements were observed in the residual low temperature plasma after radiation collapse in LHD. We focused on the two dusts those real and reflected on the wall radiations could be observed simultaneously. That suggests the dusts were located near the wall. Assumed plane was utilized to analyze the dust movements. The dusts velocities are 1 – 15 m/s in apparent, and they looks to be accelerated. The moving direction of one of dusts was changed clearly after its collision with the wall, and that suggests the interactions between dusts and the wall are important process to predict the dust movement in fusion devices.

We observed the real and reflected radiation of a dust as mentioned above, and we will be able to obtain the real three-dimensional dust’s position. Unfortunately, we have not obtained

that for several technical problems. This is a merit of metallic wall device, and this method can be applied in other fusion devices with metallic wall such as ASDEX-U.
From the simple theoretical model, we indicated that the dust's size have been estimated with assuming the spherical shape of the dust.

Acknowledgements
This work is supported by a Grant-in-Aid for Scientific Research from Ministry of Education, Science and Culture of Japan (19055005) and NIFS budget 07ULPP515. The authors would like to thank Dr. B. J. Peterson for use of the infrared camera.

References

[1] FEDERICI, G., et al., "Tritium inventory in the ITER PFC's: Predictions, uncertainties, R&D status and priority needs", Fusion Eng. Design **39-40** (1998) 445.
[2] ROTH, J., et al., "Flux dependence of carbon erosion and implication for ITER", J. Nucl. Mater. **337-339** (2005) 970.
[3] KIRSCHNER, A., et al., "Modelling of tritium retention and target lifetime of the ITER divertor using the ERO code", J. Nucl. Mater. **363-365** (2007) 91.
[4] SHARPE, J.P., SAGARA, A., et al., "Characterization of dust collected from ASDEX-Upgrade and LHD", J. Nucl. Mater. **313-316** (2003) 455.
[5] SHARPE, J.P., MASAKI, K., et al., "Characterization of dust collected from NSTX and JT-60U", J. Nucl. Mater. **337-339** (2005) 1000.
[6] KOGA, K., et al., "Characterization of Dust Particles Ranging in Size from 1 nm to 10 μm Collected in LHD", Plasma Fusion Res. to be submitted.
[7] ROQUEMORE, A.L., et al., "3D measurements of mobile dust particle trajectories in NSTX", J. Nucl. Mater. **363-365**(2007) 222.
[8] NARIHARA, K., et al., "Observation of dust particles by a laser scattering method in the JIPPT-IIU tokamak", Nucl. Fusion **37** (1997) 1177.
[9] WEST, P., et al., "Correlation of submicron dust observed in DIII-D during plasma operation with plasma operating parameters", J. Nucl. Meter. **363-365** (2007) 107.
[10] RHODE, V., et al., "On the formation of a-C:D layers and parasitic plasmas underneath the roof baffle of the ASDEX Upgrade divertor", J. Nucl. Mater. **313-316** (2003) 337.
[11] KRASHENINNIKOV, S.I., TOMITA Y., et al., "On dust dynamics in tokamak edge plasmas", Phys. Plasmas **11** (2004) 3141.
[12] MOTOJIMA, O., et al., "Recent advances in the LHD experiment", Nucl. Fusion **43** (2003) 1674-1683.
[13] NISHIMURA, K., et al., "Development of the plasma operational regime in the large helical device by the various wall conditioning methods", J. Nucl. Mater. **337-339** (2005) 431.
[14] ASHIKAWA, N., et al., "Comparison of boronized wall in LHD and JT-60U", J. Nucl. Mater. **363-365** (2007)1352.
[15] JUNGE, C.E., "Air Chemistry and Radioactivity", Academic Press **113** (1965).
[16] PIGAROV, A., et al., "Dust-particle transport in tokamak edge plasmas", Phys. Plasmas **12** (2005) 122508.
[17] SMIRNOV, R.D., et al., "Modelling of dynamics and transport of carbon dust particles in tokamaks", Plasma Phys. Control. Fusion **49** (2007) 347.
[18] TOMITA, Y., et al., "Effect of truncation of electron velocity distribution on release of dust particle from plasma-facing wall", J. Nucl. Mater. **363-365** (2007) 264.