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ABSTRACT

We present a laboratory study of photoelectric charging of dust particles and their lofting on a conducting surface in the presence of external electric fields. Insulating particles with diameter $<45\,\mu$m are dispersed on a conducting surface exposed to ultraviolet (UV) light. In addition to the UV exposure, a positive or negative external electric field is applied. Independent of the orientation of the external electric field, the dust particles are found to be positively charged but with different mechanisms. It is shown that the orientation of the external electric field controls the dynamics of photoelectrons emitted from the dust particles and the conducting substrate surface. Distinctly different lofting results are shown between these two electric field cases. The results provide insight for understanding dust charging and release and helping develop mitigation solutions in particle accelerators, semiconductor manufacturing, fusion reactors, and space exploration to planetary bodies.

I. INTRODUCTION

Dust charging, lofting, and transport on surfaces is a fundamental problem in a variety of scenarios. In space, electrostatic dust lofting and transport is related to several unresolved observations on the Moon,[1] asteroids,[2,3] and Saturn's rings.[4,5] Dust is known to pose risks for lunar exploration as learned from the Apollo missions.[6,7] Particle contamination control is critical during wafer processing in semiconductor manufacturing.[8,9] Dust is recorded to transport across fusion reactors, causing disruptions.[10,11]

Dust–beam interactions have been observed in numerous particle accelerators, primarily within storage rings. For some accelerators, these interactions had a substantial impact on performance, reducing availability, and even damaging components.[12–15] Dust–beam interactions have been observed in thousands of beam-loss events in CERN's Large Hadron Collider (LHC), some of them led to premature beam dumps and even magnet quenches.[16,17] Understanding dust dynamics in high-energy particle accelerators[18,19] is important for maintaining their performance, in particular for LHC, including its upgrade[20] for Super-KEKB[21] and for the Future Circular Collider (FCC) planned at CERN.[22] Due to the substantial interest in this subject, a workshop was recently convened to enhance understanding of beam–dust issues in particle accelerators, with participation from colleagues within the particle-accelerator, space-research, and nuclear-fusion communities.[23]

For a long time in these studies, dust particles were treated to be part of the surface, and their charge is assumed to be shared by the surface charge density determined by the sheath electric field.[24] Due to the stochastic process of electrons and ions arriving at a surface, fluctuations can generate intermittent charge enhancements on dust particles[24–26] but are insufficient to lift particles off the surface. An advanced patched charge model (PCM)[27] looks into this problem on a microscale. The PCM shows that the emission and reabsorption of secondary electrons and/or photoelectrons within microcavities between dust particles builds substantial negative charges on the surrounding particles, and subsequently, the strong Coulomb repulsion leads to lofting of these particles.[27] The PCM has been validated by a series of laboratory experiments (e.g., Refs. 27–34) and numerical simulations.[35] Recent simulations[9,36] studied dust charging on a surface exposed to an electron beam or in a plasma, by taking into account the geometry between a dust particle and the substrate surface.

Most of the previous studies focused on dust particles on an insulating surface. However, dust particles on a conducting surface, which exist in many scenarios such as semiconductor manufacturing, particle accelerators, fusion devices, and space exploration, have not been well studied. Previous experiments show that the dust charge and subsequent mobilization vary with the bias potential of a conducting surface, which manipulates the fluxes of electrons and ions to the surface and the dust particles.[37] Here we present a new laboratory study of dust charging and lofting on a conducting surface under ultraviolet (UV) exposure and in the presence of external electric fields, which is particularly relevant to the electrical environment in high-energy particle accelerators.

Depending on the type of accelerator, dust particles that adhere on the vacuum chamber wall can become charged through various mechanisms.[19] In circular accelerators where synchrotron radiation is prevalent, particularly in electron and positron accelerators, one primary charging mechanism arises from the photoelectric effect. Additionally, in high-beam-current scenarios such as in the LHC, clouds of photoelectrons emitted from the chamber wall may form within the vacuum chamber. These electrons are collected by dust particles, and their high-energy tail also generates secondary electrons from the dust particles. Overall, the net charge for dust particles due to these charging mechanisms is typically negative as observed experimentally in accelerators[16] and investigated theoretically.[19] However, the initial charge and subsequent release of dust in these accelerators remain unclear.

Meanwhile, a radial electric field is created between the charged particle beam and the chamber wall. The electric field points either to the chamber wall in a proton beam accelerator[19] or to the beam center in an electron beam accelerator.[18] In synchrotrons, where particle beams are bunched, the electric field magnitude can reach up to 1 kV/cm when accounting for the electric field of a passing bunch. It is approximately one to two orders of magnitude lower when considering DC beams, e.g., when assuming that the beam particles in the bunches are distributed along the circumference.[38,39]

In this work, we studied on how the external electric field alters photoelectric charging and the subsequent lofting of dust particles on a conducting surface.

II. EXPERIMENTS

The experiments were conducted in a small stainless steel vacuum chamber [Fig. 1(a)] at a base pressure of $\sim 10^{-6}$ Torr. The body of the chamber is spherical, 20 cm in diameter. Monolayered and irregularly shaped SiO_2 dust particles ($<45\,\mu$m in diameter and a mass density of $2.2\,\text{g cm}^{-3}$ based on the datasheet from MSE Supplies) were dispersed on a grounded aluminum surface. A microscopic image shows the particle shape and sizes [Fig. 1(b)]. A metal mesh was placed 1 cm above the aluminum surface, and a bias voltage of ± 2 kV was applied to the mesh to create an external electric field. With a negative bias, a positive electric field is created pointing upward from the surface, and with a positive bias, a negative electric field is created pointing downward to the surface. The dust particles were exposed to UV light (172 nm wavelength and 7.2 eV energy with an OSRAM Xenon-excimer lamp) shining from the top of the chamber through the mesh to the surface. In the experiments, a bias voltage was applied to the mesh before the UV light was turned on. Given that the photon energy (7.2 eV) is lower than the ionization energy of both nitrogen (15 eV) and oxygen (13.6 eV), no ionization of low residual atmosphere is expected by the UV light. A high-speed camera was used to record the trajectories of lofted dust particles at 1500 frames-per-second (fps), and a Python code was developed to track the trajectories, to measure the size and initial launch velocities of the lofted particles. Multiple trials for each external electric field case were performed to have a sufficient number of particle trajectories for the characterization of particle dynamics in each case.

III. RESULTS AND DISCUSSION

A. Negative external electric field

When the mesh was biased to $+2$ kV, a large fraction of dust particles were recorded to bounce on the surface to an average height of ~ 1.5 mm [Fig. 2(a)]. As shown in Fig. 2(b), photoelectrons emitted from a dust particle and the substrate conducting surface are accelerated vertically upward, leaving the dust particle to be charged positively. Due to the low pressure ($\sim 10^{-6}$ Torr), the electron–neutral mean free path is much larger than the distance between the mesh and substrate surface, and ionization due to accelerated electrons is negligible. The accelerated electrons hitting the mesh are expected to generate secondary electrons, but these secondary electrons will be returned to the mesh immediately due to the large electric field and are thus expected to have negligible effects on dust charging. These conditions apply to a positive external electric field case as well (Sec. III B). As shown in previous studies,[40,41] the particle emits photoelectrons and becomes increasingly positively charged, until a non-monotonic sheath forms around the particle's surface to return the emitted photoelectrons to reach equilibrium [Fig. 2(b)].

Intuitively, the positively charged dust particles should remain unmoved due to the electric force pointing downward to the surface. However, the recorded video shows that the dust particles are bouncing on the surface while also rotating. A possible explanation is that the irregular shape of the dust particles and the non-uniformity of the external electric field and surface charge distributions on the dust particles result in torques that rotate the particles. Rotation also causes the irregularly shaped particles to hit the surface to bounce upward, which are then pushed back down due to the downward pointing electric force and gravity, resulting in repetitive bouncing motion. Note that not all particles were lofted and bouncing, and they were bounced to different heights. The spots without showing trajectories are unmoved particles that remain on the surface. Factors that may affect the bouncing motion include (1) particle charging that depends on the particle geometry and size and (2) the adhesive force that depends on the particle–surface contact area.[31]

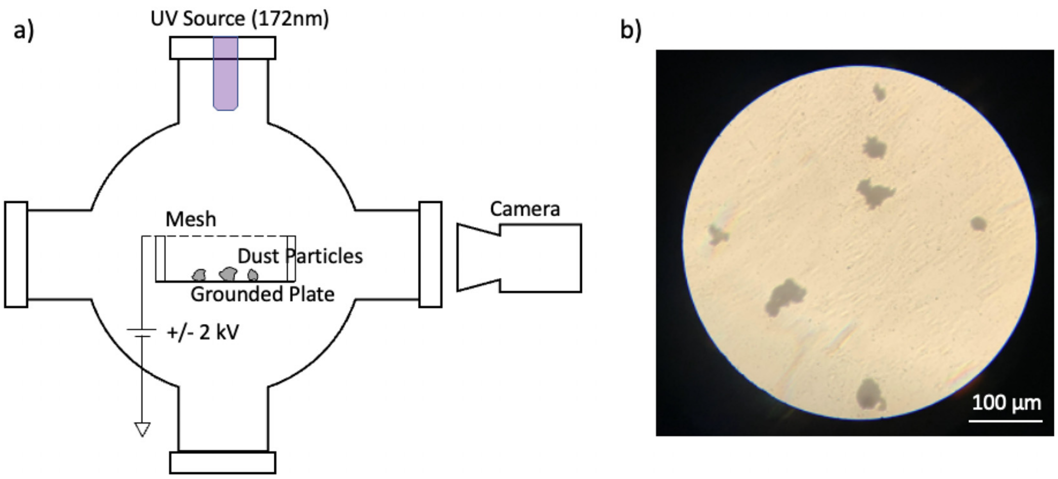

FIG. 1. (a) Schematic of the experimental setup. (b) Microscopic image of dust particles.

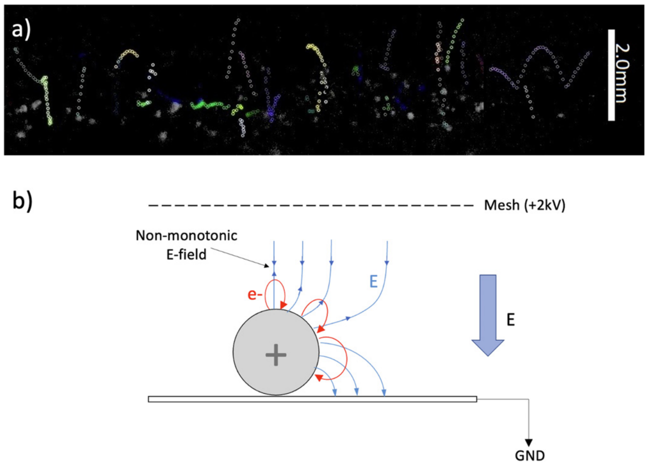

FIG. 2. (a) Trajectories of dust particles bouncing on the surface with a negative external electric field. The trajectories are shown as consecutive circles in different colors, and unmoved particles are shown to rest on the surface. (b) Diagram of photoelectric charging of a dust particle on a conducting surface with a negative external electric field. When reaching equilibrium, a non-monotonic electric field is formed, returning emitted photoelectrons to the surface of the particle.

The characteristic bouncing height H and velocity v are $\sim$1.5 mm and $\sim$0.3 m/s, respectively [Fig. 2(a)]. The average charge Q of the particles with an average size of 22 μm in diameter is estimated to be 1.2×10^{-15} C (i.e., 7.5×10^3 electrons), based on the following equation:

$$H = v^2/[2(g - QE/m)], \tag{1}$$

where g is gravity, m is the mass of a dust particle, and E is the external electric field. The surface potential of dust particles is calculated as

$$\phi = Q/C, \tag{2}$$

where $C = 4\pi\varepsilon_0 r$ and r is the particle radius.[42] The surface potential of the lofted dust particles as a function of the particle size is plotted in Fig. 3, showing an average potential of +1.3 V that is in agreement with the charge (1.2×10^{-15} C)/potential (+1 V) derived from the lofting height.

The work function of SiO_2 is $\sim$5.5 eV, and the photon energy is 7.2 eV, resulting in the cutoff energy of the photoelectrons emitted from the dust particles to be 7.2–5.5 = 1.7 eV. The estimated surface potential +1.3 V, thus falls slightly below the cutoff energy $\sim$1.7 eV, as expected. The particle-particle Coulomb force can be estimated to be 7.4×10^{-13} N, much smaller than the external electric field force of 3.6×10^{-10} N, which determines the particle bouncing dynamics.

B. Positive external electric field

When the mesh was biased to −2 kV, a handful of dust particles were recorded to be lofted and accelerated off the surface vertically [Fig. 4(a)]. This result indicates that the dust particles must be charged

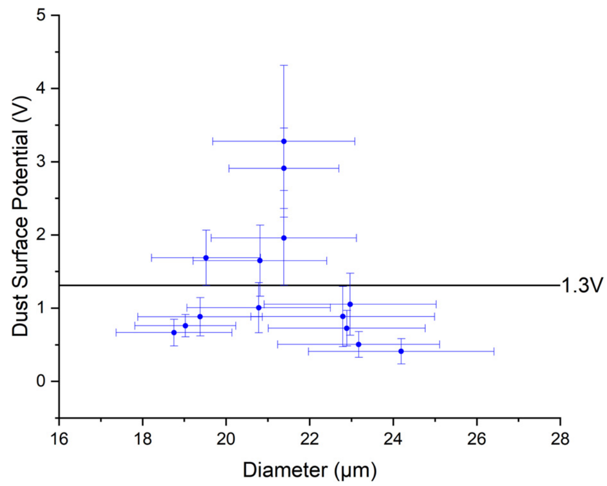

FIG. 3. The surface potential of dust particles as a function of size with a negative external electric field.

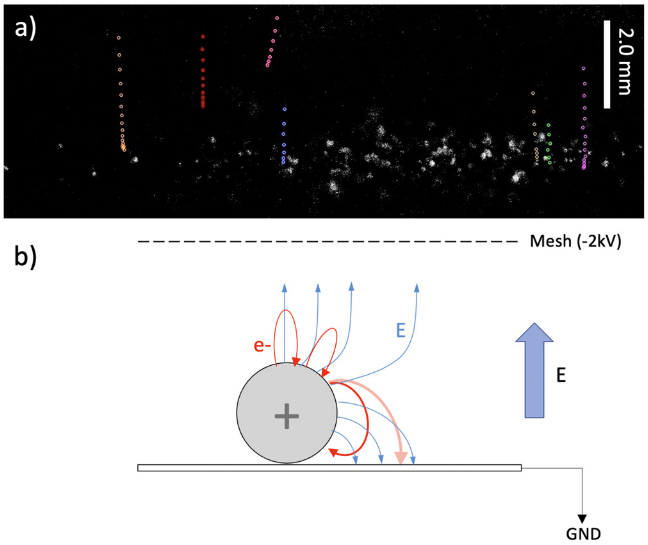

FIG. 4. (a) Trajectories of dust particles accelerated vertically with a positive external electric field. The trajectories are shown as consecutive circles in different colors, and unmoved particles are shown to rest on the surface. (b) Diagram of photoelectric charging of a dust particle on a conducting surface with a positive external electric field. The light red color shows that photoelectrons emitted from the dust particle are accelerated downward by the external electric field and collected by the substrate surface. The solid red color shows that photoelectrons are returned to the particle surface due to an increased surface potential of the particle.

positively. This was contradictory to expectations as the external electric field suppresses photoelectrons from being emitted from both the dust and conducting substrate surfaces. Given the maximum energy of 1.7 eV, the photoelectrons are returned at the maximum height of 8.5 μm. Hence, the dust particles with an average size of 25 μm in diameter should remain none or little charged. To explain the observation, we describe a mechanism as illustrated in Fig. 4(b). It shows that most of the photoelectrons emitted from the conducting surface and from the top area of a dust particle are returned to the surfaces by the strong positive external electric field. However, due to the height of the dust particle, a fraction of the photoelectrons emitted from the particle, especially near the edge between the particle and the substrate surface, will be accelerated downward by the positive electric field and collected by the substrate conducting surface, instead of the dust particle itself, leaving the particle to be charged positively.

By analyzing the acceleration of the dust particles due to the electric field, the charge and surface potential of the particles can be calculated. As shown in Fig. 5, the average surface potential is about +4.5 V. Based on the photoelectron cutoff energy described above, the maximum surface potential is expected to be +1.7 V, much smaller than the measurements. As shown in Fig. 4(b), the positive charge and thus the surface potential increases as more photoelectrons emitted from the particles are collected by the substrate surface. When the surface potential is large enough, such that the electric field in the vicinity of the particle overturns the external electric field, the emitted photoelectrons will be returned to the surface of the particle, reaching an equilibrium potential. In this experiment, the "near-dust" electric field, which is on the scale of the average particle radius ($\sim$12.5 μm), needs to be larger than the external electric field of 2 kV/cm, resulting in the surface potential of the particle to be larger than +2.5 V, which is in agreement with the measured average potential +4.5 V.

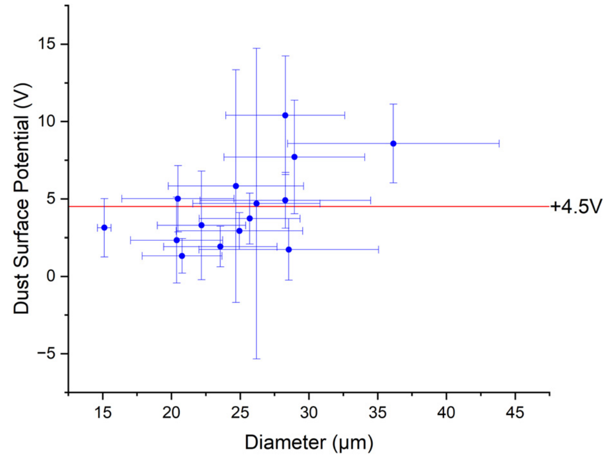

FIG. 5. The surface potential of dust particles as a function of size with a positive external electric field.

Given the average size of 25 μm in diameter of lofted dust particles (Fig. 5), the upward lifting force F_E due to the external electric field is estimated to be 1.3×10^{-9} N. The downward gravitational force F_g is 1.8×10^{-10} N. For a conductive substrate, these charged dust particles induce image charges with an opposite polarity, resulting in an image force $F_{im} = 5.7 \times 10^{-10}$ N that also points downward in this experiment and larger than F_g. The additional F_{im} requires a larger uplifting electric force to lift off dust particles than that in the case of an insulating surface. It shows $F_E > F_g + F_{im}$ in this experiment, explaining the recorded lofting. Key characteristics of lofted dust particles in both negative and positive electric field cases are summarized in Table I.

IV. CONCLUSION

Photoelectric charging of dust particles and their release from a conducting surface were studied in the presence of external electric fields. Both positive and negative external electric fields were tested. Surprisingly, dust particles were found to be positively charged in both cases.

For the negative electric field, photoelectrons emitted from the dust particles and the conducting substrate surface are accelerated vertically, leaving the particles to be charged positively as expected. The dust particles were recorded to bounce on the surface to an average height of $\sim$1.5 mm. Torques, acting on the irregularly shaped and unevenly charged particles, caused the particles to rotate. The particles initially bounced upward and are then pushed back down by the electric force, resulting in a repetitive bouncing motion.

For the positive electric field, the dust particles were unexpectedly accelerated vertically upward from the conducting surface, indicating that they must carry positive charges as well. A fraction of the photoelectrons emitted from the dust particles, instead of returning to the particle itself, are accelerated downward by the electric field and collected by the substrate conducting surface, causing the particles to be charged positively.

TABLE I. Characteristics of lofted dust particles (|E|: 2 kV/cm; UV wavelength: 172 nm).

Parameter	Negative electric field	Positive electric field
Motion	Bouncing	Vertical acceleration
Diameter D (μm)	22 ± 2	25 ± 3
Charge Q (C)	$(1.2 \pm 0.3) \times 10^{-15}$	$(6.2 \pm 0.5) \times 10^{-15}$
Surface potential ϕ (V)	$+1.3 \pm 0.9$	$+4.5 \pm 1.9$
Initial velocity v (m/s)	0.3 ± 0.1	0.4 ± 0.1
Lofting height H (mm)	1.5 ± 0.1	Across the electrodes
Lofting acceleration a (m/s^2)	9.99 ± 1.58	41.37 ± 2.29

These results provide a new insight into dust release mechanisms from conducting surfaces exposed to UV radiation and can lead to new mitigation approaches to improve the safe operation of particle accelerators, minimize losses in semi-conductor manufacturing, and maintain the thermal and optical properties of conducting surfaces of equipment on the lunar surface, for example.

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AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

Author Contributions

Kelyan Taylor: Data curation (equal); Formal analysis (equal); Visualization (equal); Writing – review & editing (equal). **Amanda Elliott:** Software (equal); Writing – review & editing (equal). **Xu Wang:** Conceptualization (equal); Investigation (equal); Methodology (equal); Supervision (equal); Writing – original draft (equal); Writing – review & editing (equal). **Mihály Horányi:** Conceptualization (equal); Funding acquisition (equal); Investigation (equal); Resources (equal); Writing – review & editing (equal). **Rudiger Schmidt:** Conceptualization (equal); Validation (equal); Writing – review & editing (equal). **Daniel Wollmann:** Conceptualization (equal); Writing – review & editing (equal). **Christoph Wiesner:** Conceptualization (equal); Writing – review & editing (equal). **Philippe Belanger:** Writing – review & editing (equal).

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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