ELECTROSTATIC DUST LOFTING: A POSSIBLE CAUSE FOR BEAM LOSSES AT CERN'S LHC

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Abstract

Dust particles interacting with the proton beams have caused many thousand beam-loss events at CERN's Large Hadron Collider (LHC), some of which led to premature beam dumps and even magnet quenches. It has been hypothesised that dust particles on the vacuum chamber wall of the LHC are negatively charged due to electron clouds and can detach from the chamber wall by the electric field of the beam. To test this hypothesis, we performed experiments to study the electrostatic lofting of dust particles from a conducting surface. A monolayer of SiO2 particles with a diameter of <44 um is deposited on such a surface and exposed to an electron beam of ~120 eV. An external electric field of up to 3 kV/cm is then applied. The properties of dust charging and levitation are characterised from recorded high-speed videos. We observed that dust particles are lofted both during electron beam charging and during the application of the external electric field. Our results provide experimental evidence that dust particles can be detached from a conducting surface and help to understand the mechanism of how dust particles can enter the LHC beam.

DUST IN THE LHC

Dust grains interacting with the beam in particle accelerators are the cause of detrimental effects such as beam losses, emittance growth, pressure bursts, magnet quenches and even damage of accelerator components.

During CERN's Large Hadron Collider (LHC) operation, tens of thousands of beam loss events, referred to as unidentified falling objects (UFOs), have been attributed to isolated dust grains interacting with the proton beam. Such events happen at a rate of a few occurrences per hour all along the accelerator and are characterized by beam losses lasting up to a few milliseconds, typically with an asymmetric Gaussian profile [1].

If the beam losses measured by beam loss monitors exceed a threshold, the beams are extracted to prevent detrimental effects such as magnet quenches.

The presence of dust grains in the LHC vacuum chamber is not fully understood. Observations suggest that dust was introduced during assembly of the machine. It seems unavoidable, even with careful cleaning measures. It is also possible that solid dust grains are created by the flaking or sputtering of the inner walls of the chamber with time.

Dust grains can be made of insulating or conductive materials, or possibly a mixture of both. For dust grains made of conductive material, it is possible that an oxidised layer creates an electrical separation between dust grain and adjacent surface. From energy deposition studies and dust collection in sections of the accelerator, the size of the grains leading to observable beam losses is believed to be in the order of 1 μm − 100 μm. The precise composition of the contaminants is not known, although metallic and ceramic components have been found.

There is evidence for the presence of ceramic dust in the LHC. In 2010 and 2011, many UFOs were observed at a specific location in the LHC and later identified as macro particles originating from the ceramic tube inside the injection [2]. The problem was solved by modifying the kickers [3].

The initial hypothesis to explain UFO events was that dust grains fall from the top of the beam screen / vacuum chamber due to gravity and enter the vicinity of the beam, where they are ionized and eventually repelled.

To explain the time profile of beam losses, in particular the fast rise times observed, it has been shown that an initial negative charge is required on the grains [4]. This is in line with observations indicating that dust grains can enter the beam from a position not directly above the beam and are attracted towards the beam due to their negative charge. The charging mechanisms acting on a single dust grain relevant for LHC are assumed to be [5]:

1. Electron collection: Incoming low energy electrons, for example from electrons clouds, are captured in the bulk of the grain. This mechanism leads to a negative charging current.
2. Secondary electron emission (SEE): Particles, typically electrons, deposit energy in the bulk of the grain and excite secondary electrons escaping the dust grain. This mechanism leads to a positive charging current.
3. Photoelectric emission: Photons, typically generated by synchrotron radiation, excite electrons that then escape the grain due to the photoelectric effect. This mechanism leads to a positive charging current. These electrons can be captured by other grains and lead to a negative charging current.

Synchrotron radiation photons that hit the beam screen close to the dust grains could release electrons that could further contribute to charging the dust grain. From the beam loss analysis, the mechanism of interactions between dust grains and the beam is well understood. It remains to be explained how charged dust grains adhering to a conductive vacuum chamber overcome image charge forces and other forces and detach from the chamber.

Since it is likely that dust contamination will also occur in the High Luminosity upgrade of the LHC (HL-LHC)

[6] [7] and in future accelerators such as the Future Circular Collider (FCC [8]), it is important to understand how dust grains enter the beams in an accelerator.

DUST IN SPACE RESEARCH

Levitation of dust grains has been observed for many years in laboratory studies in the Laboratory for Atmospheric and Space Physics (LASP).

Recent laboratory studies at NASA's Institute for Modelling Plasma, Atmospheres and Cosmic dusT (IMPACT) at LASP have revolutionized the understanding of dust charging and lofting from planetary surfaces in space. A novel patched charge model is developed for multi-layered dust charging due to exposure to plasma and/or UV light. Re-absorption of secondary and/or photoelectrons within microcavities between dust particles can cause substantial negative charges on the surrounding particles leading to strong electric repulsive forces, and subsequent dust grain lofting, in line with experimental observations [9].

There are many similarities between dust grains on planetary bodies and accelerators (e.g., size, material). One difference is that in accelerators the dust grains are present in monolayers, whereas on planetary bodies there may be thick layers of dust. Another difference in the environment comes from the presence of high intensity particle beams and strong magnetic fields. In the LHC, about $3\cdot10^{14}$ protons are circulating in the vacuum chamber with a diameter of 56 mm. The proton beam creates a dense cloud of electrons with an energy between a few eV and some keV and the chamber is filled with synchrotron radiation photons emitted by the protons. The electric field of the proton beam attracts negatively charged dust grains.

Observations of dust lofting at LASP offer a new way to study the detachment of dust grains from the vacuum chamber in particle accelerators and have triggered experiments conducted at LASP in collaboration with CERN.

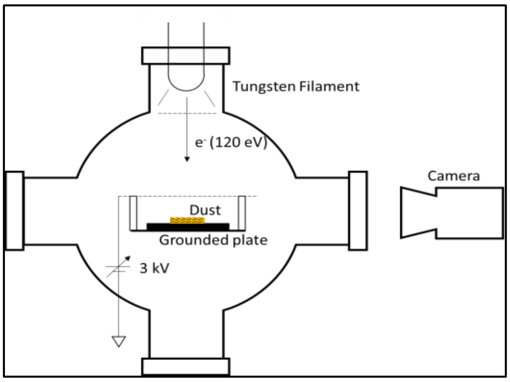

Figure 1: Experimental setup (principle).

EXPERIMENTAL PROCEDURE

Experiments were performed in an existing vacuum chamber at the University of Colorado IMPACT lab to study charging and release of dust particles from a surface with mono-layered dust particles (Figure 1 and 2). The experimental procedure has of the following steps:

1. Deposit a monolayer of silica dust, SiO_2, < 44 µm in diameter onto a grounded conducting plate under a metallic mesh. The distance between mesh and plate is 0.5-1 cm.
2. Pump chamber down to less than $5\cdot10-6$ Torr.
3. Ground the mesh above the plate. Charge the dust by a tungsten filament that generates a beam of 60-120 eV energy electrons with a current of up to 180 mA.
4. Turn off charging. Apply a bias voltage to the mesh up to 3 kV, generating an electric field of ~3 kV/cm.
5. Record dust movement during charging and HV (Steps 3-4) with a high-speed camera at 900-1500 fps.

The camera recordings are analysed with a particle tracking script developed for the detection of lofted grains. The script estimates their size and tracks their trajectories to obtain velocity, acceleration, and charge.

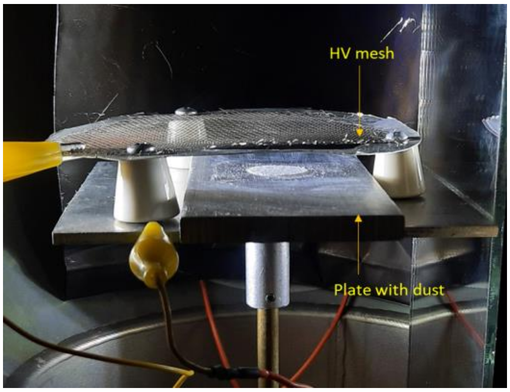

Figure 2: Experimental setup (photo).

OBSERVATIONS

High Voltage Lofting

With an electric field, the dust grains travel in vertical trajectories [10]. The charge q is calculated from the equation of motion

$$F_y = ma_y = m\frac{dv_y}{dt} = qE - mg \tag{1}$$

with the electric field

$$E = V/d, a_y \tag{2}$$

the vertical acceleration measured from the recorded trajectories, mg the force due to gravity, V the voltage on the mesh and d the distance between the mesh and plate surface. The surface potential is given by

$$\varphi = q/(4\pi\varepsilon_0 R) \tag{3}$$

with R the dust radius. The surface potential of the grain cannot exceed the energy of the electron beam. This is used to verify the consistency of the script results. In Fig. 4, the charge of the grain is shown as function of its size.

Although the data are not yet conclusive, there is a tendency that the magnitude of the charges increase with the size of the grains.

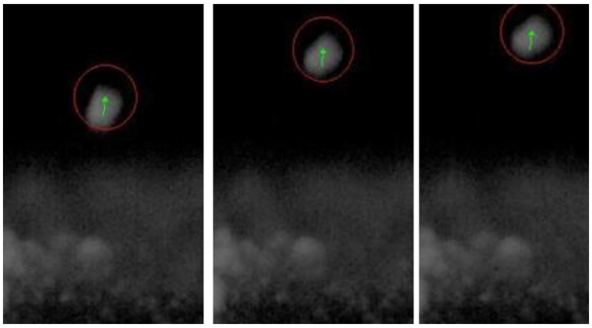

Figure 3: Example for vertical dust grain lofting in presence of an external electric field.

Lofting during Charging

Without high voltage, dust grain trajectories are parabolic (see Figure 5). The launch velocity is calculated by video analysis. In Figure 6, the launch velocity for our experiments is compared to data from previous experiments [10], where lofting was observed for multi-layer dust.

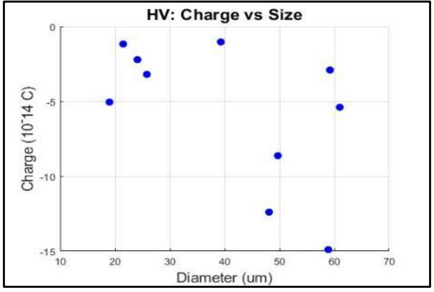

Figure 4: Charge versus grain size for lofting with an electric field, obtained from video analysis.

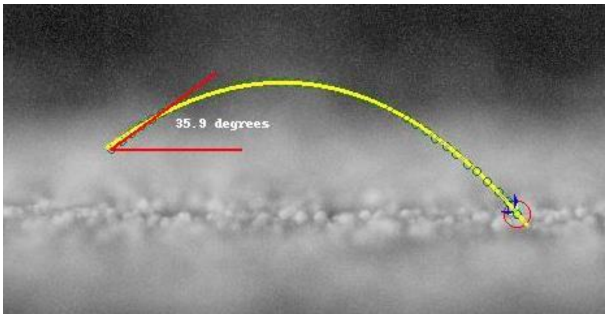

Figure 5: Example for dust grains lofting with a parabolic trajectory during charging (no external electric field).

Other Observations

During one experiment, a 1-2 mm thick glass plate was inserted between conducting plate and dust grains. The lofting rate strongly increased. This can be explained by a strong reduction of the image charge and subsequent image force between grain and conducting plate that tend to prevent lofting.

Without insulating surface between dust and conducting surface, only a small fraction of the dust grains is lofted. When the experiment is repeated with the same dust sample, the lofting rate is not very reproducible.

The lofting rate is higher when the chamber is filled with fresh dust. This observation is like observations in the LHC: it is more likely that UFOs originate from newly installed equipment than from other parts of the machine.

DISCUSSION

There is a clear observation of dust grain lofting of monolayer dust from conducting surfaces. Several forces act on the dust grain to prevent it from lofting: gravity and the adhesive forces between the plate and the grain.

In the case of charged grains, the image charges and the resulting image force also counteract lofting.

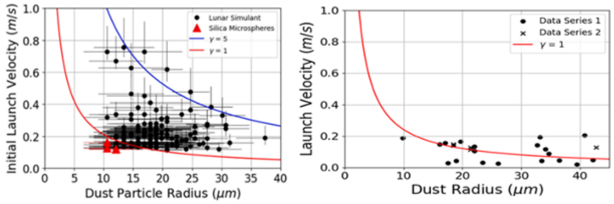

Figure 6: Initial launch velocity for multi-layer dust (left) versus monolayer dust (right). The theoretical curves (solid lines) for Lunar Simulants and Silica Microspheres are taken from [10]. γ accounts for the geometric effects and contributions of other nearby particles to the net repulsive force.

This force is proportional to the square of the dust grain charge and decreases with the square of the distance between dust grain and conductive plate. The force from the electric field, proportional to the charge, can cause lofting. For very small values of the grain charge, gravity is strongest; for large values of the charge, the image forces dominate. In both cases, lofting is expected to be prevented.

It is surprising that for monolayer dust, lofting occurs during the charging process even without an electric field. The mechanics is not fully understood and requires further investigations. Charge, shape, and material parameters of the dust grains can play a role. The quality of the surface could also play a role. Lofting from rough and polished surfaces is expected to be different. Forces from a torque on a dust grain that are anisotropic could also play a role.

CONCLUSIONS

We observed that dust particles are lofted both during electron beam charging and during the application of an external electric field. There is consistently high activity when charging at 80 eV and low currents, when compared with other energies ranging from 60 eV to 120 eV. We theorize the presence of a space-charge limited (SCL) plasma sheath [11] between the plate and the mesh, which would explain why the 80 eV charging potential is preferred.

Our results provide experimental evidence that dust particles can be detached from a conducting surface and help to understand the mechanism of how dust particles can detach from the vacuum chamber and enter the LHC beam.

Future investigations are required to fully understand the mechanisms involved in charged monolayer dust lofting from conducting surfaces. Once understood, dust lofting mitigation techniques could be developed and implemented in the LHC and future accelerators.

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