Dust Charging and Lofting Experiments at IMPACT

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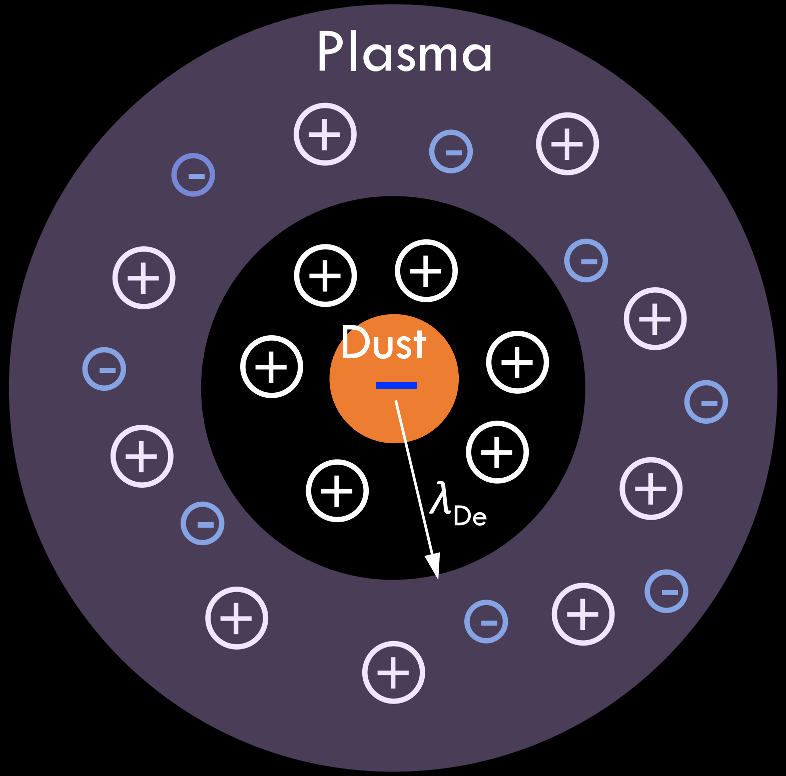
Two Phases of Electrostatic Dust Lofting Problems

I. Dust dynamics after being lofted

(More advanced studies)

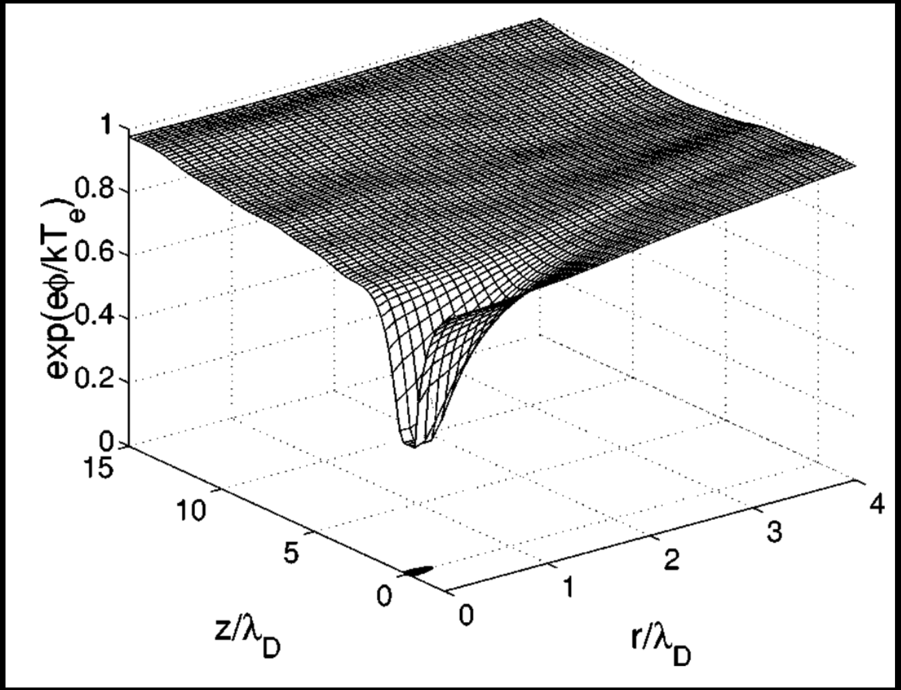
Charging of Dust *Suspended* in a Plasma



Debye Shielding

(λ_{De}: the Debye length)

Potential Contours around a charge dust particle



Lapenta, 1999

$Q = C\phi$

where, $C = 4\pi\varepsilon_0 r$;

ϕ is determined by the electron and ion current balance to the particle.

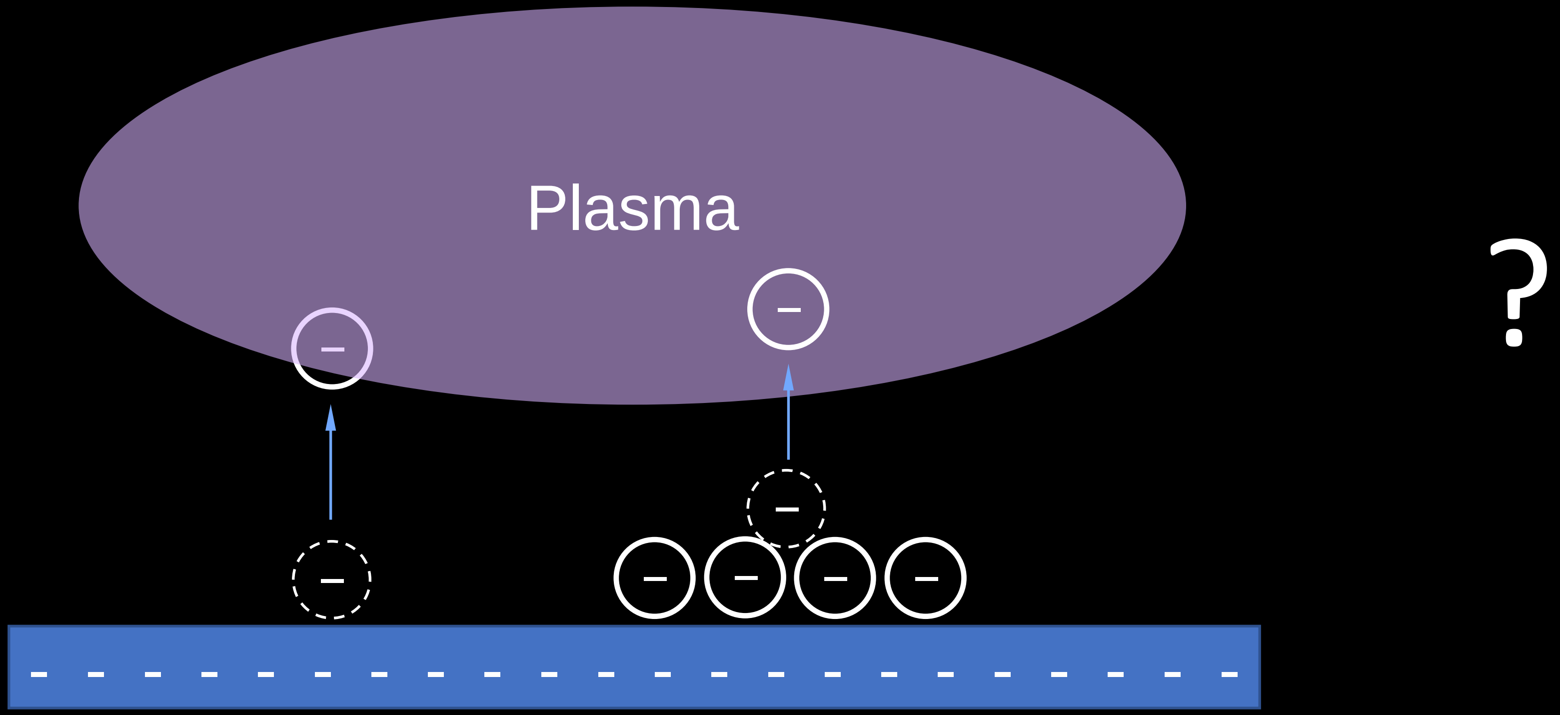
When $r \ll \lambda_{De}$, the Orbital Motion Limited (OML) theory (Tonks and Langmuir, 1929) is used to determine the current collection by a dust particle.

Two Phases of Electrostatic Dust Lofting Problems

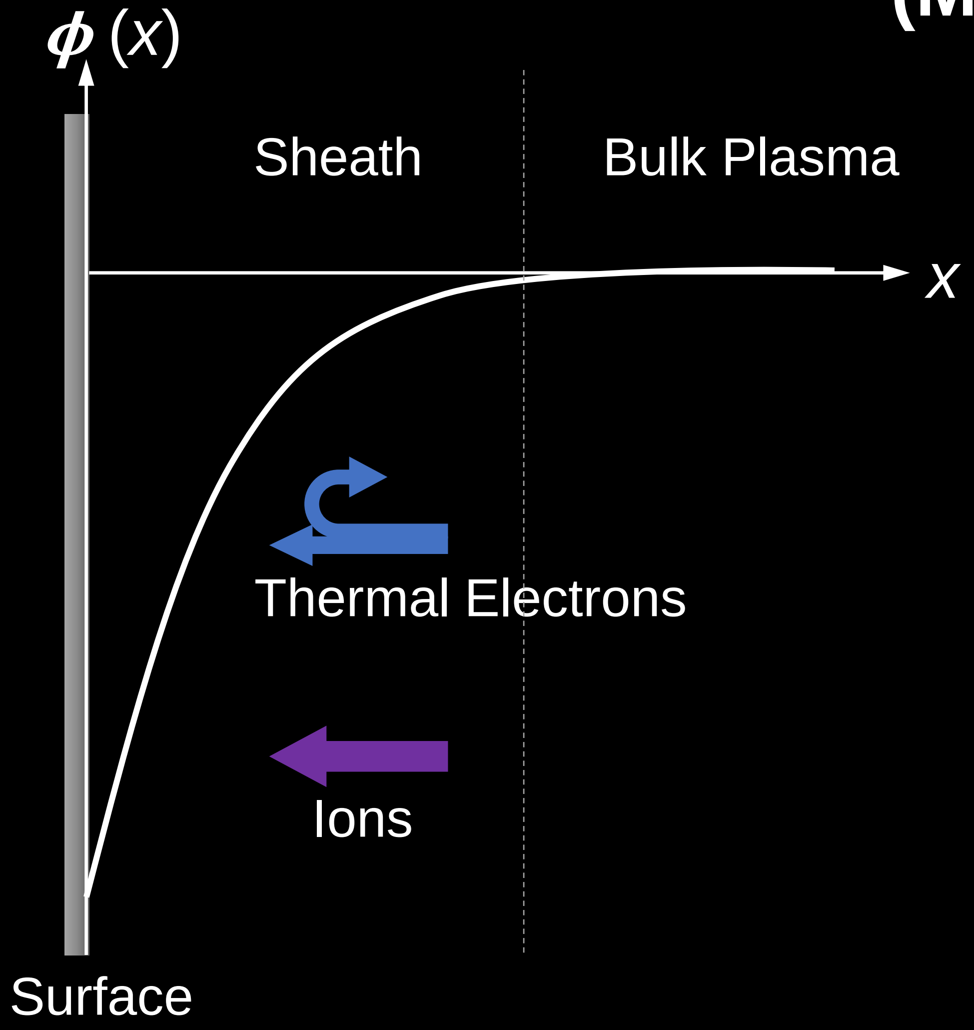
II. Initial dust lofting from a surface

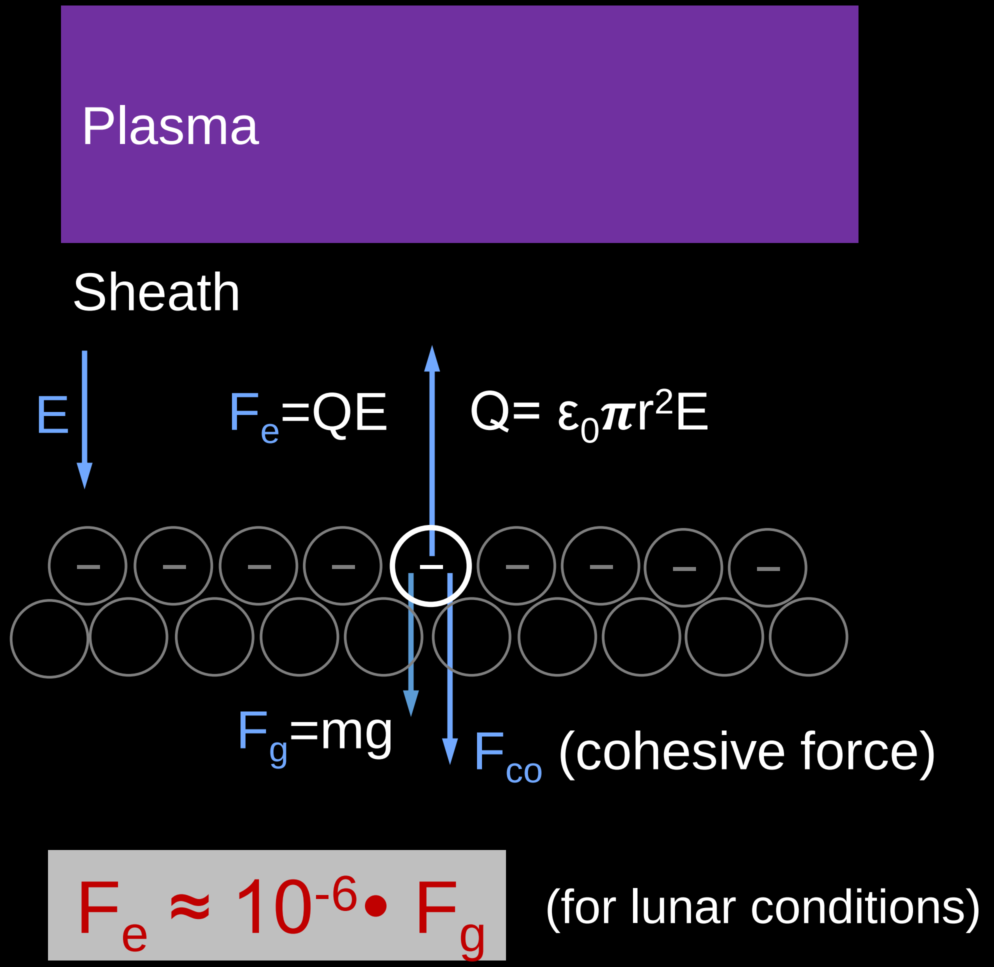
(Not so well-understood)

Charging and Lofting of Dust *on* a Surface



A Conventional Theory - Shared Charge Model
(Macroscale)



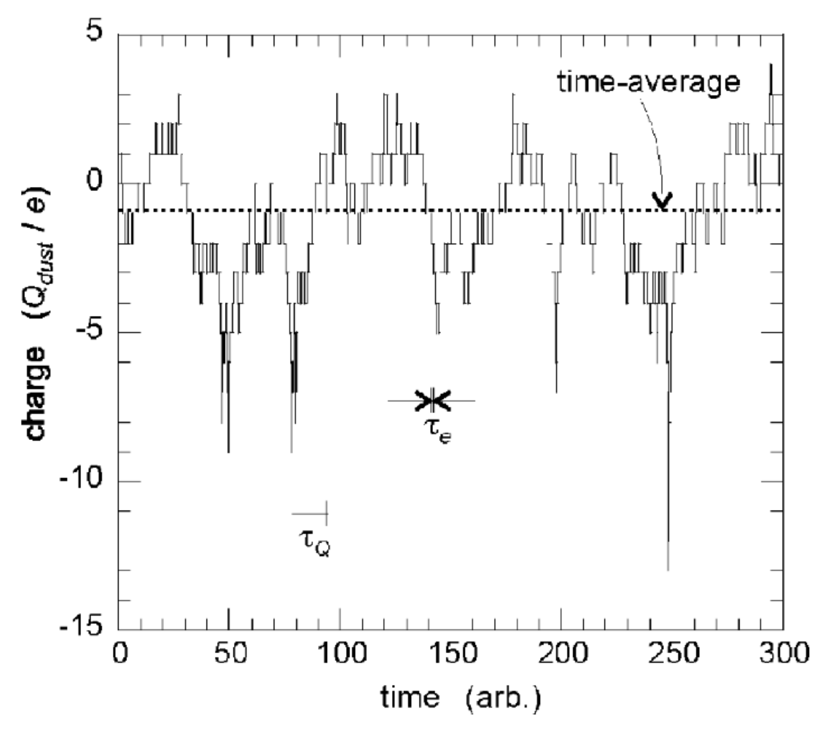


Sheath, a non-neutral region, balances the fluxes of electrons and ions to a solid surface.

Charge and thus electrostatic force is too small for dust particles to be lifted from the lunar surface.

A Charge Fluctuation Theory **(Macroscale)**

Stochastic process of individual electrons and ions collected by a surface (Sheridan et al., 1992; Cui et al., 1994; Flanagan and Goree, 2006), so



Flanagan and Goree, 2006

$$Q_{dust}(t) = \overline{Q_{dust}} + \delta Q_{dust}(t)$$

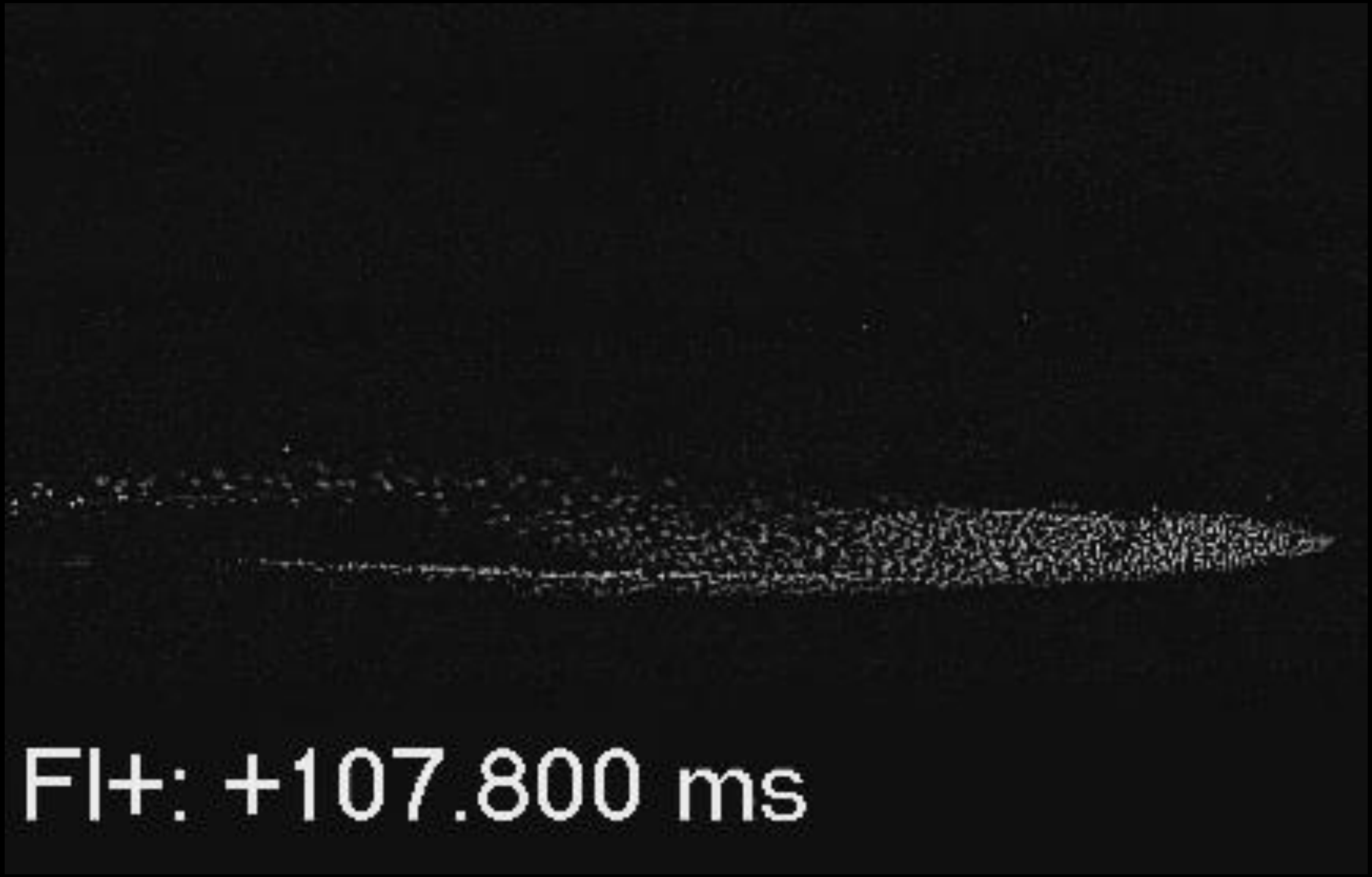
The fluctuation magnitude can be estimated as (Sheridan and Hayes, 2011)

$$\frac{\delta Q_{dust}^{rms}}{e} = \sqrt{\frac{CT_e}{e}}$$

where, C is the capacitance of the particle-surface system
T_e is the electron temperature
e is the elementary charge

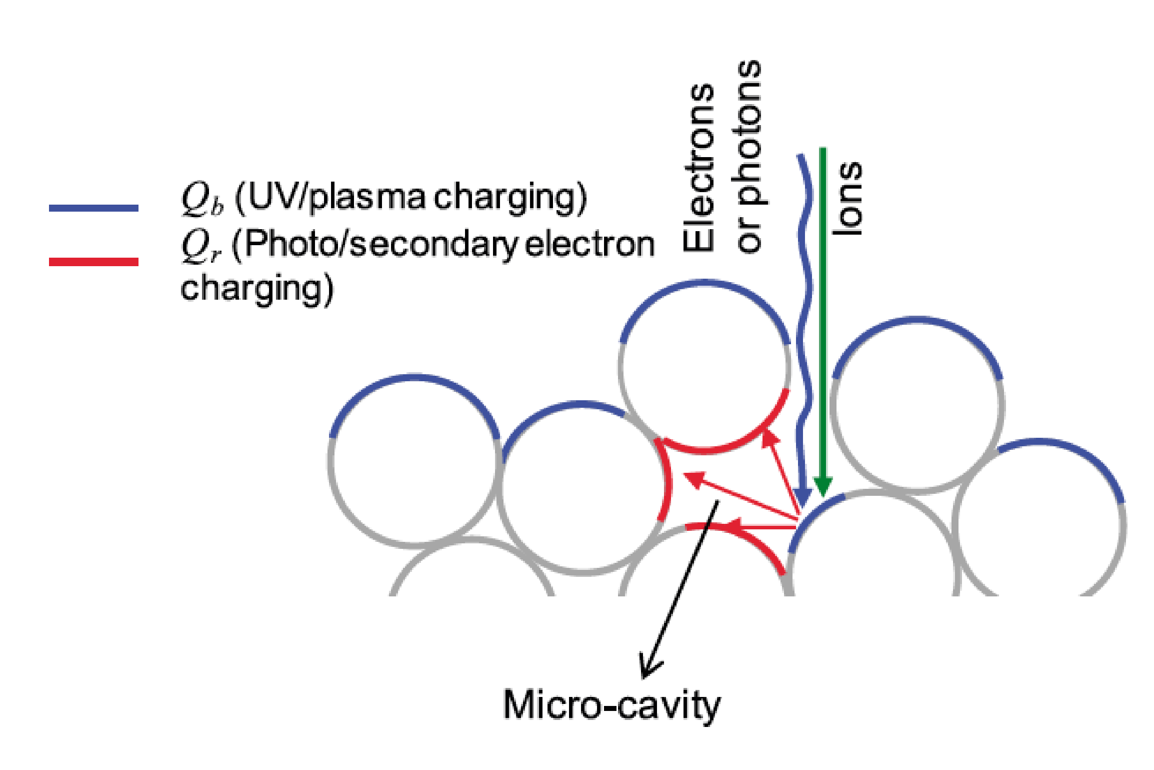
Charge and thus electrostatic force is **still too small** to lift dust from the lunar surface

Dust Lofting Experiments in the Laboratory



Dust lofting trajectories recorded under exposure to 120 eV electron Beam

Novel “Patched Charge Model” (Microscale)



Wang et al., 2016

According to Gauss’s law

$Q_b \propto (\phi_b - \phi_p) / \lambda_{De}$

$Q_r \propto (\phi_r - \phi_b) / r$

$\boldsymbol{Q_r >> Q_b}$ **due to** $\boldsymbol{r << \lambda_{De}}$

$\boldsymbol{Q \approx Q_r \approx -0.5C(\eta T_{ee}/e)}$**,**

where, $C = 4\pi\varepsilon_0 r$

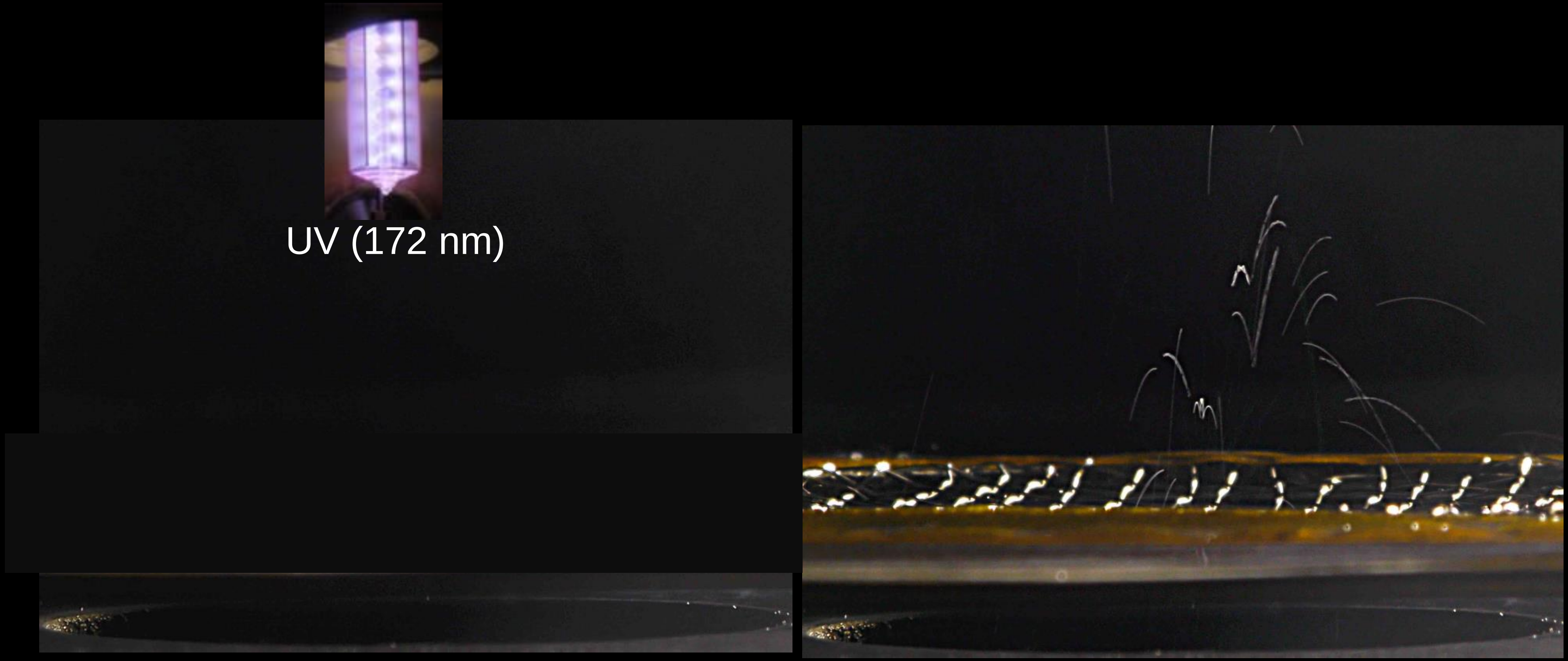
T_{ee} is the emitted electron temperature in eV.

ηT_{ee} represents high-energy tail electrons.

η: 4 ~ 10, empirical constant determined from experiments.

- **Photo- or secondary electrons** are absorbed within **microcavities** and collected by the surrounding dust particles, resulting in **substantial negative charges** on their surfaces.
- **Repulsive forces** between the negatively charged particles cause them to be lofted from the surface.

Charge Measurements (Polarity)



Negative voltage (-3 kV) grid

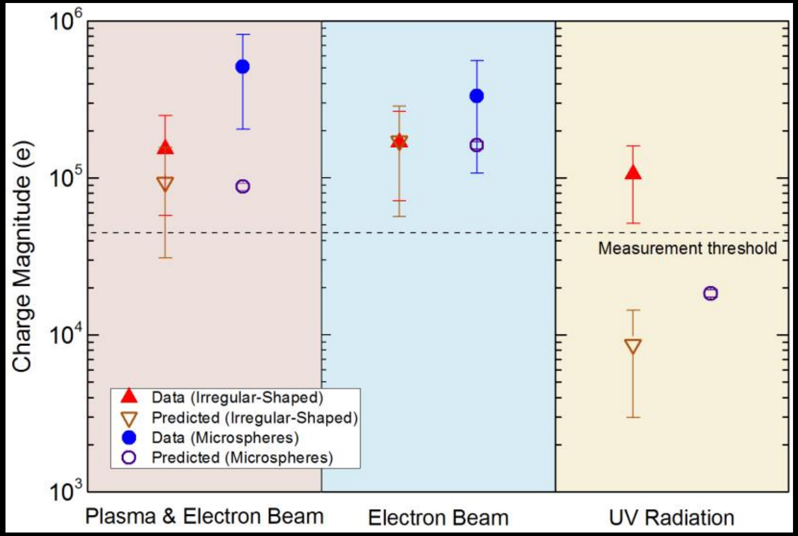
Positive voltage (+0.5 kV) grid

Schwan et al., 2017

All lofted dust particles are charged negatively, even under UV radiation. This is contrary to the generally expected positive charge due to photoemission but agrees with the Patched Charge Model.

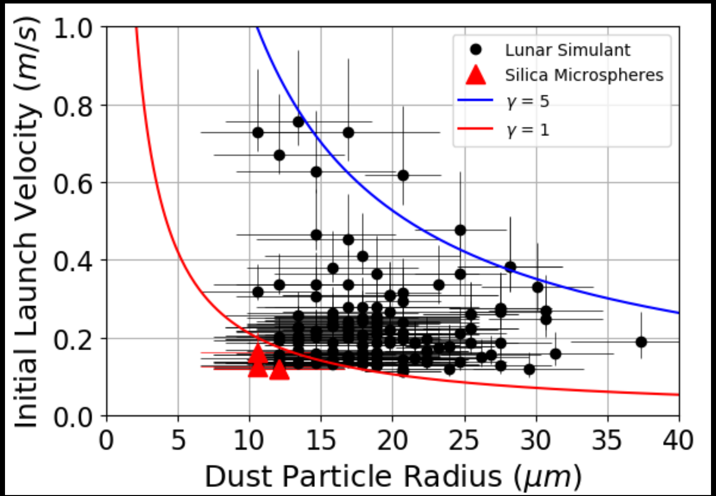
Characteristics of Lofted Dust Particles

Charge Magnitudes



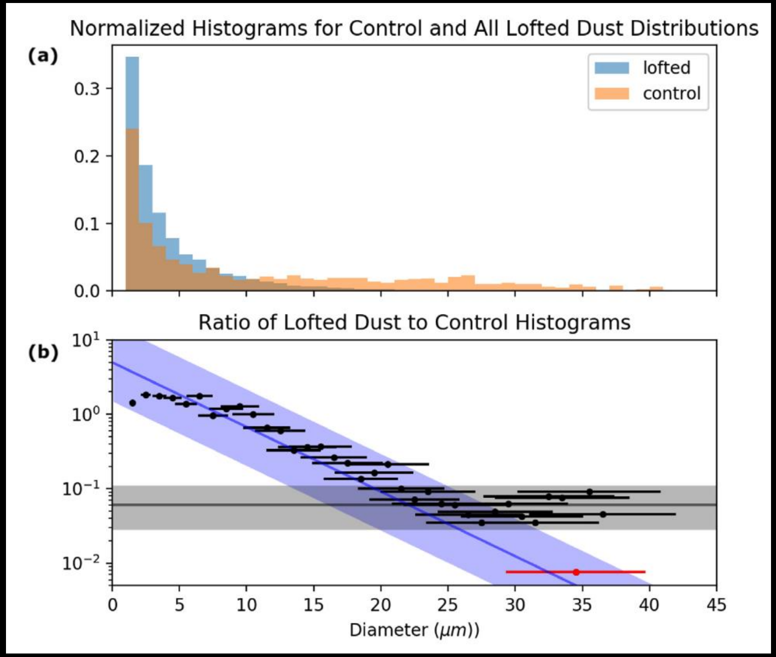
Schwan et al., 2017

Initial Velocities



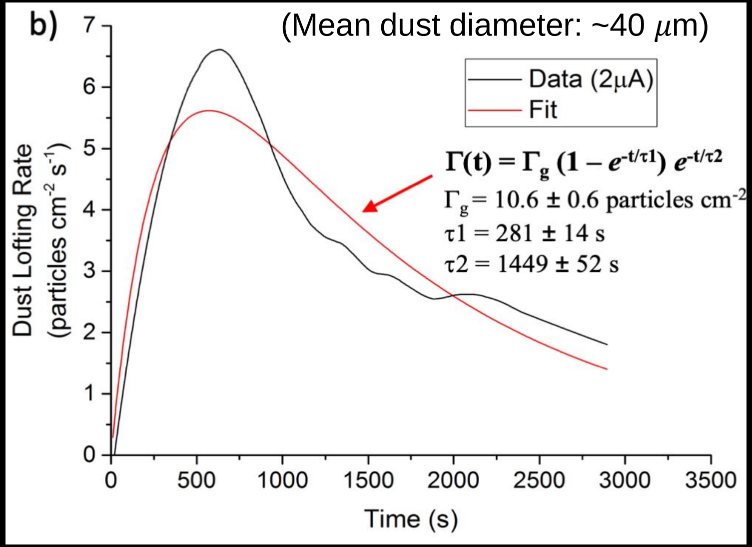
Carroll et al., 2020

Size Distributions



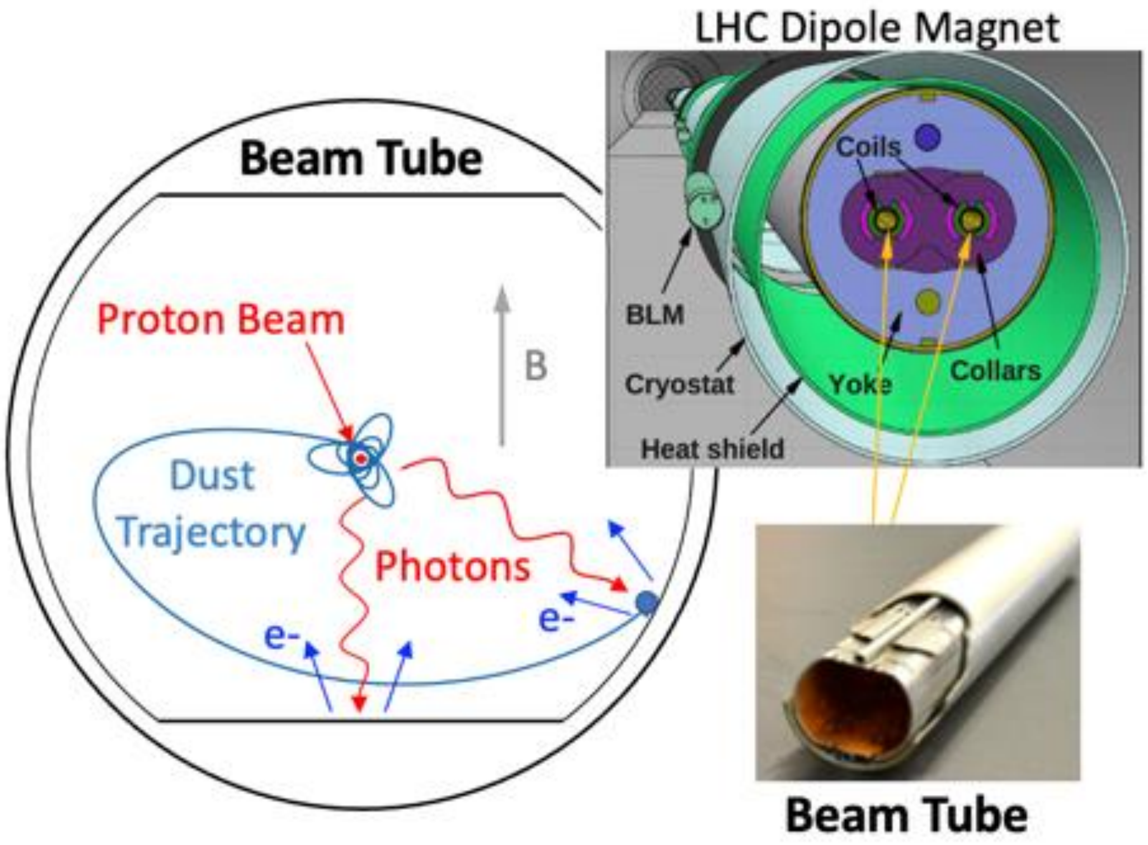
Hood et al., 2022

Lofting Rates



Hood et al., 2018

Experiments for CERN Dust

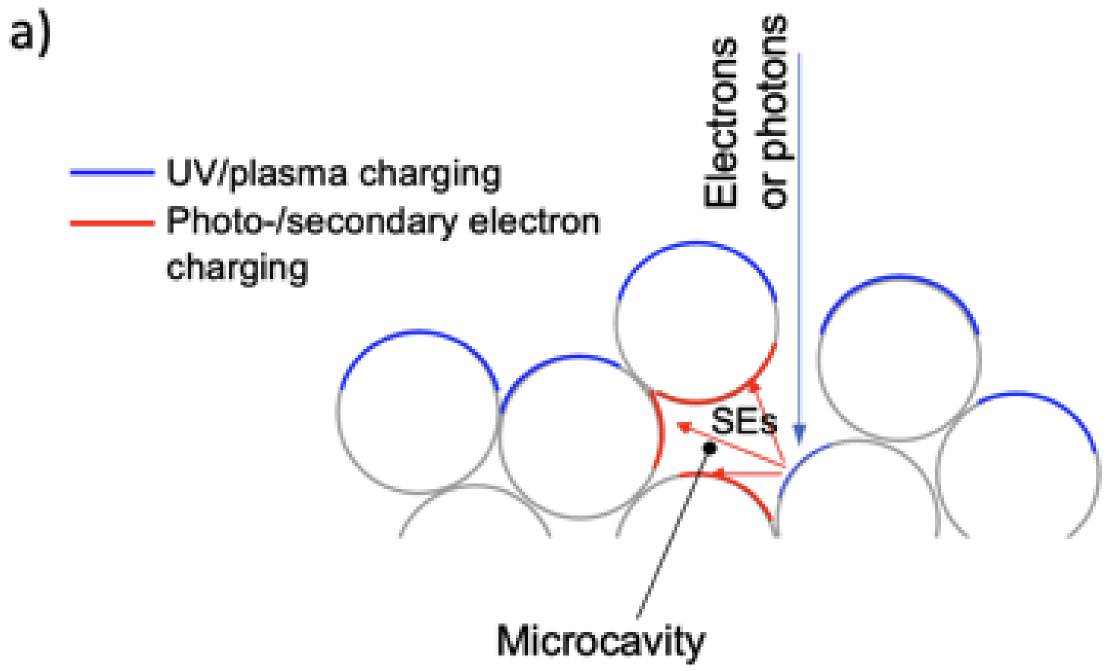


The **goal** is to understand dust charging and lofting from the chamber wall in the LHC beam tube

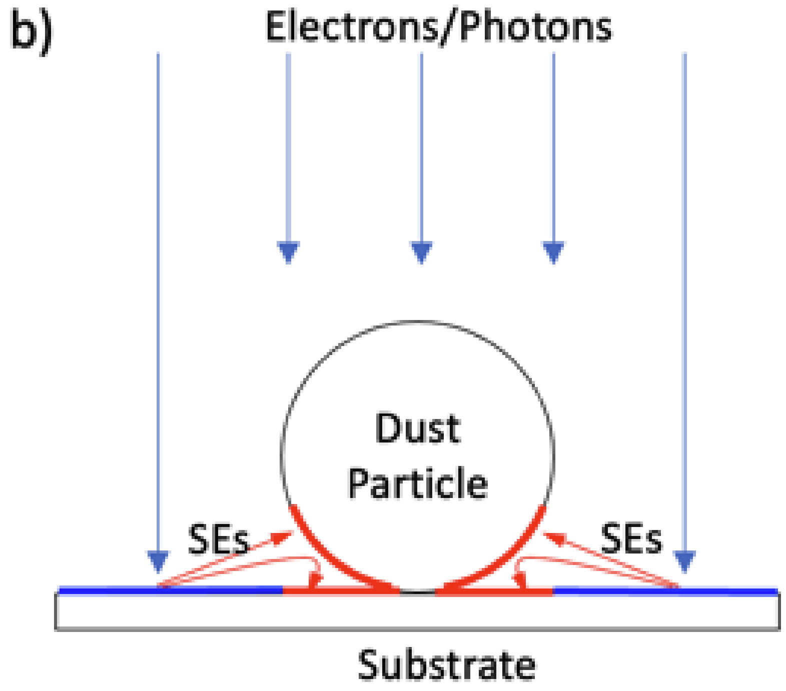
Key conditions:

- Single dust particles on a conducting surface
- Photons from synchrotron radiation
- Energetic and thermal electrons
- E field: ~ 2000 V/m
- B field (not included in current studies)

Extended Patched Charge Model



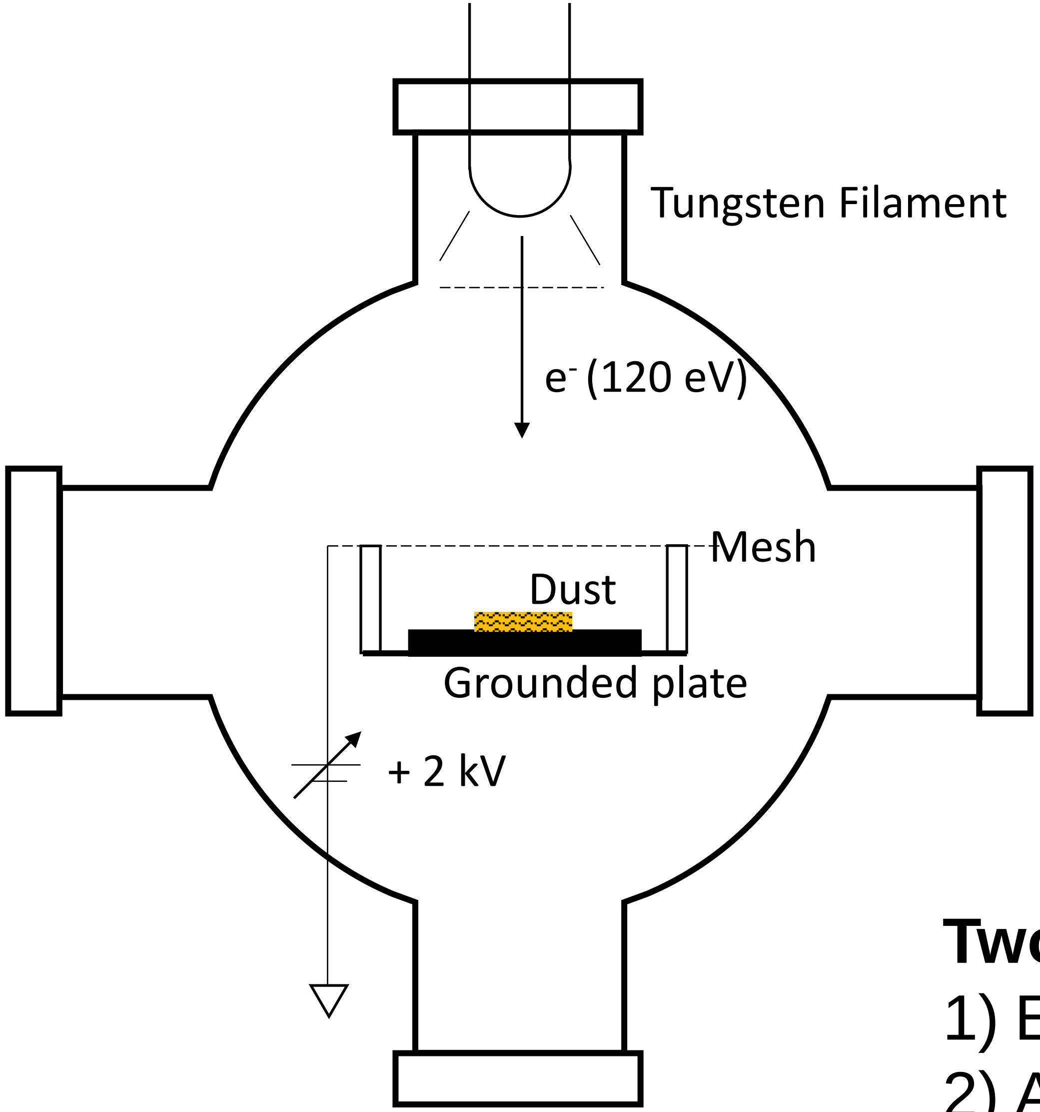
Multi-layer Dust

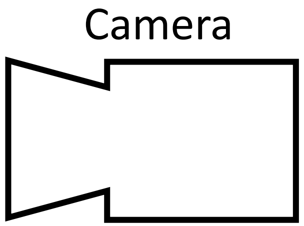


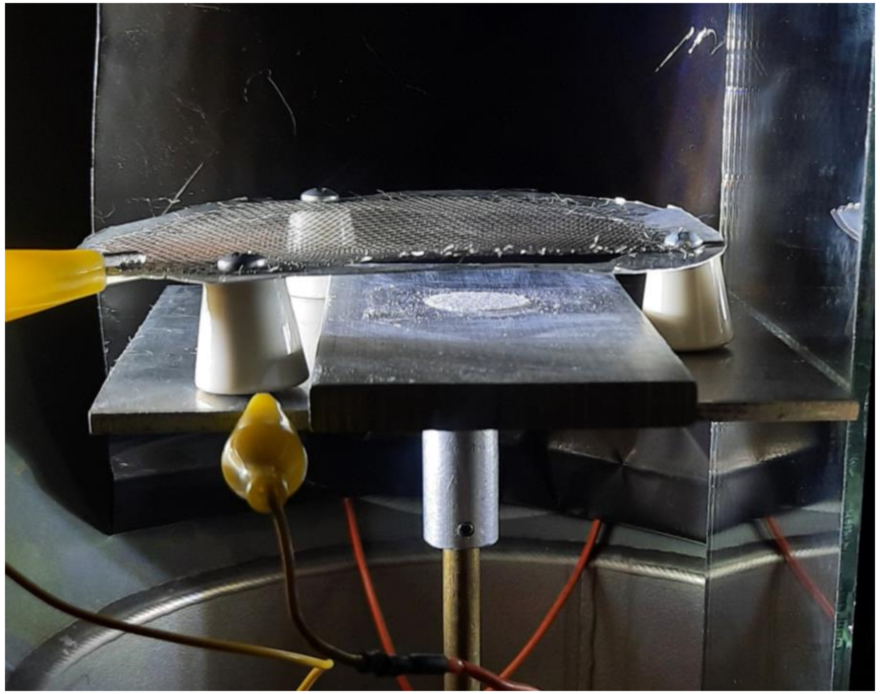
Mono-layer Dust

* A thin oxide layer is often formed on a conducting surface

E-beam Charging and Lofting Experiment



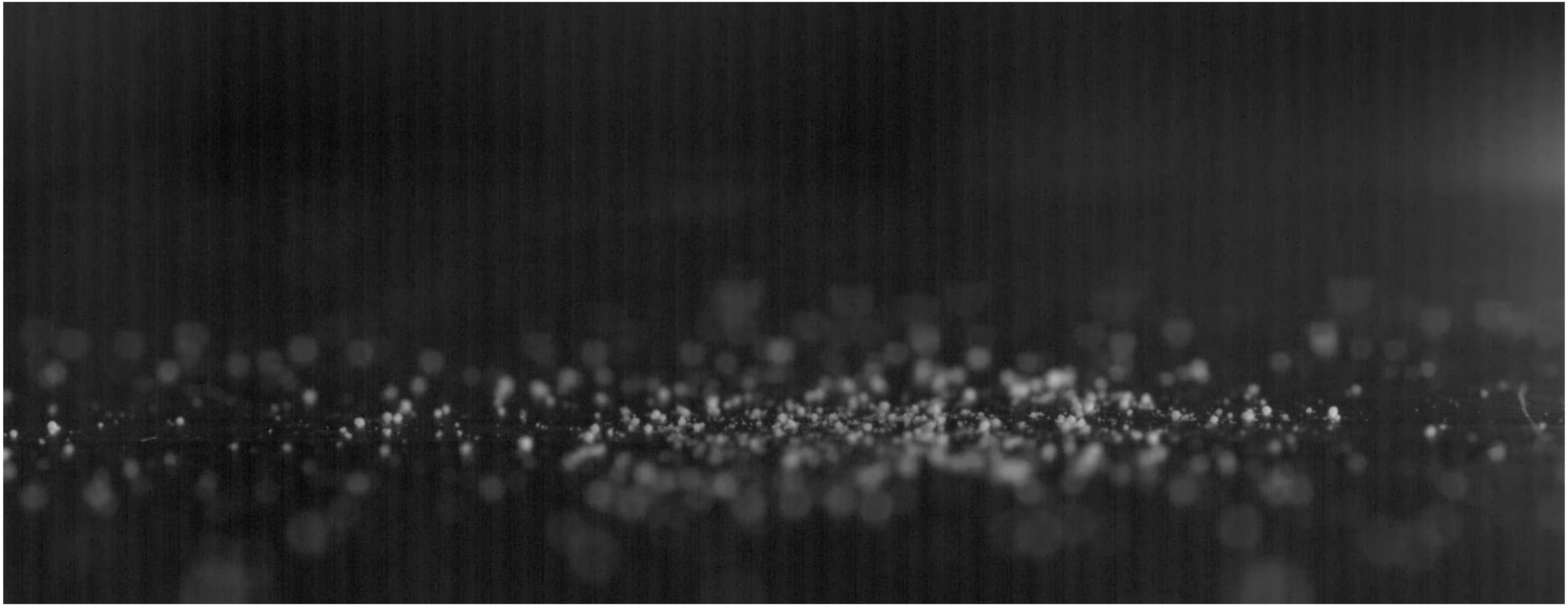




Two Steps:
1) E-beam charging
2) Apply HV on mesh

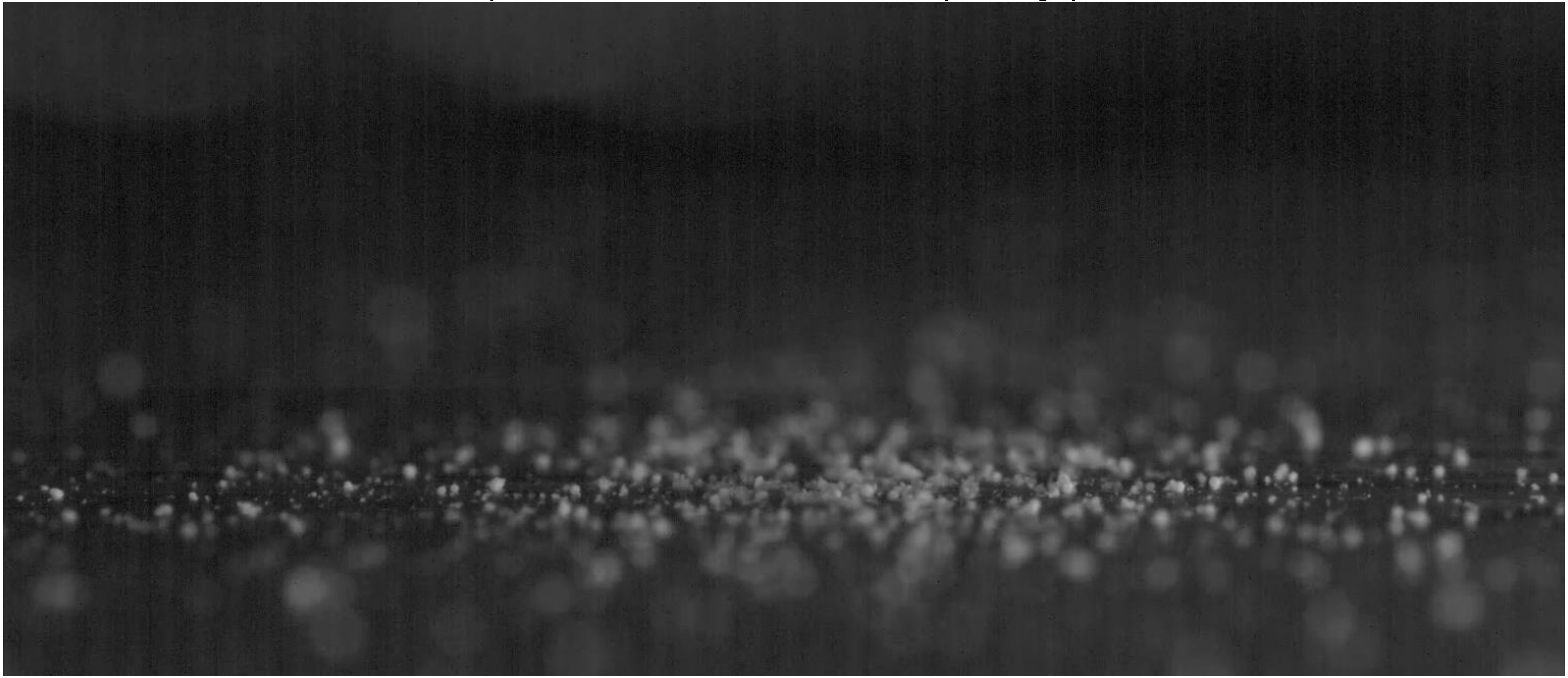
I. **Slow Increase** in Beam Current

- No dust movement was observed during charging
- **Applying HV after charging shows a handful of particles lofted**



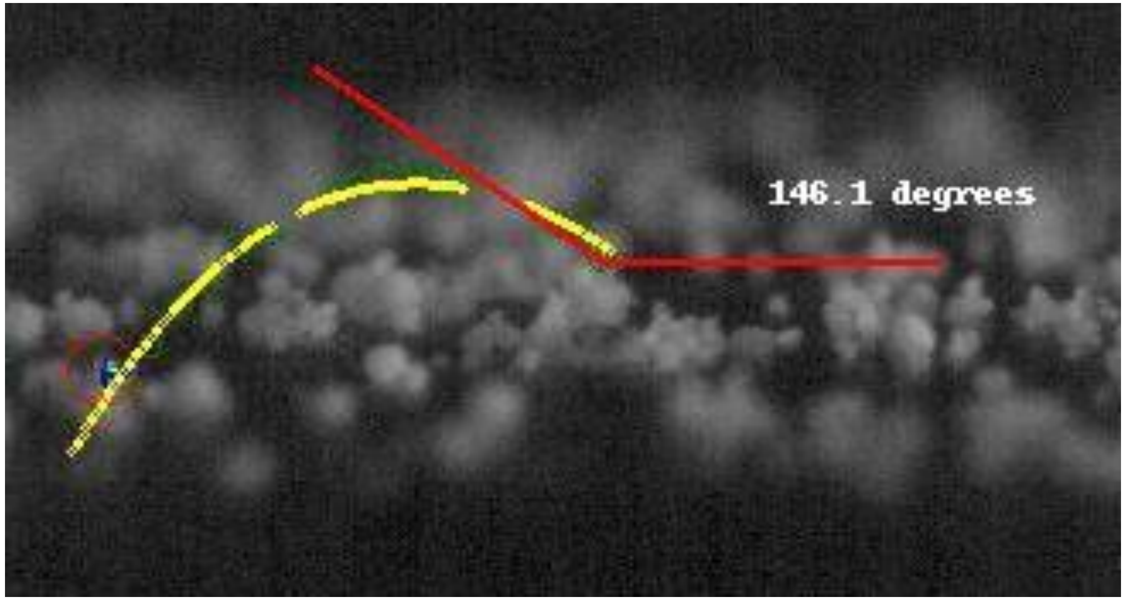
II. **Step Increase** in Beam Current

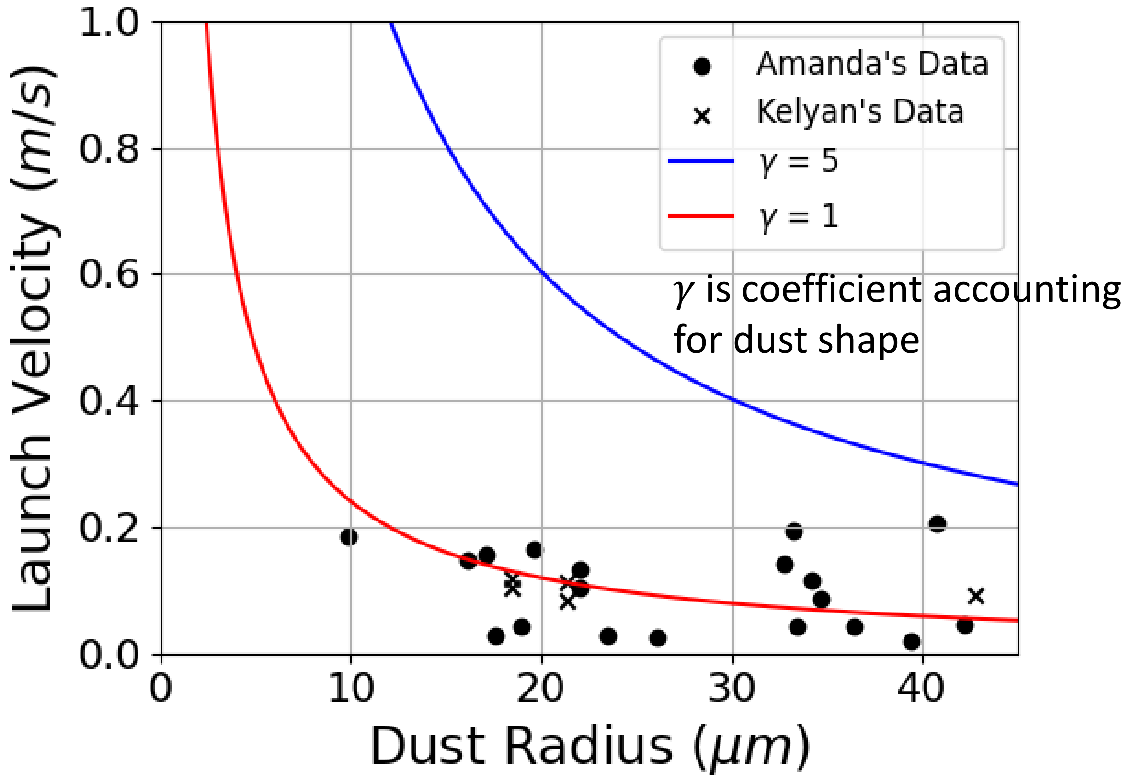
(a similar case of beam bunch passage)



Dust lofting is observed. It could be because a transient high flux of the beam causes a **charge overshoot** before reaching equilibrium, resulting in dust lofting.

II. **Step Increase** in Beam Current

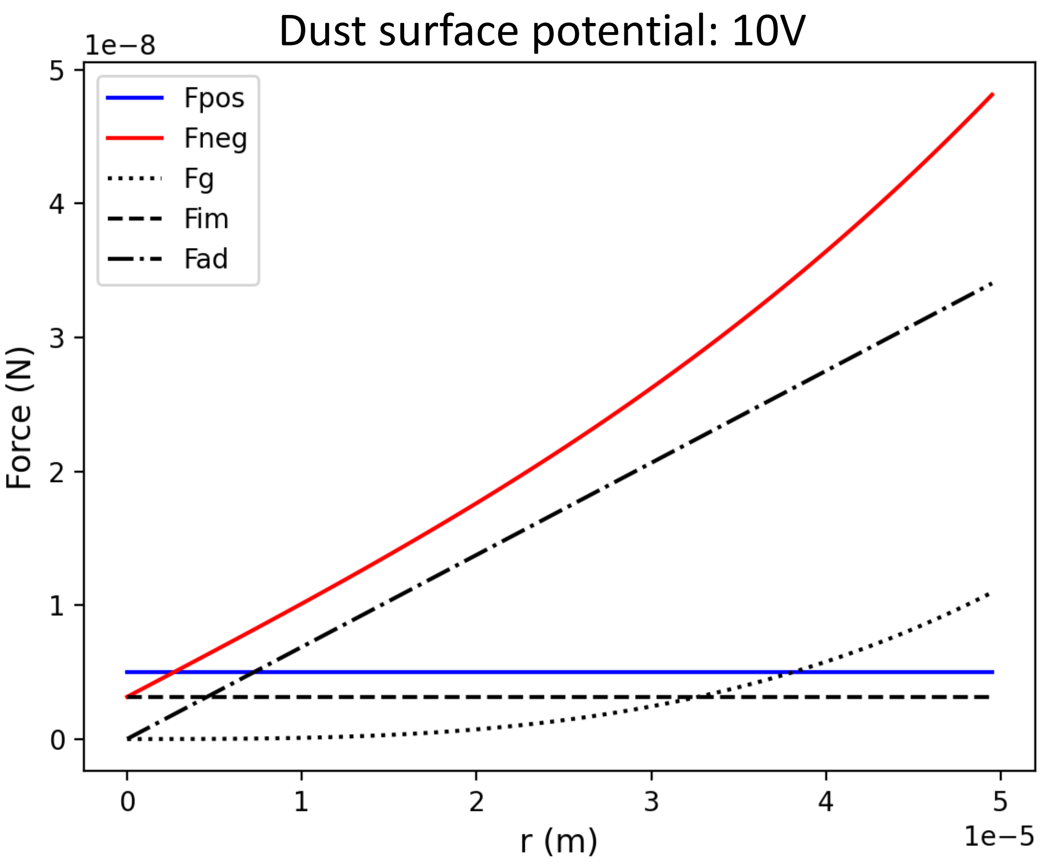




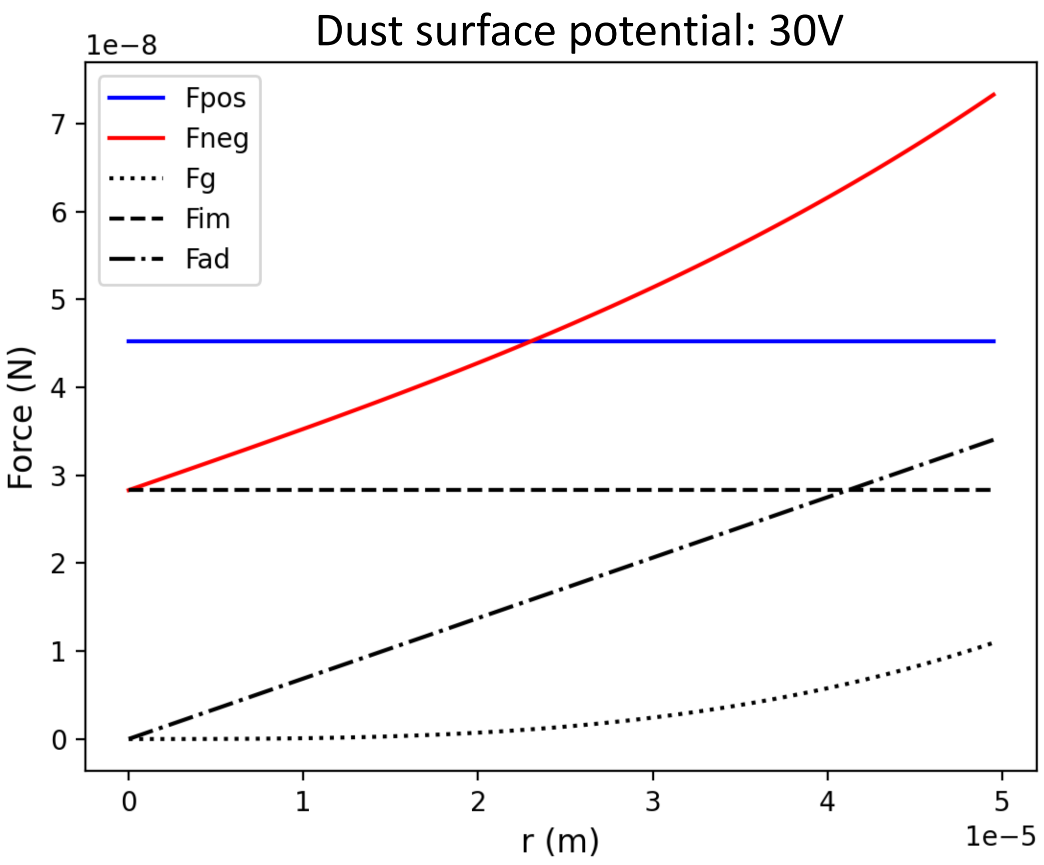
1) Monolayered dust is more difficult to be lofted due to smaller vertical components of the repulsive forces.

2) **Image force** between the charged dust and conductive surface attracts the dust on the surface, making lofting more difficult than from an insulating surface.

Forces vs. Dust Size (Simple Exercise)



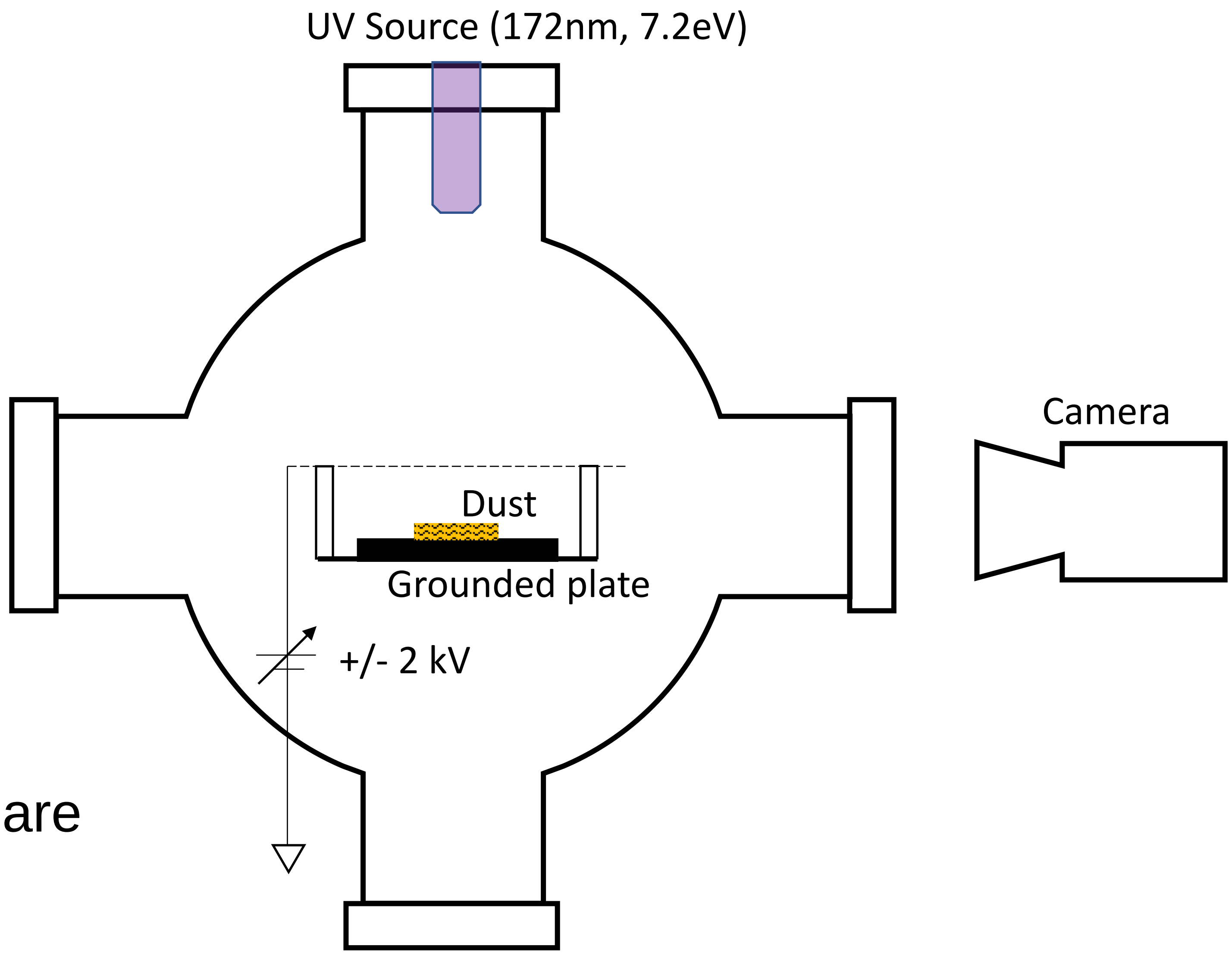
Dust with r < 3μm is lofted



Dust with r < 23μm is lofted

- Image force decreases lofting probability
- Increase in charge enhances lofting probability

UV Charging and Lofting Experiment



One Step:
Both UV and HV (+ or -) are applied simultaneously

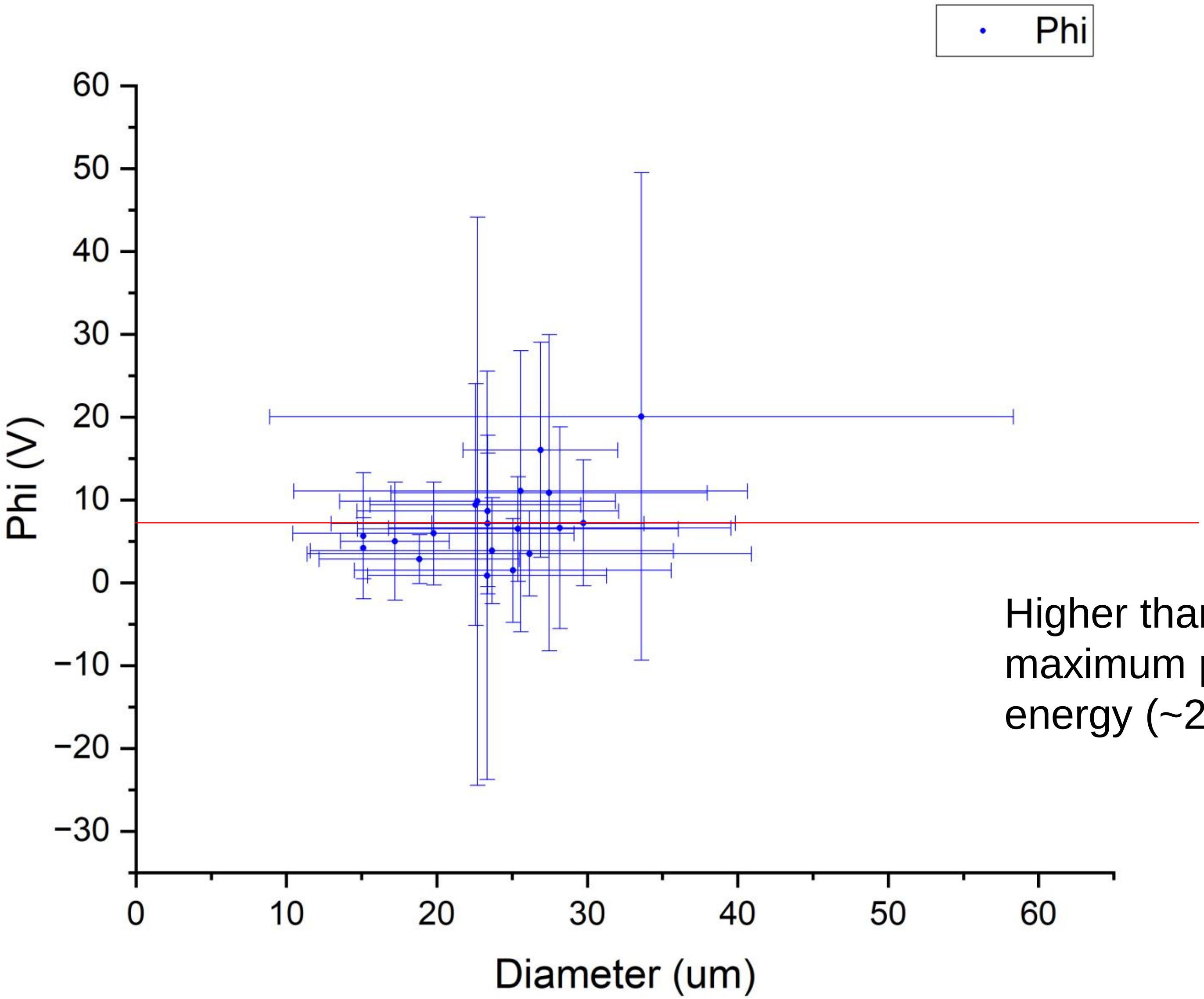
Negative HV w/ UV Charging

Dust particles are lofted in vertical trajectories

Dust surface potential vs. size (Preliminary Analysis)

- Charge is calculated from the equation of motion:
  $F_y = ma_y = m\frac{dv_y}{dt} = qE - mg$ and $E = V/d$.

  Surface potential: $\varphi = q/(4\pi\varepsilon_0 R)$



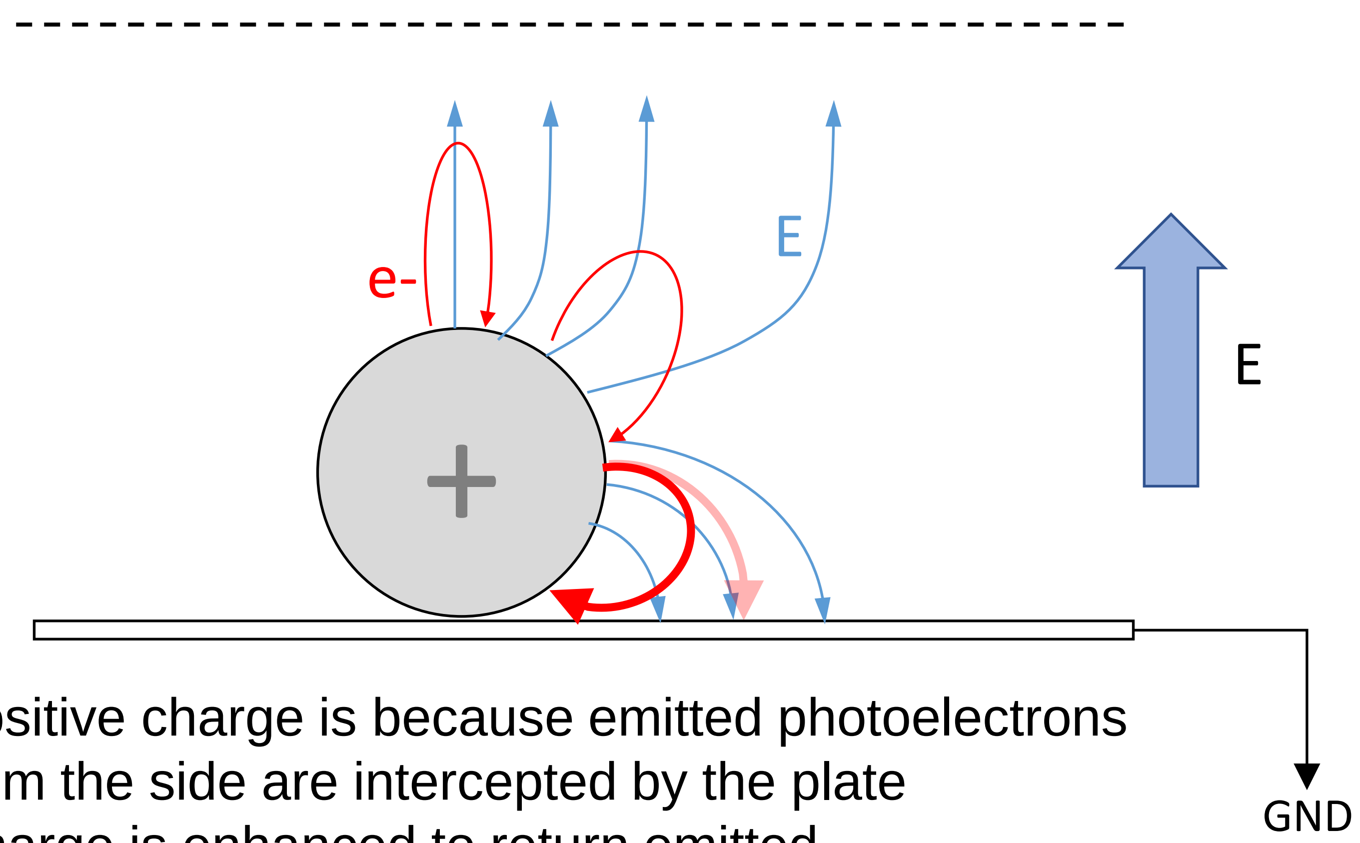
+7V

Higher than the maximum photoelectron energy (~2 eV) **?**

Qualitative Interpretation

<u>HV is negative</u>

Dust particles are lofted vertically, indicating particles are charged **positively**.



- Positive charge is because emitted photoelectrons from the side are intercepted by the plate
- Charge is enhanced to return emitted photoelectrons from the side, causing ϕ_d (+7V) > E_{ph_max} (<2 eV)

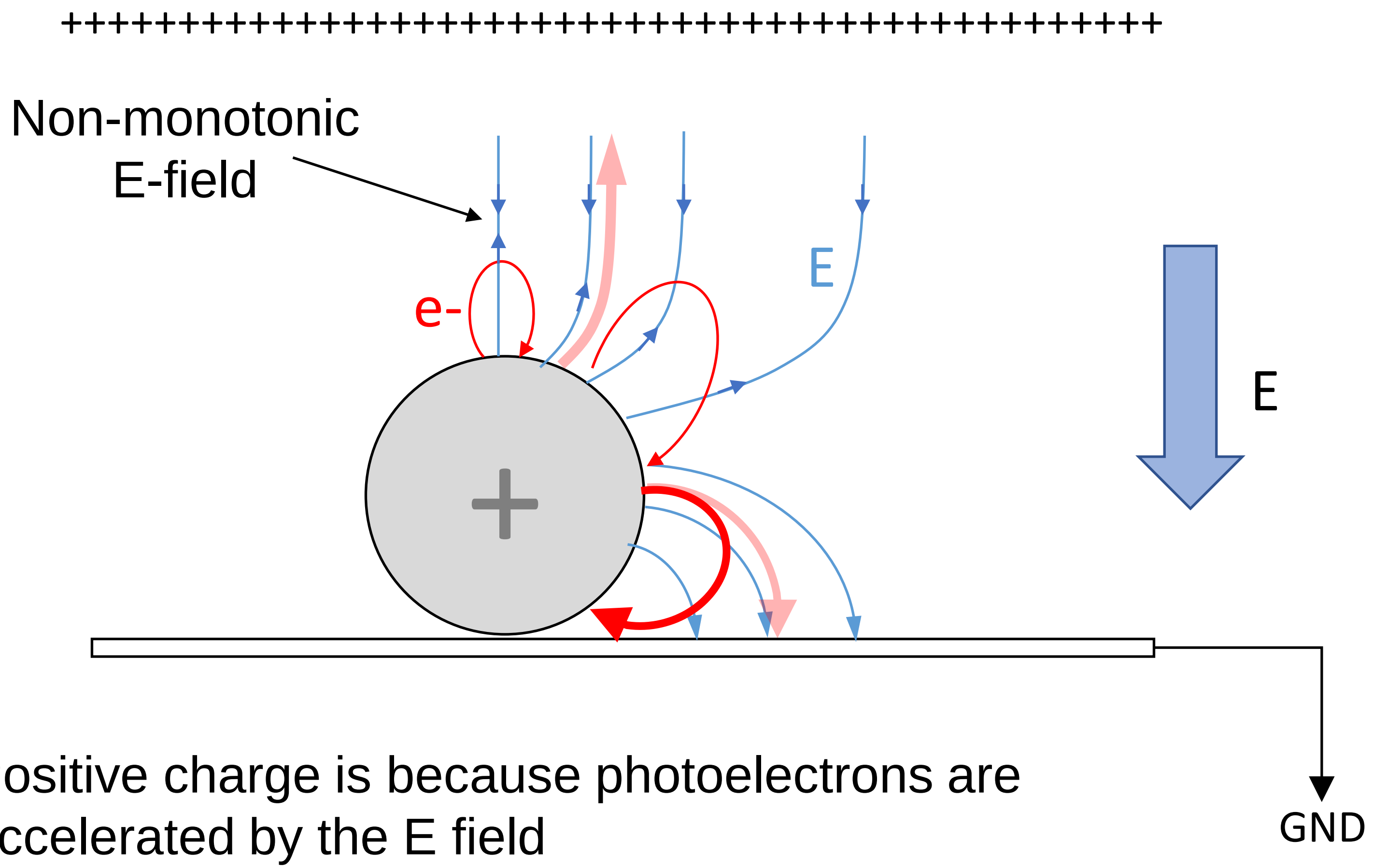
Positive HV w/ UV Charging

Dust particles spin and “bounce” on the surface

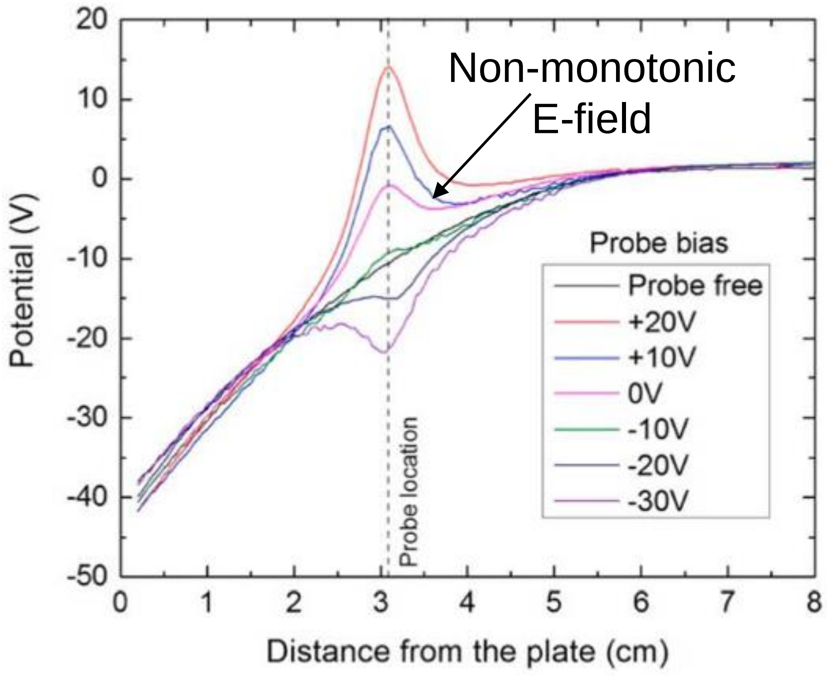
Qualitative Interpretation

<u>HV is positive</u>

Dust particles hop around on the surface. Particles must be charged **positively** otherwise would be lofted vertically.



Spherical Langmuir Probe in Sheath



Wang et al., 2018

- Positive charge is because photoelectrons are accelerated by the E field
- Dust particles spin due to inhomogeneous electric forces, resulting in torque and then bouncing on the surface

Summary

- Dust charging and lofting on a conducting surface is studied in the laboratory in various charging environments with e-beam and UV. External E field shows significant effects on charging processes.

- Patched charge model for multilayered dust is extended into understanding monolayered dust charging.

- Dust particles are recorded to be lofted under certain conditions. The charging mechanisms will be further investigated to ultimately address various dust issues in particle accelerators.