Simulation and experimental investigation of dust charging and adhesion

25th SPINE workshop, ESTEC, Noordwijk, NL, 24/10/2018

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return on innovation

Context - Dust on Airless Bodies

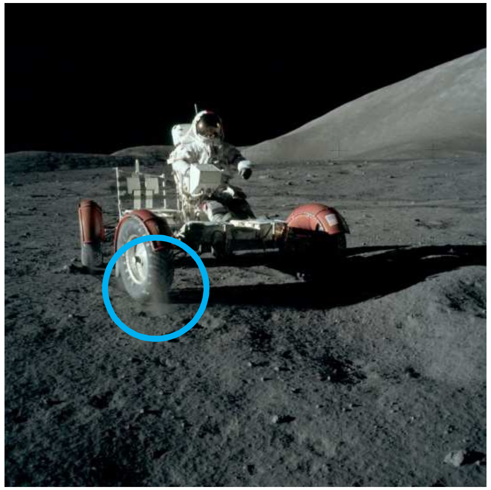
Space is full of dust …
- Intergalactic dust
- Comets (cf. missions Rosetta, Hayabusa, …)
- Moon, Mars …

➔ Contain valuable information on solar system origins

Regain of interest in the exploration of the lunar surface (science and ISRU)
➔ Lunar Orbital Platform-Gateway project (NASA, ROSCOSMOS, ESA, JAXA, CSA + private operators) would allow manned mission to cislunar orbit and missions to the lunar surface as well (e.g. HERACLES project at ESA).

Dust present however some threats to human and/or robotic missions
- Sticking to materials
- Health hazards to astronauts
- Seal/clogging …

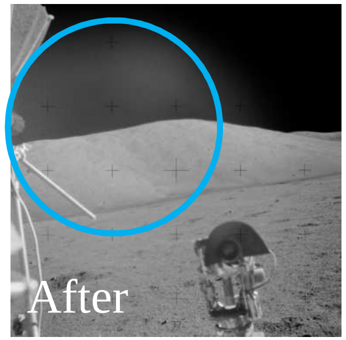
Context - Dust contamination on the Moon

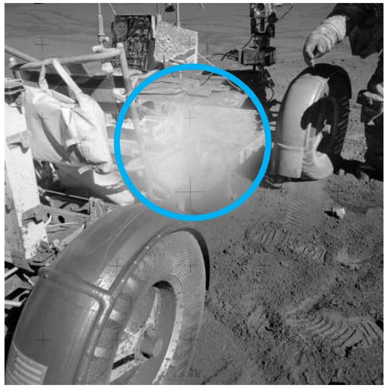


Space suit anomalies

Lunar module contamination

Surface obscurations

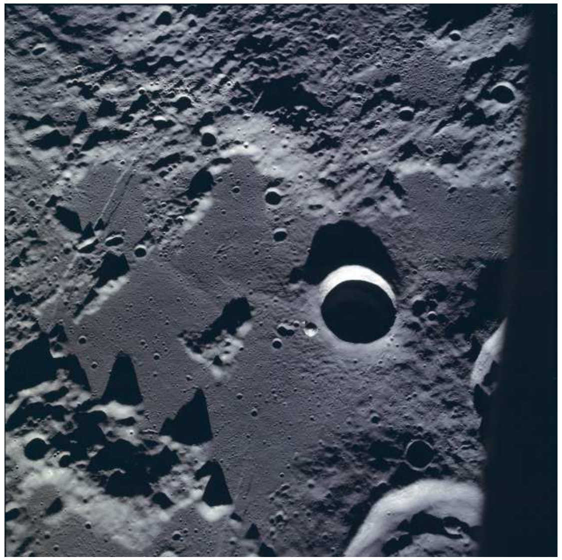




Credit: NASA
Apollo archives

Context - the Moon soil

- Moon surface is covered in dust layer called regolith (< 1cm)
- Lunar dust is the < 20 µm portion of the regolith
- Results from differents processes:
  - Impact of large and small meteoroids
  - Steady bombardment of particles from the Sun
- Thickness between 5 m (mare areas) and up to 15 m (highlands)
- **Dust adheres a lot and lead to heavy dust contamination**



Moon surface (Apollo 11)
Credit: NASA

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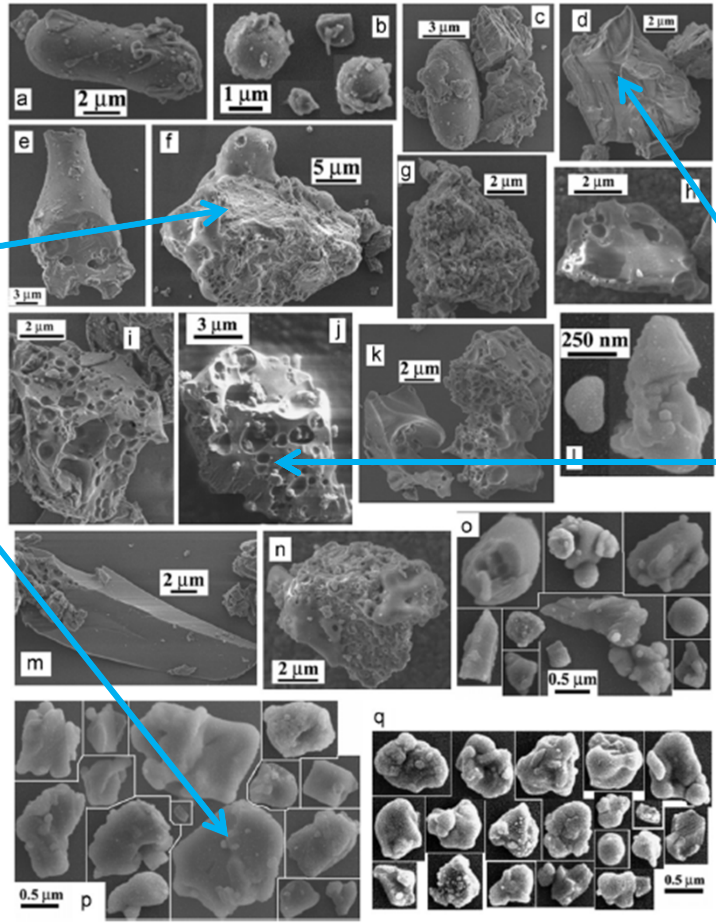
Context - Shape of lunar samples

SEM photos of lunar dust samples



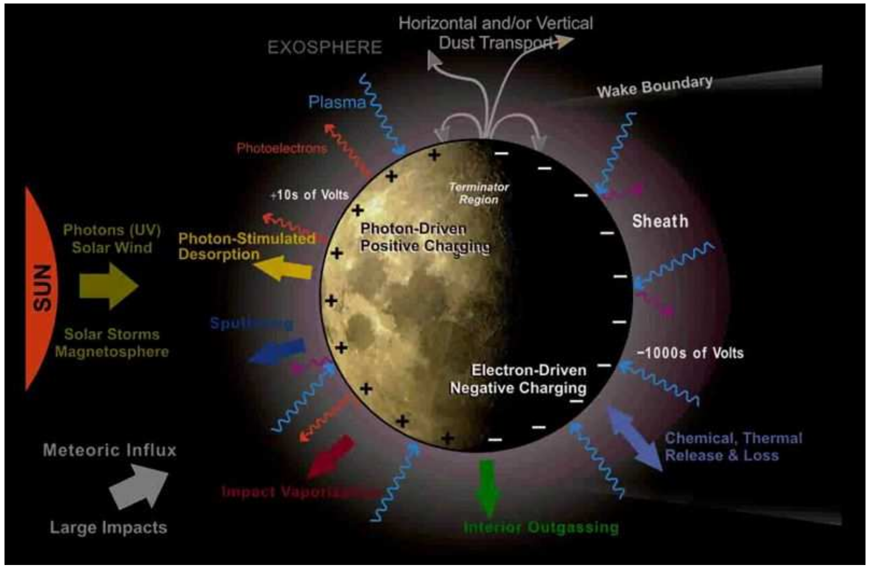
- Irregular shape
- Rugged forms
- « somewhat elongated »

- Asperities
- Porous

Credit: Liu, 2011 (and references thereby)

Context - Origins of dust charging on the Moon

- Bombardment of meteroids
- Charging environment around the Moon
  - Electron recollection from solar wind → negatively charged surface
  - Day-side: photoemission phenomena → positively charged surface
  - At the night/day frontier: electrostatically lofted dust (Horizon Glow)
- **Any released dust is significantly charged**

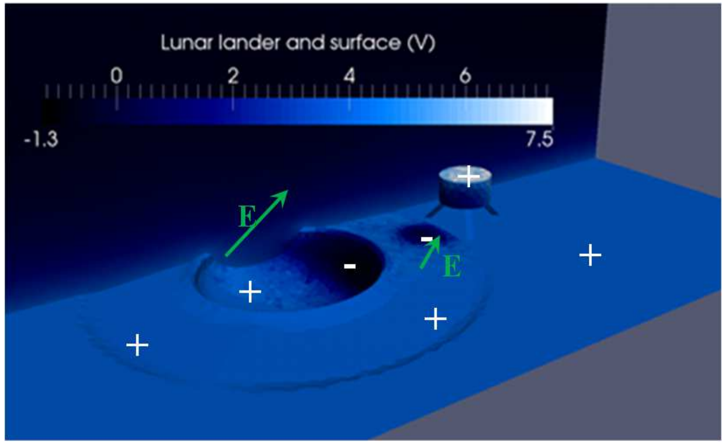


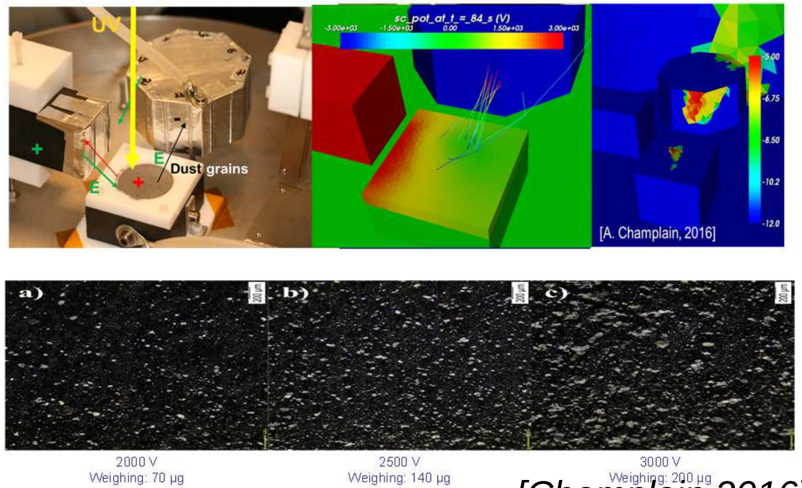
[*NASA*]

Photo of the Horizon Glow taken by the Clementine probe

Objectives (and content)

1. Develop and validate a physical and numerical model describing dust charging and adhesion in space-like environments, as a follow-up of SPIS-DUST initially developed under ESA funding (F. Cipriani)





[Champlain 2016]

2. Develop experimental setups allowing measuring the electrical properties of dust (conductivity so far)

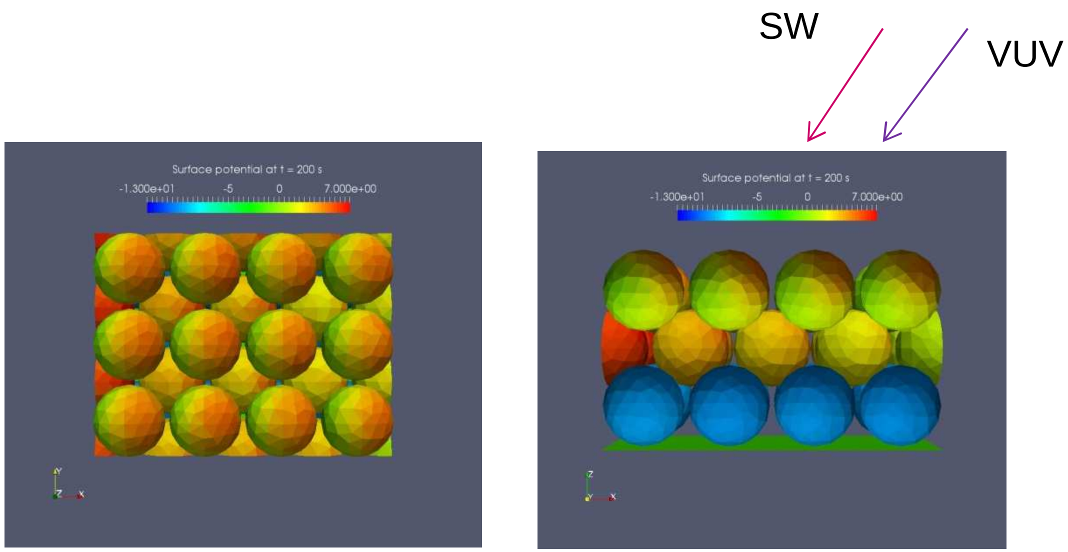
3. Develop a test setup allowing quantifying dust adhesion forces

<u>Constraints </u>: virtually impossible to handle the problem in its full complexity

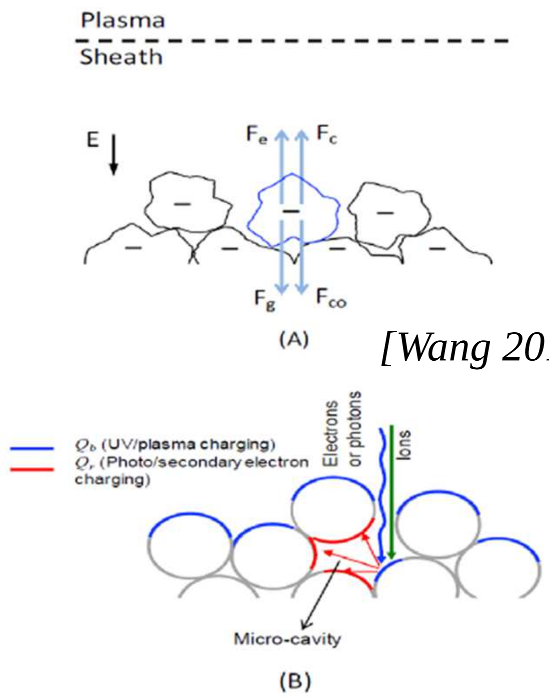
<u>Method</u> : simplify the problem to extract the core science and extrapolate to real situations

1. Dust pile charging at the Moon surface

Numerical simulations with SPIS 5.2.4 to compare and extend work by Zimmerman et al. (2016)
200 µm diameter dust (pile of 3 layers, Lunar dust 71501 Mare)
Environment = solar wind + sun at 45° zenith angle



[Oudayer, Monnin, Matéo-Velez, Hess, Sarrailh, Roussel 2018]



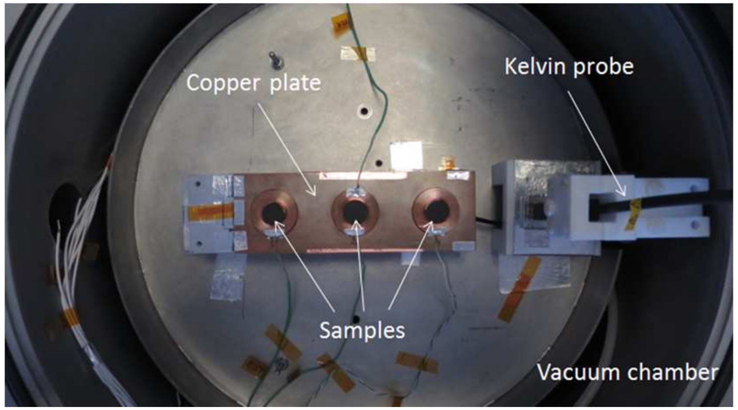
[Wang 2016]

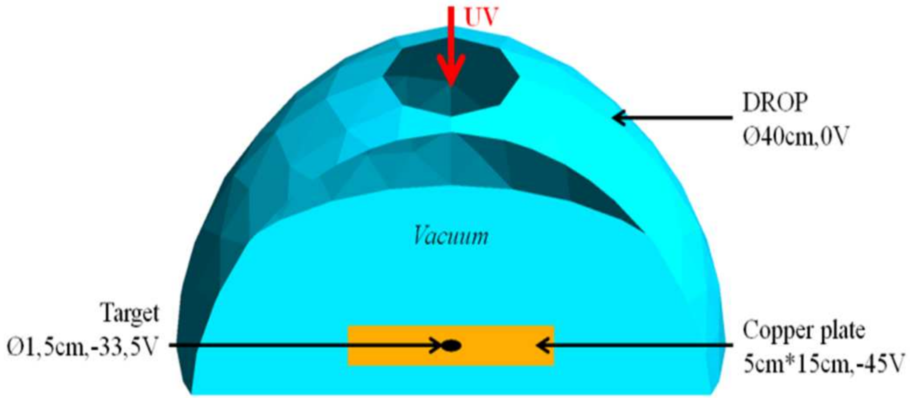
Dust pile is « porous » and high non uniformly charged :

- Layer 1 top : Positively charged by photoelectron emission
- Layer 2 top : Positively charged by VUV through interstices of layer 1
- Layer 1 bottom : Negatively charged by VUV from layer 2
- Layer 3 : Negatively charged by SW electrons through small interstices of layers 1 and 2

1. Dust pile charging in DROP chamber

50 µm diameter dust (200 µm thick pile, ~5 layers, DNA-1 lunar dust simulant)
Environment = VUV source, < 1e-6 mbar
Substrate set to a bias potential -45 V to avoid secondary electron emitted by the tank walls





Surface potential measured by contactless Kelvin probe

Measured potentials compared with simulations at macroscopic scale and used to constrain simulations at microscopic scales

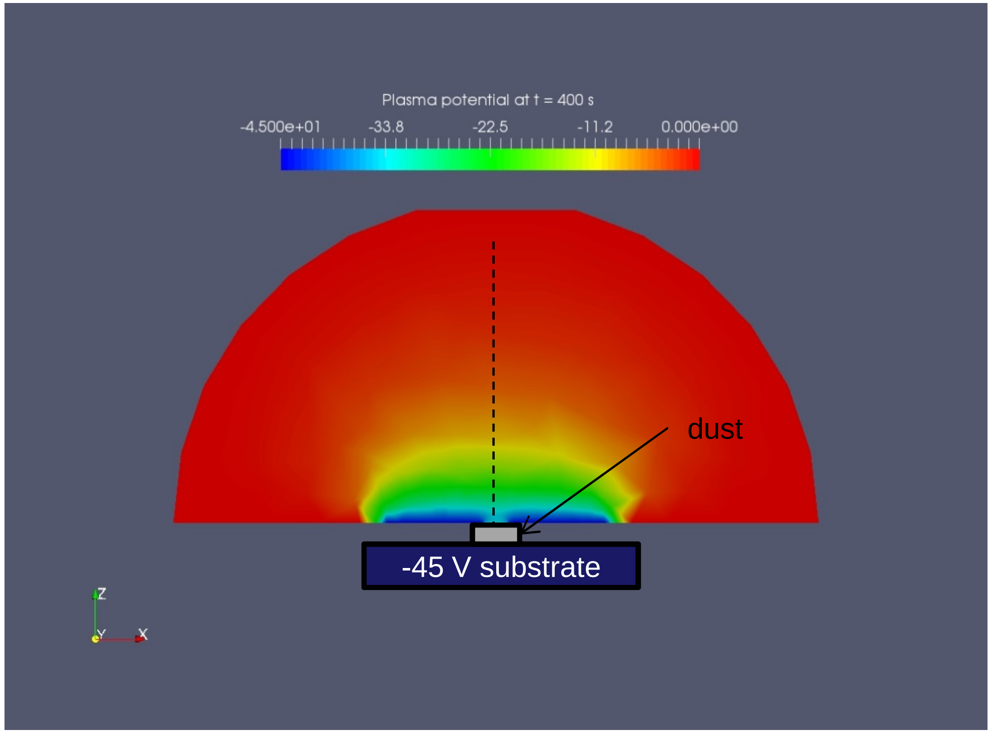
[Oudayer, Monnin, Matéo-Velez, Hess, Sarrailh, Roussel 2018]

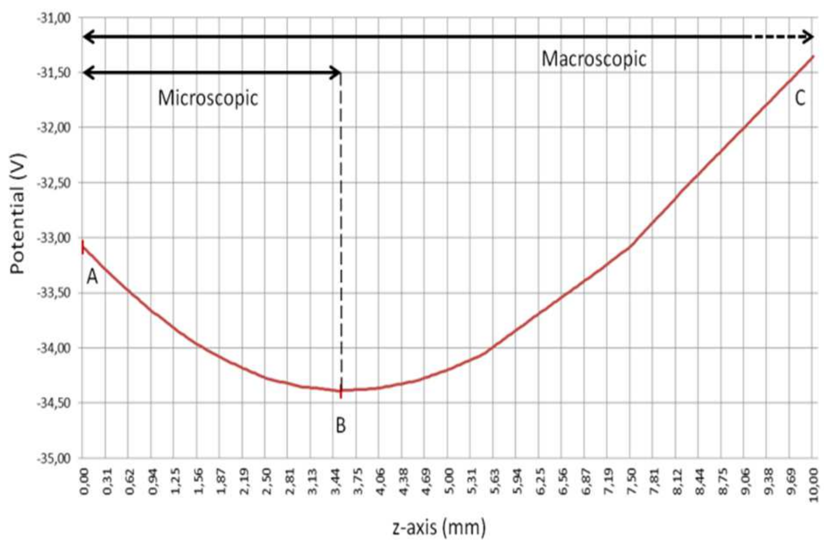
1. Dust pile charging in DROP chamber

Macroscopic scale simulations

Dust surface charging is + 12 Volts with respect to the substrate at -45 V

Confirmed the capabilities of SPIS 5.2.4 with default parameters to model that scale





Inputs for microscopic scale simulations

Barrier of potential for photo electrons emitted by dust

Photo electrons current flow from the substrate to dust (attracted by positive differential potential)

[Oudayer, Monnin, Matéo-Velez, Hess, Sarrailh, Roussel 2018]

1. Dust pile charging in DROP chamber

Microscopic scale simulations

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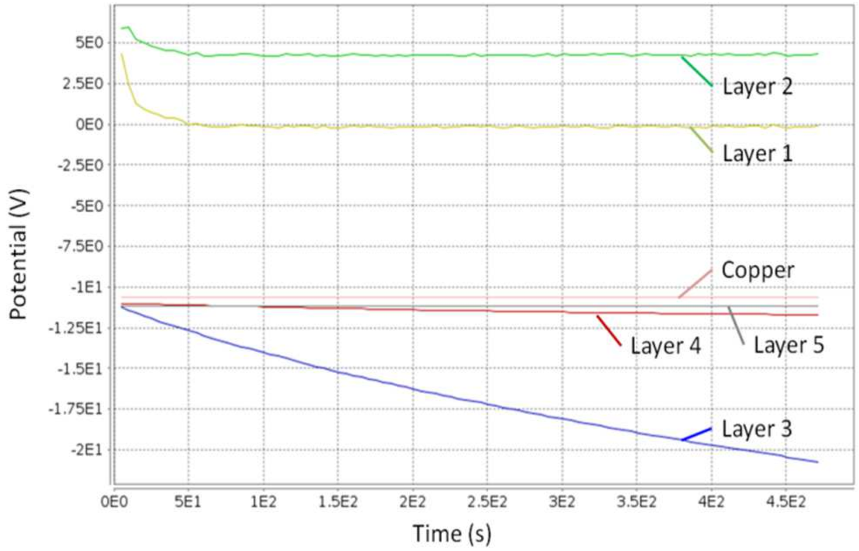
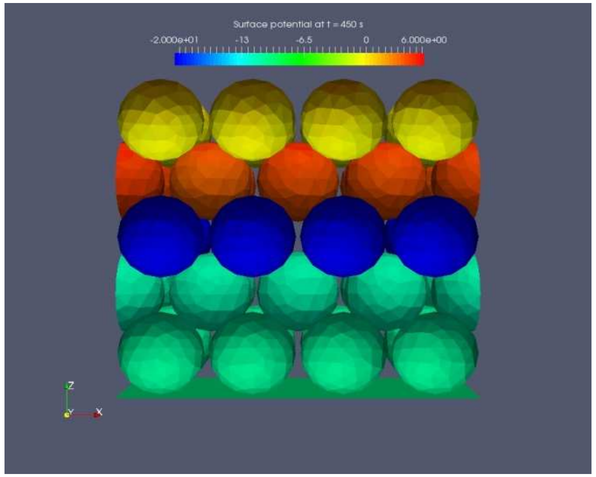
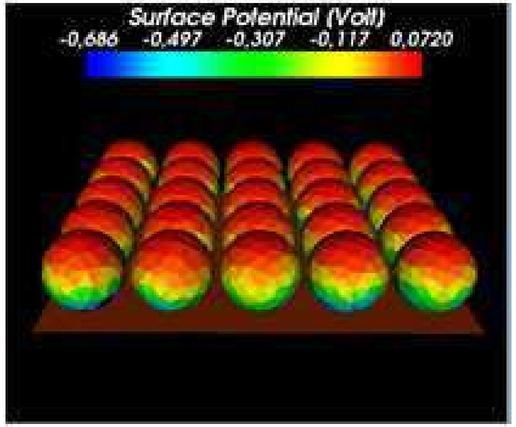




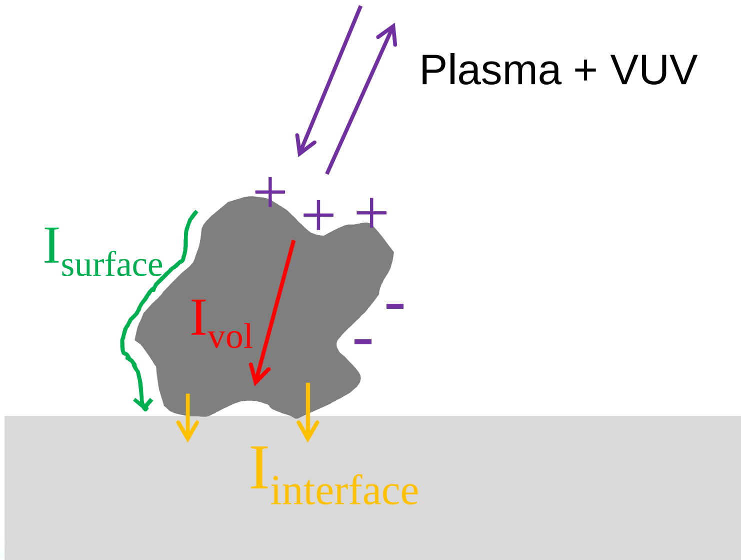
Same qualitative results as in lunar environment :

- Layer 1 top : Positively charged by photoelectron emission
- Layer 2 top : Positively charged by VUV through interstices of layer 1
- Layer 1 bottom : Negatively charged by VUV from layer 2
- Layer 3 : Negatively charged by electrons emitted by the negative substrate and deflected by the dust positive potential → ground setup representative of lunar environment
- Layers 4-5-… : uncharged

1. Next steps for dust charging assessment



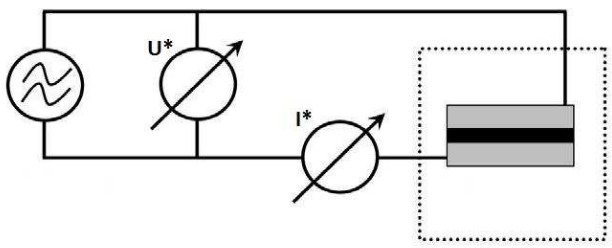
- Single layer
- Single dust
- Conduction mechanisms (mitigating charging)
  - Bulk conductivity
  - Surface resistivity
  - Contact resistivity from grain to grain and from grain to surface

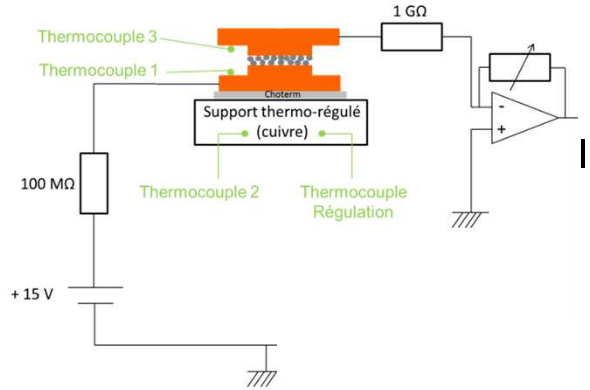


2. Characterizing conduction through dust layers

- Experimental investigations of electrical current conduction through dust layers

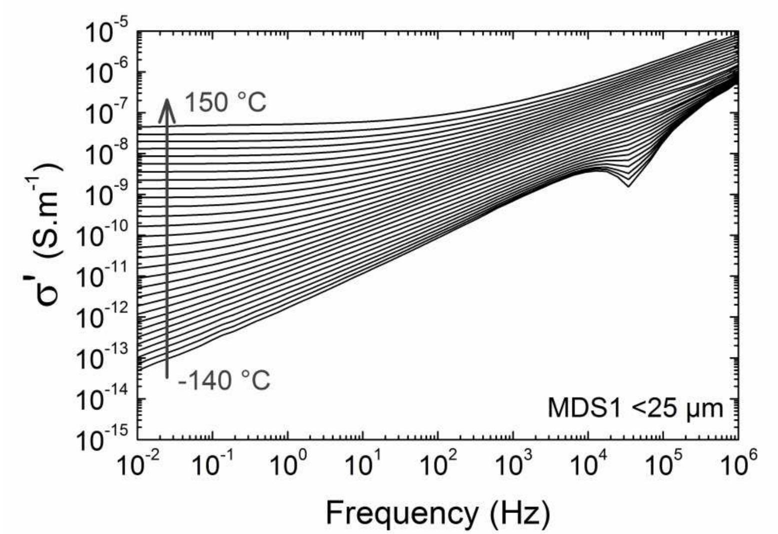
- 2 techniques used
  - Broadband dielectric spectroscopy performed at CIRIMAT (Eric Dantras) and ENSIACET (Aurélien Roggero) in Toulouse
    - 0.01-10^6 Hz
    - 133 - 400 K
    - Atmospheric pressure 99,99 % nitrogen
  - DC current measurement performed at ONERA
    - Steady state
    - 273 - 400 K
    - Secondary vacuum 10^{-7} to 10^{-6} mbar

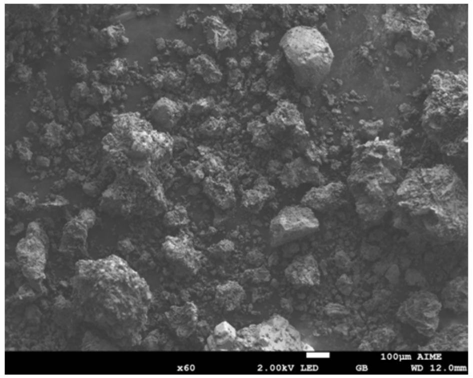


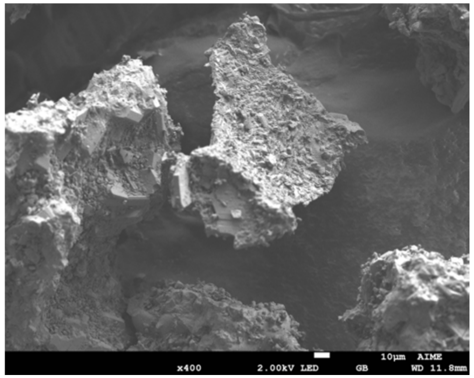


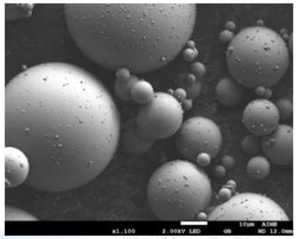
2. Characterizing conduction through dust layers

- Dust
  - DNA-1, JSC-1A terrestrial simulants of lunar dust (25-50 µm)
  - Lunar dust simulants from Politecnico de Torino (Francesca Stefania Freyria, Barbara Bonelli) and Università degli Studi di Cassino e del Lazio Meridionale (Serena Esposito): disperse size, SiO2 based matrix with nano phased iron content representative of Lunar samples (different from terrestrial simulant)
- Results of both techniques quite well agree with each other and allowed comparing lunar dust simulant properties with real lunar dust published data (Mc Kay, 1991) (paper under submission)









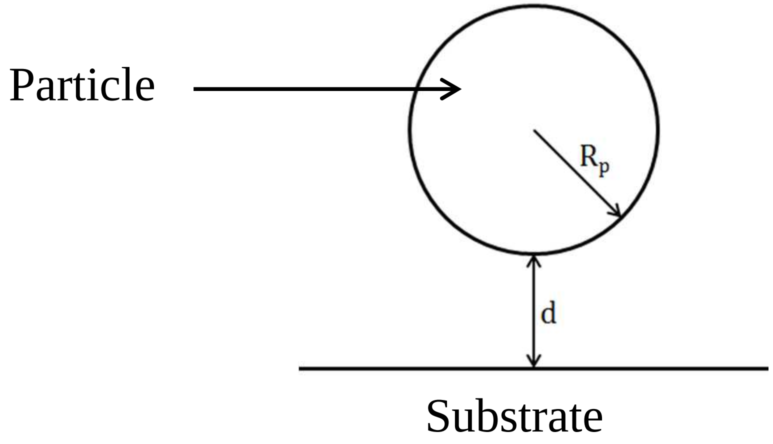
- Next step : perform measurements of calibrated dusts to assess contributions of bulk, surface and contact restistivity in simpler configurations

3. Characterizing adhesion forces

- Van der Waals force resulting of dipolar interactions: London, Debye, Keesom

- For an interaction between a smooth sphere and substrate in vacuum:

- $$F_{VdW} = \frac{AR_p}{6d^2} \propto R_p$$



- A = Hamaker constant [J]. Typical values: 10^{-20}; 10^{-19} J

R_p = particle radius [m]

- d = minimum separation distance [m]. Typical value: a few angstroms

→ Estimation of all three parameters is challenging

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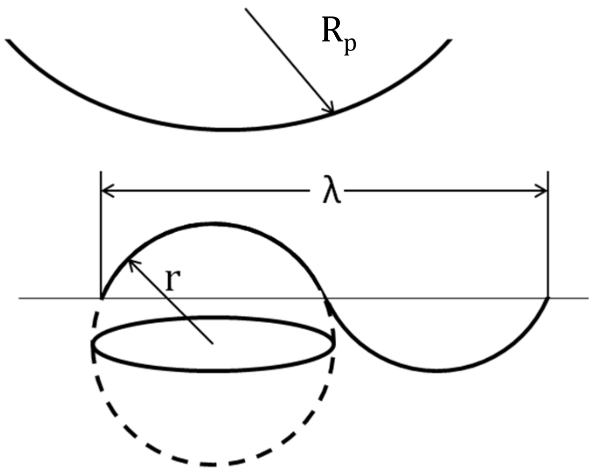
3. Effect of roughness on adhesion force

- Previous equation only supposed an interaction with a smooth surface

- (Rabinovich, 2000) proposed a more precise expression for F_{ad} where the substrate has a roughness rms

$$F_{ad} = \frac{AR_p}{6H_0^2}\left[\frac{1}{1+\frac{58\,R_p\,rms}{\lambda^2}} + \frac{1}{\left(1+\frac{1{,}82\,rms}{H_0}\right)^2}\right]$$

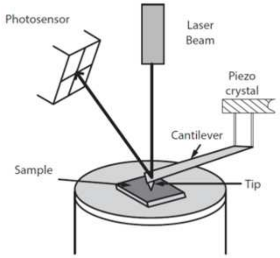


→ As substrate roughness increases, adhesion force decreases

3. Classical setups for adhesion force measurements

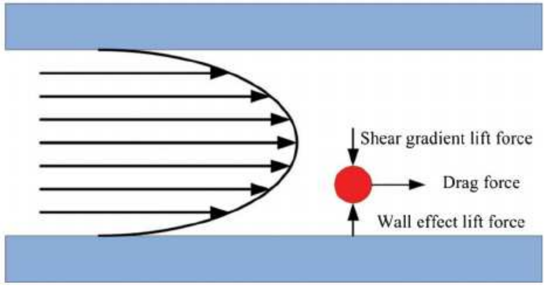
AFM (atomic force microscope)

Credit: Mittal, 2015



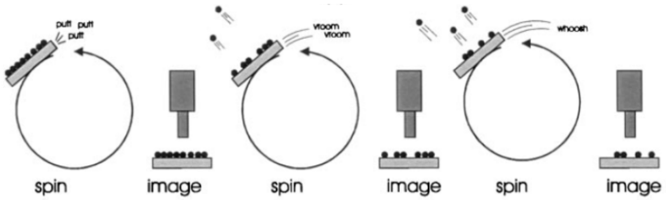
Shear strengh

Credit: http://research.iitgn.ac.in/



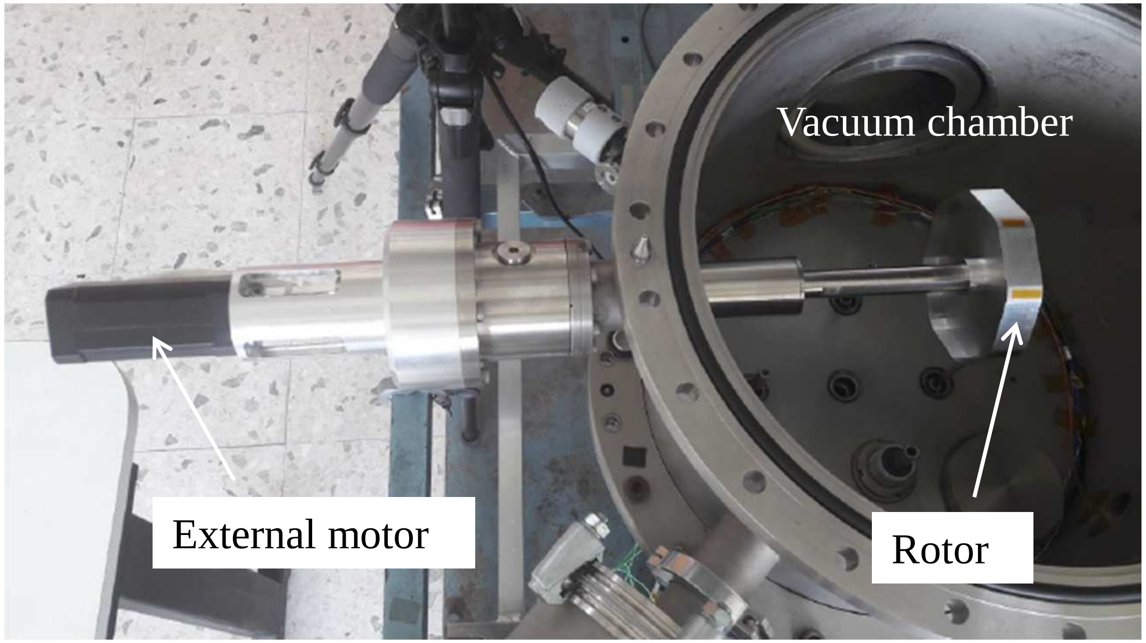
Centrifugal force

Credit: Mizes, 2008



3. New test setup

- Quantifying adhesion force → use of centrifugal force
- Vacuum chamber called DROP (Dust Regolith or Particles)
- Vacuum: < 10^{-6} mbar
- External motor goes from 100 rpm to 1500 rpm
- Measurement ex-situ: binocular magnifier

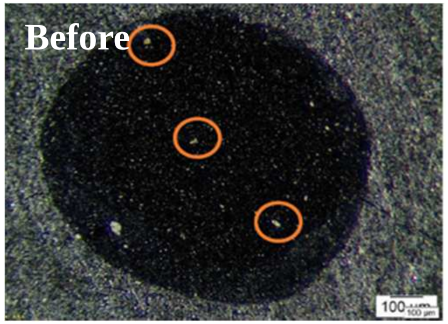


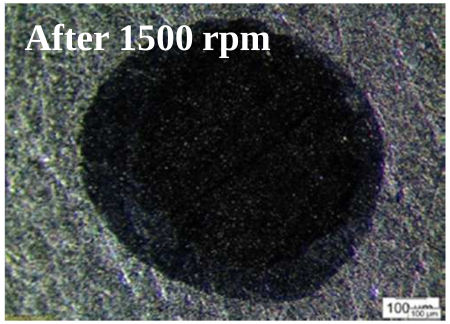
3. Preliminary results

Individual lunar simulant grains on aluminum substrate, scale=100µm:

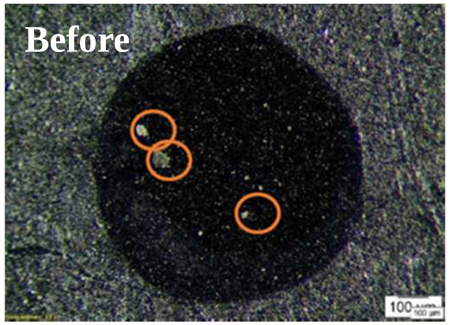
Particle mean size: 22 µm

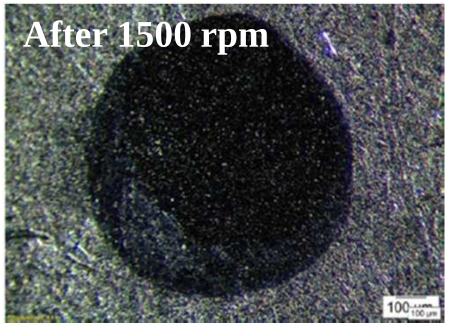
F_{ad} ~ 20-30 nN



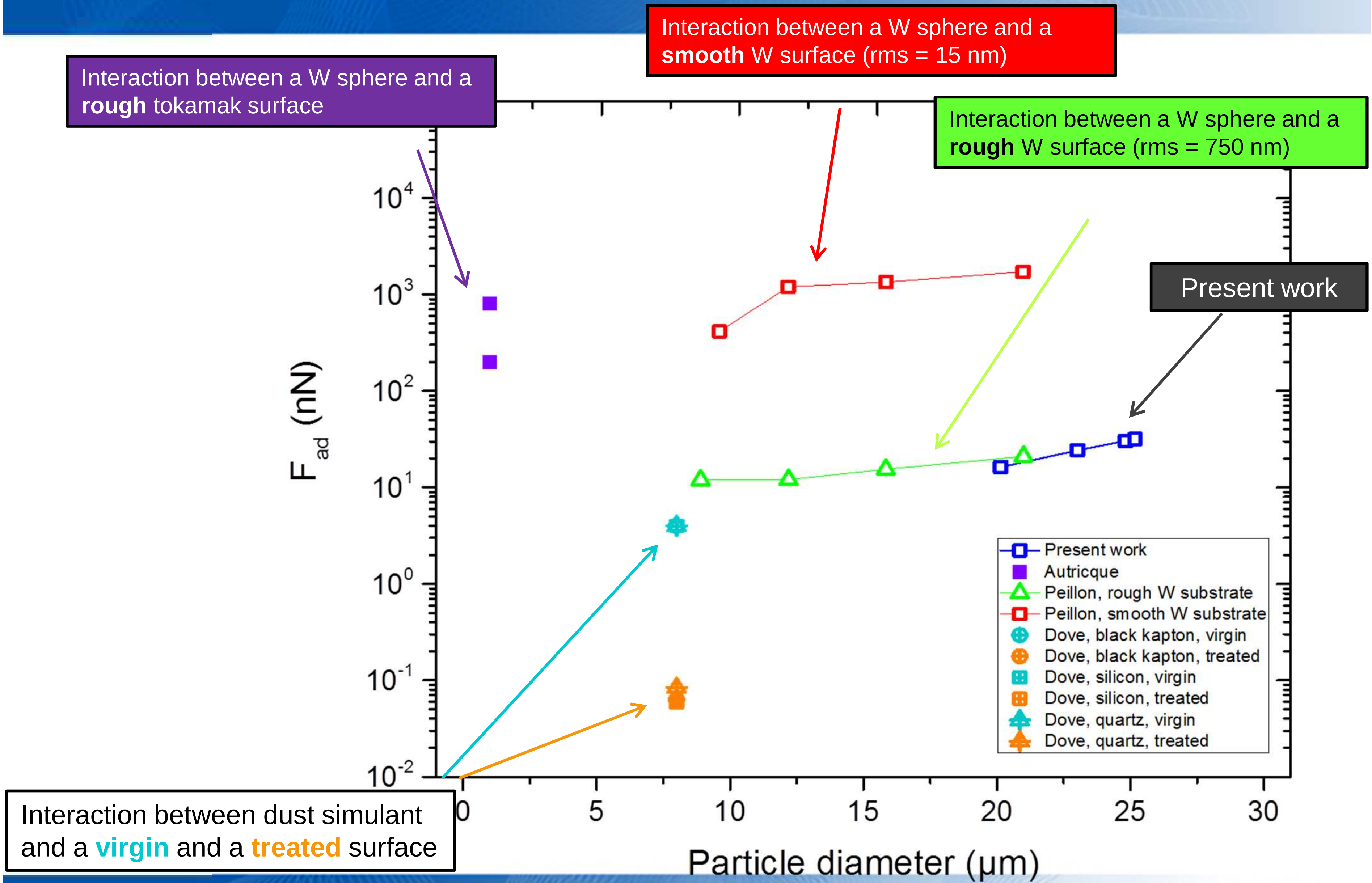


Particle mean size: 35 µm





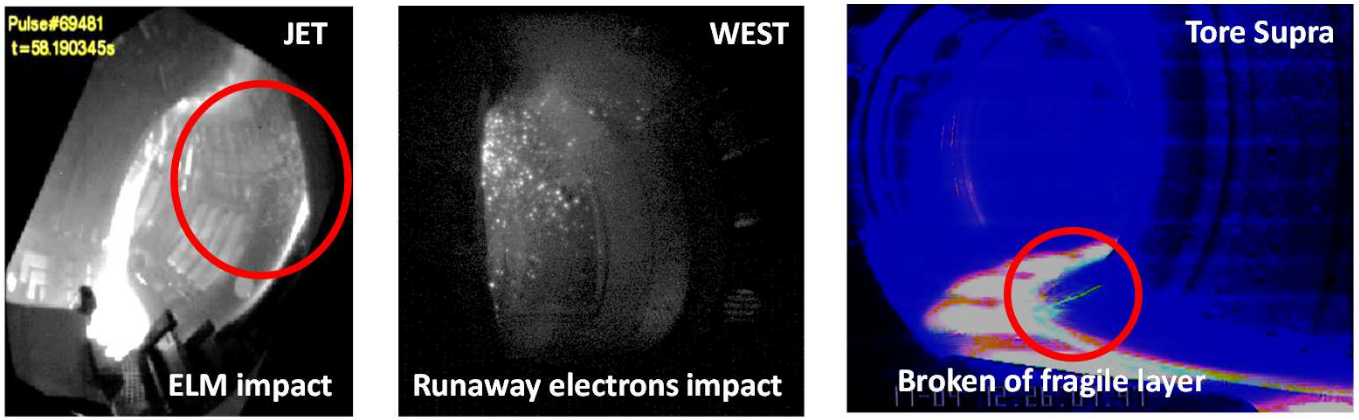
3. Comparison with literature



Oudayer et al. Proceedings of ISMSE, 2018

Perspectives

- Pursue manufacturing the building blocks of dust charging and adhesion modelling and characterization in continued collaboration with academic partners
- Ideally : include all models inside SPIS to have the full picture (dust grain charging and discharging, surface interaction, adhesion force, …)
- Help specifying dust hazards for future missions and possibly help finding solutions in partnership with agencies and private partners
- Collaborate with nuclear power agencies and industry : dust generation in Tokamak



Examples of dust creation processes in operating tokamaks

Credits : Grisolia, Peillon et al.

Acknowledgments

- Francesca Stefania Freyria (Cassino Univ), Serena Esposito and Barbara Bonelli (Polito de Torino) for lunar dust simulants
- Aurélien Roggero (ENSIACET Toulouse) and Eric Dantras (CIRIMAT Toulouse) for BDS data
- C. Grisolia and A. Autricque (CEA Cadarache) and F. Gensdarmes and S. Peillon (IRSN Paris) for providing adhesion data