

Lunar Electrostatics and Dust Mitigation (LEDMM) Tool: Mitigating Electrostatics on the Moon!

National Aeronautics and
Space Administration



Dr. David Lund (Bennett Aerospace, KSC)

Dr. Charles Buhler (NASA, KSC)

Tim Provin (NASA, KSC)

Jerry Wang (NASA, KSC)

Malay Shah (NASA, KSC)

James Phillips (NASA, KSC)

Chris Forney (NASA, KSC)

Monica Hooks (NASA, KSC)

Dr. Aaron Olson (NASA, KSC)

Rene Formoso (NASA, KSC)

Dr. Joe Toth (NASA, KSC)

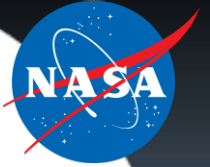
Joseph DeRienzo (NASA, KSC)

Marty Grashik (NASA, KSC)

Lexis Mazerski (Aetos, KSC)

Electrostatics and Surface Physics Laboratory
NASA Kennedy Space Center, FL 32899

The Lunar Plasma Environment



- The lunar surface is directly exposed to the solar radiation and solar wind plasma
- Leading to electrically charged dust grains and lunar surface

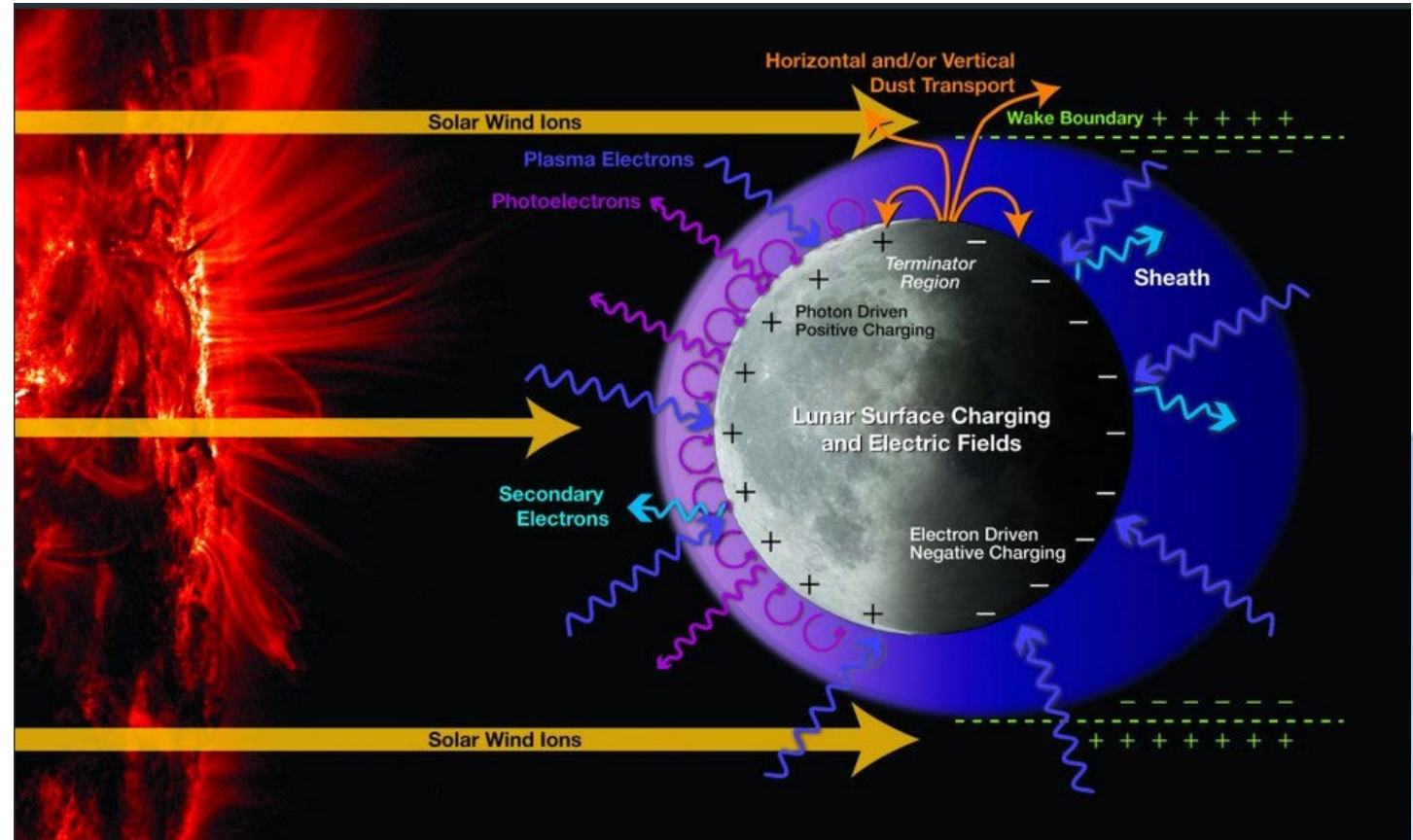
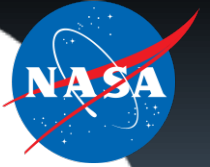


Photo Credit: NASA

The Lunar Dust Problem

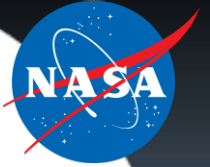


- Charged particles attach to instruments/spacesuits/vehicles which could generate issues leading to:
 - risk of instrument failure and
 - threat to astronaut's wellbeing
- Mitigating the lunar dust and threat of electrostatic discharge becomes a priority



Photo Credit: NASA

What do we know about the natural electrostatics environment on the moon?



- The particles are good dielectrics (permittivities between 2-3) and resistivities (ρ above $10^{13} \Omega\text{m}$) and are most likely charged (positive and/or negative) or net zero total charge (bipolar). *No such thing as **uncharged** particles.*
- The surface of the moon is also a dielectric (no electrical ground)
- Very, very dry – no moisture to allow for charge decay ($\tau = RC = \rho\epsilon\epsilon_0$).
- The allowed electric field is much higher than the Earth and Mars. Charge levels on particles can reach the maximum electric field of the environment.

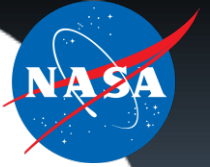
E_Moon >> E_Earth >> E_Mars

$10^8 \text{ V/m} >> 10^6 \text{ V/m} >> 10^4 \text{ V/m}$

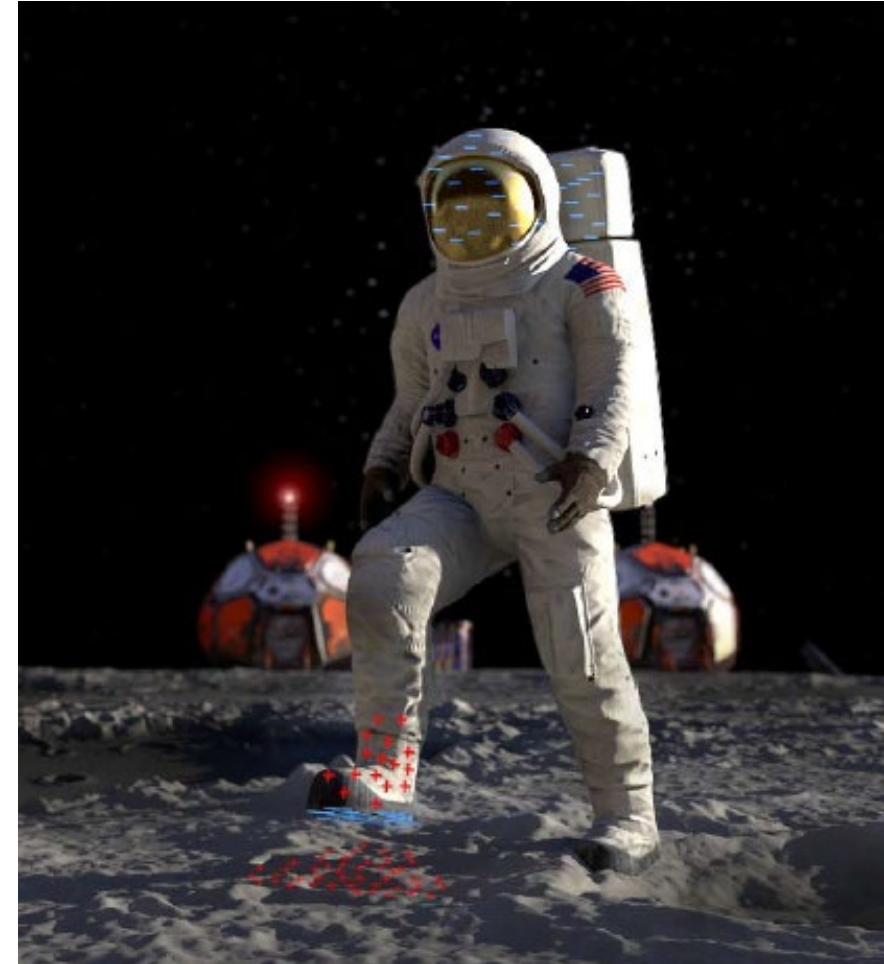
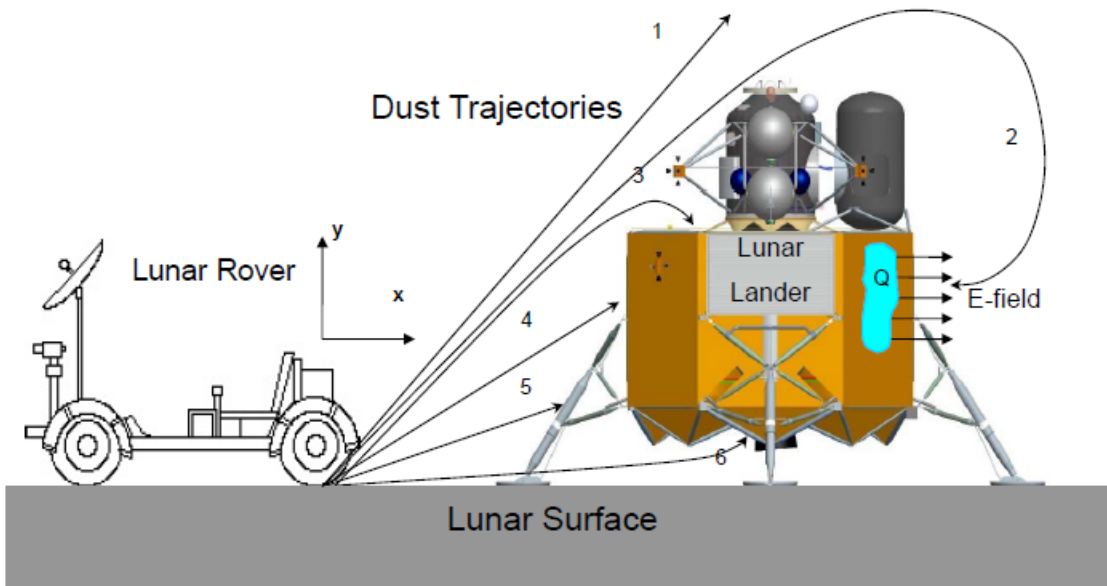
Field Emission >> Air Breakdown >> CO_2 at Paschen minimum

- *Natural Environmental Charging could result in surface potentials as high as **-4 kV** in shadowed and ambipolar regions* (H. Hodes, 2021).
- **Artemis Missions are planned for the South Pole!**

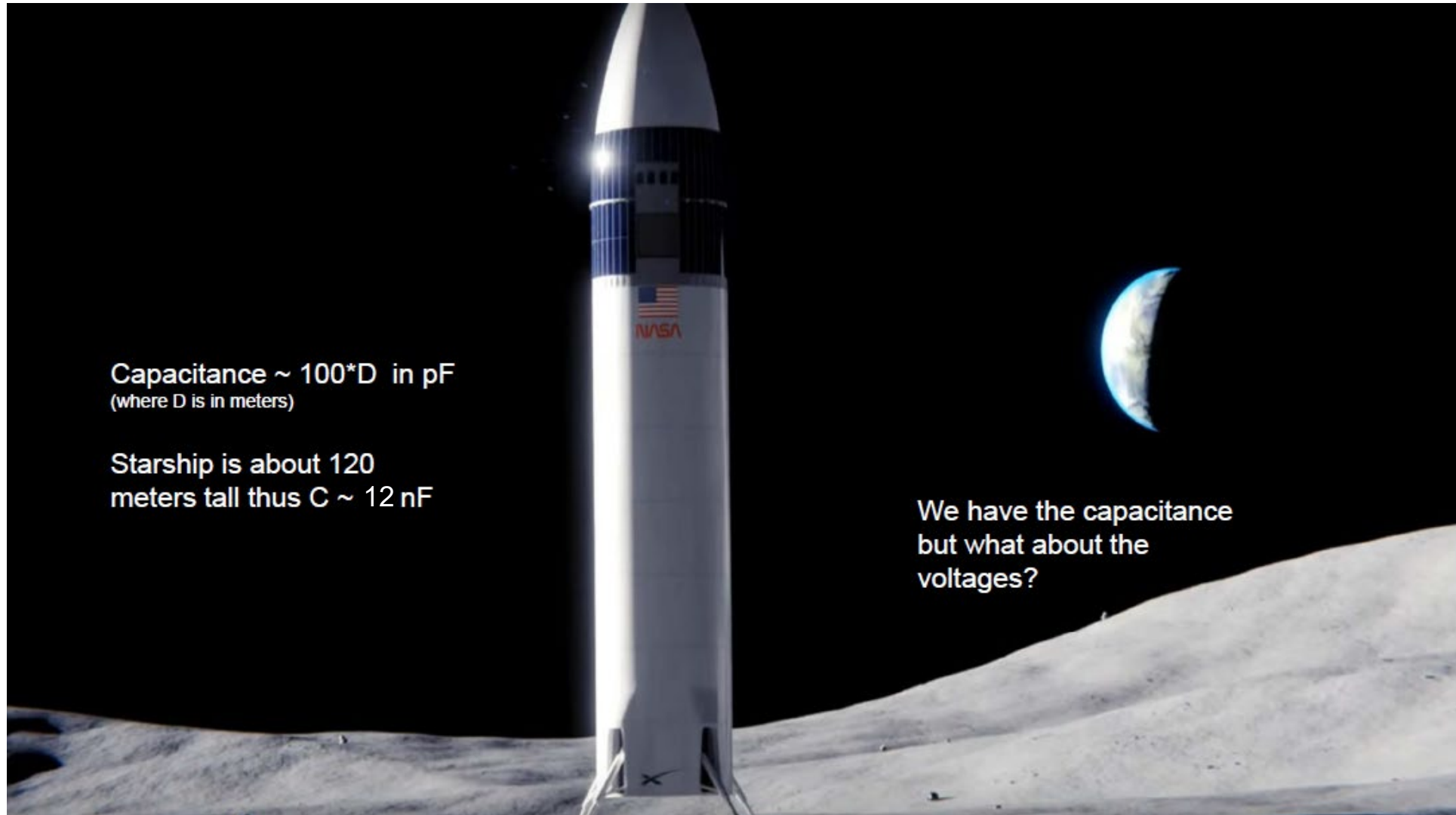
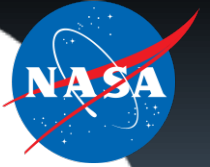
The Induced Lunar Environment



- The triboelectric effect: electric charge transfer between two objects when they contact or slide against each other



What if an astronaut touches this?

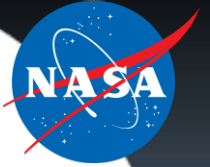


Capacitance $\sim 100 \cdot D$ in pF
(where D is in meters)

Starship is about 120
meters tall thus $C \sim 12$ nF

We have the capacitance
but what about the
voltages?

Best Practices for ESD Avoidance:



- 1) Have part of human system in sunlight
- 2) Have human system in high plasma density flow
- 3) Stay away from shadowed regions (like the South Pole!)

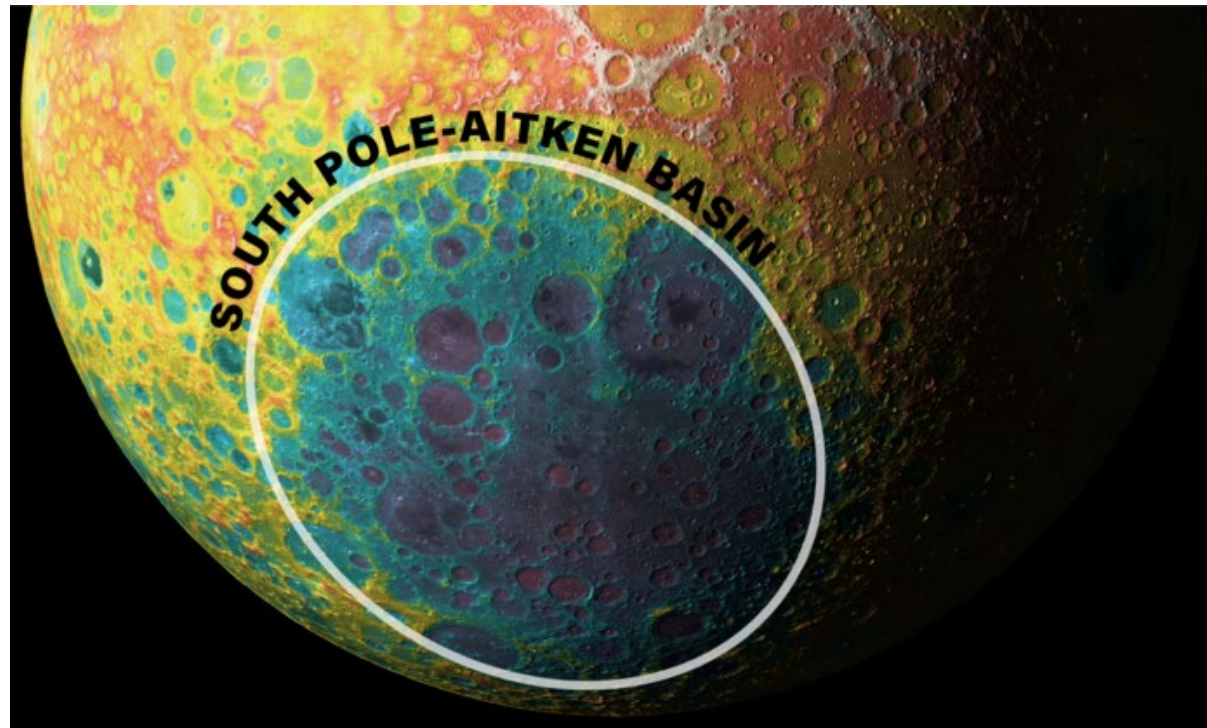


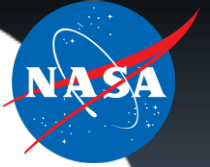
Photo Credit: NASA

AND..... LEDM!

The Lunar Electrostatic and Dust Mitigation Tool



LEDMM Overview



Three core tool functions:

1. Dust removal

2. Charge removal

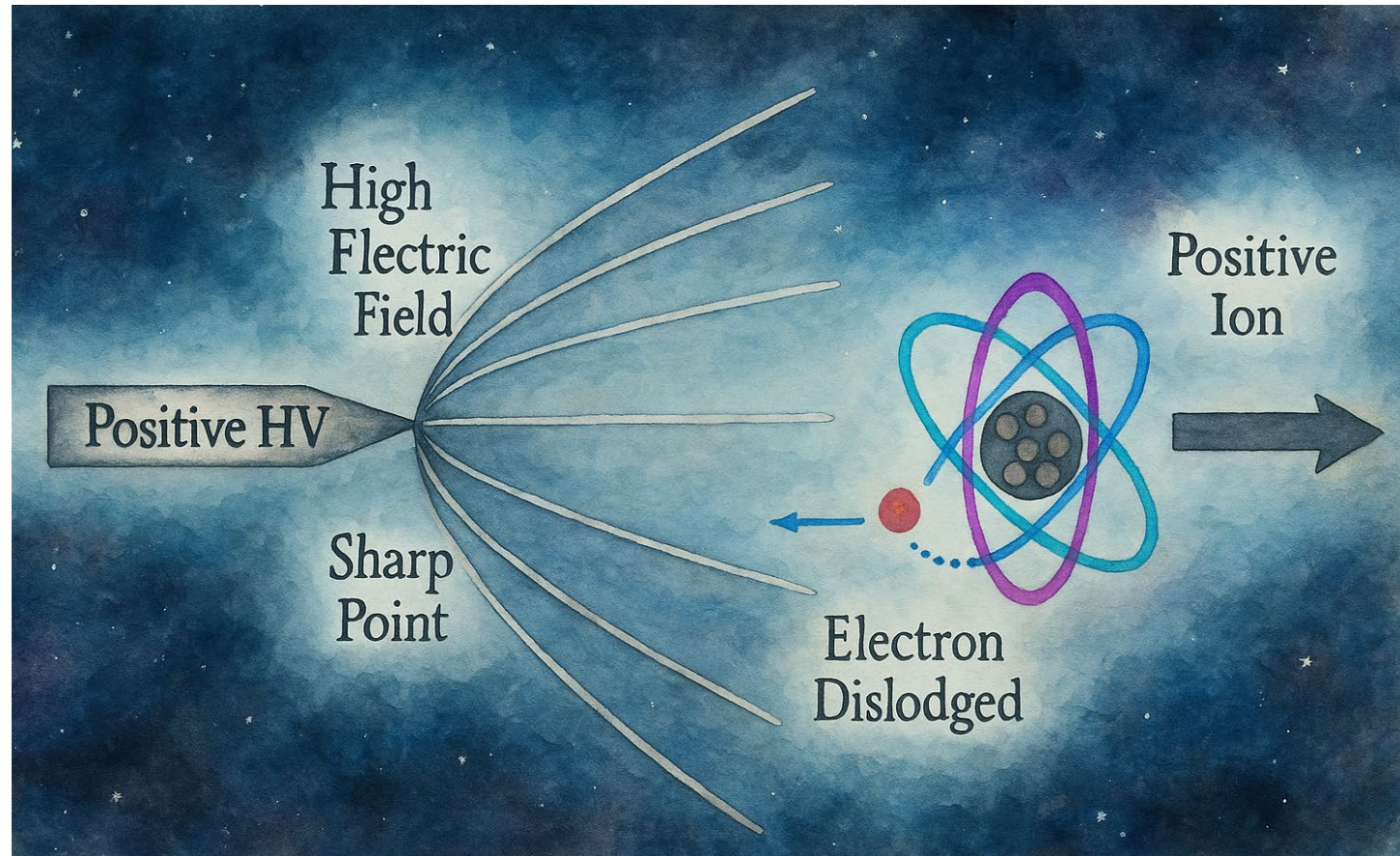
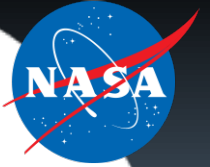
- Astronauts will remove dust and neutralize electrostatic charge from materials in a lunar environment

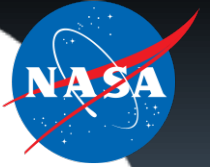
3. Electrometer

- Measure voltages on a target surface to tailor the high voltage waveform output to create the neutralizing plasma
- Check the surface voltage after cleaning to confirm charge neutralization

LEDM Breakdown

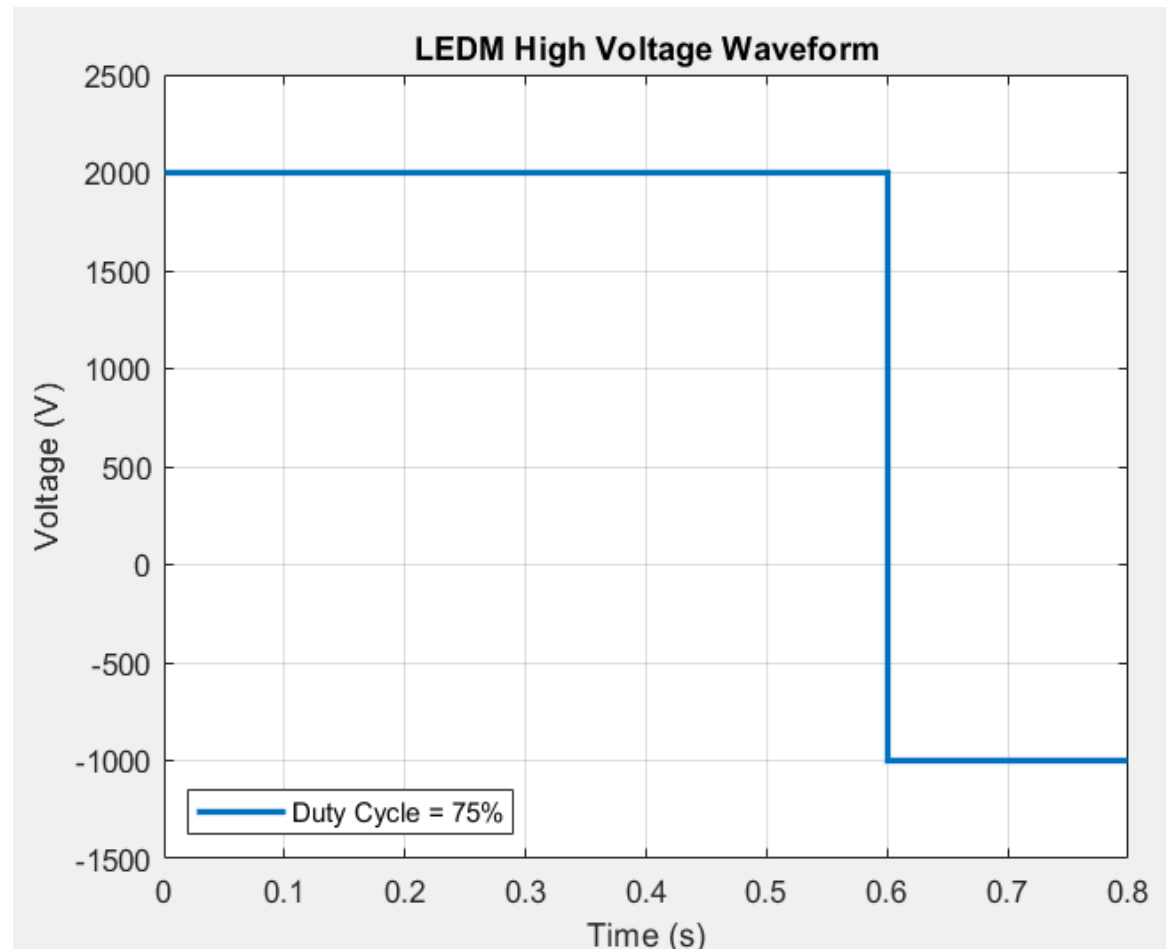
- Nitrogen gas





Gas Breakdown and High Voltage Waveform

- At 10^{-5} torr, the nitrogen ionizes at a minimum voltage of:
 - +600 V
 - -400 V



Demo 1 Unit Overview



Demo 1 Design without housing



Demo 1 Design with housing (and Joe)

Tool Mass: 15 lbs.

Dimension: 60"x35"x25"

Power: External benchtop power supply.

Gas: Air.

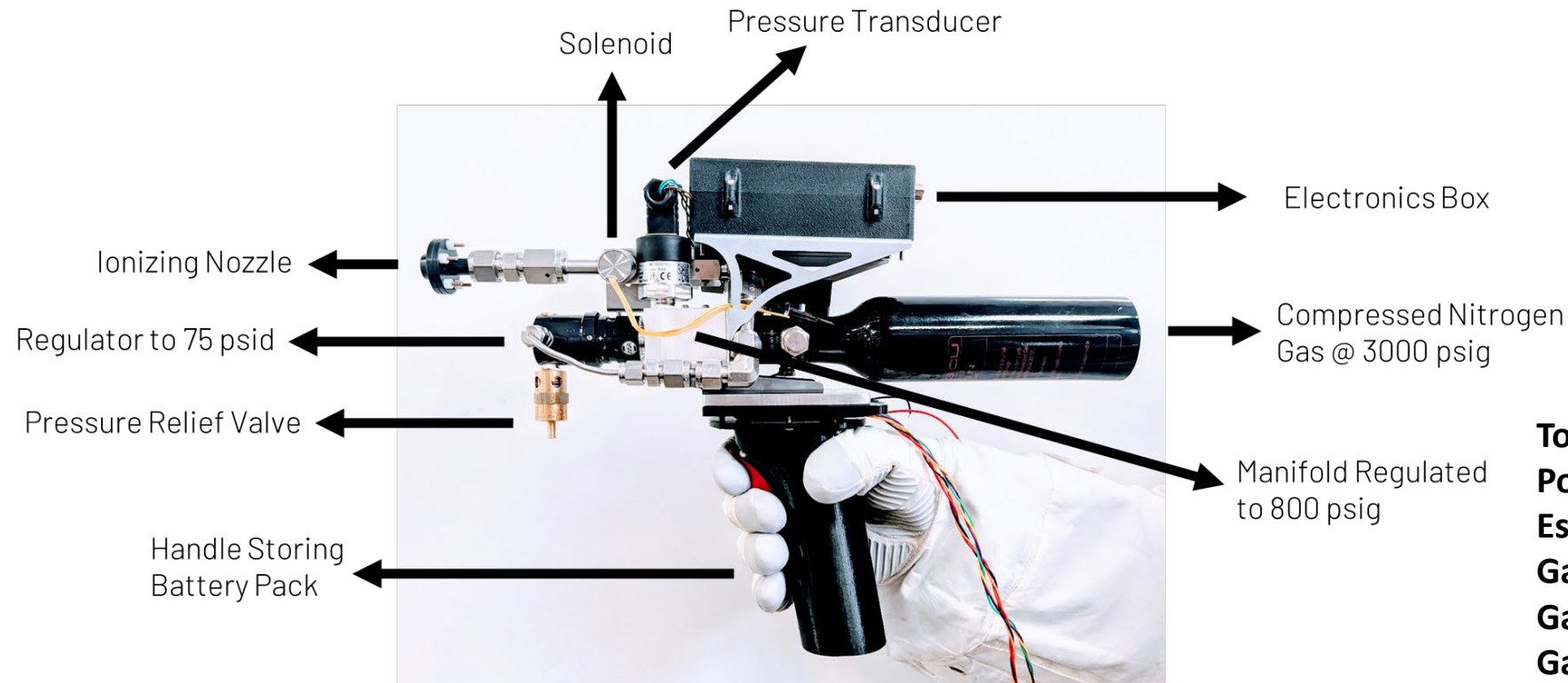
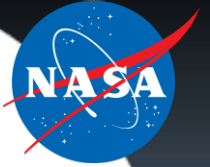
Gas supply: Shop air.

Gas pressure: 40 psid.

Pulse time: 1.0 second.

Demo 1 tool consisted of all COTS items.
Most COTS items selected here were not meant for handheld tool designs
(heavy/bulky), resulted in poor ergonomics.

Demo 2 Unit Overview



Demo 2 Design without housing

Refined the COTS fluid items to be more handheld compatible (airsoft bottles and regulators.)

Demo 2 tool included a custom manifold to tie in COTS fluid system items.

Tool Mass: 4.8 lbs.

Power: Battery powered.

Estimated battery life: 13 hours

Gas: Nitrogen stored at 3000 psi.

Gas per pulse @ 75 psid: 0.73 g.

Gas per pulse @ 35 psid: 0.39 g.

Maximum # of shots @ 75 psid: ~70 shots.

Maximum # of shots @ 35 psid: ~130 shots.

Pulse time: 0.4 second.

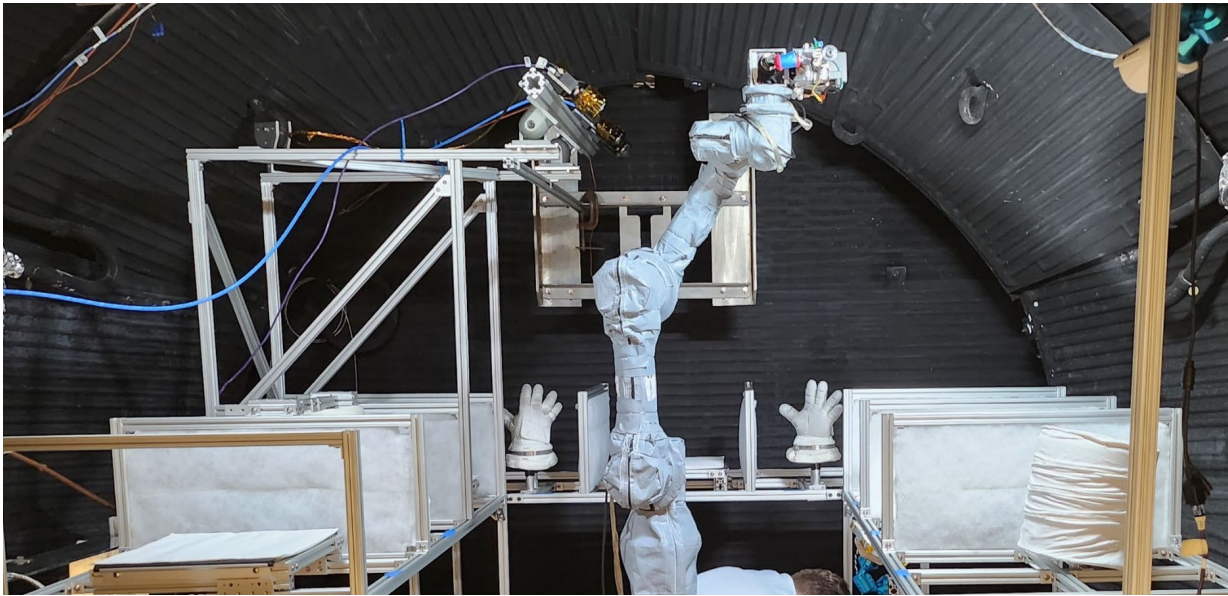
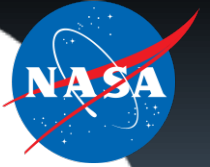
Discharge time scale: ~1 to 2 seconds.

Tool effective distance: 4" to 8".

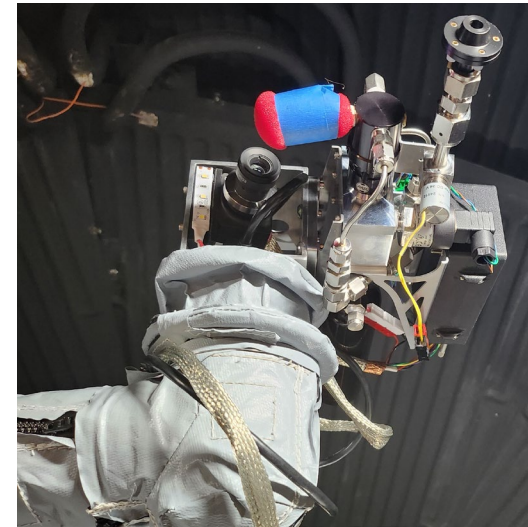
Surface potential neutralized in one pulse on insulators: ± 1200 V

Current TRL: 4

JSC Testing Summary and Results



**JSC 15' Dirty TVAC Testing with 9 test articles,
robotic arm and Demo 2**



*Demo 2 mounted to
Modified Robotic Arm
with protective suit*

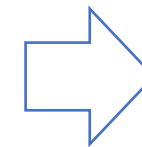


ESTA 15' TVAC Chamber with hatch closing



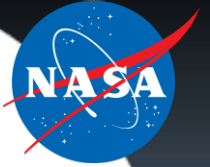
*Leg Simulator with
~10 grams of Simulant*

After
Cleaning

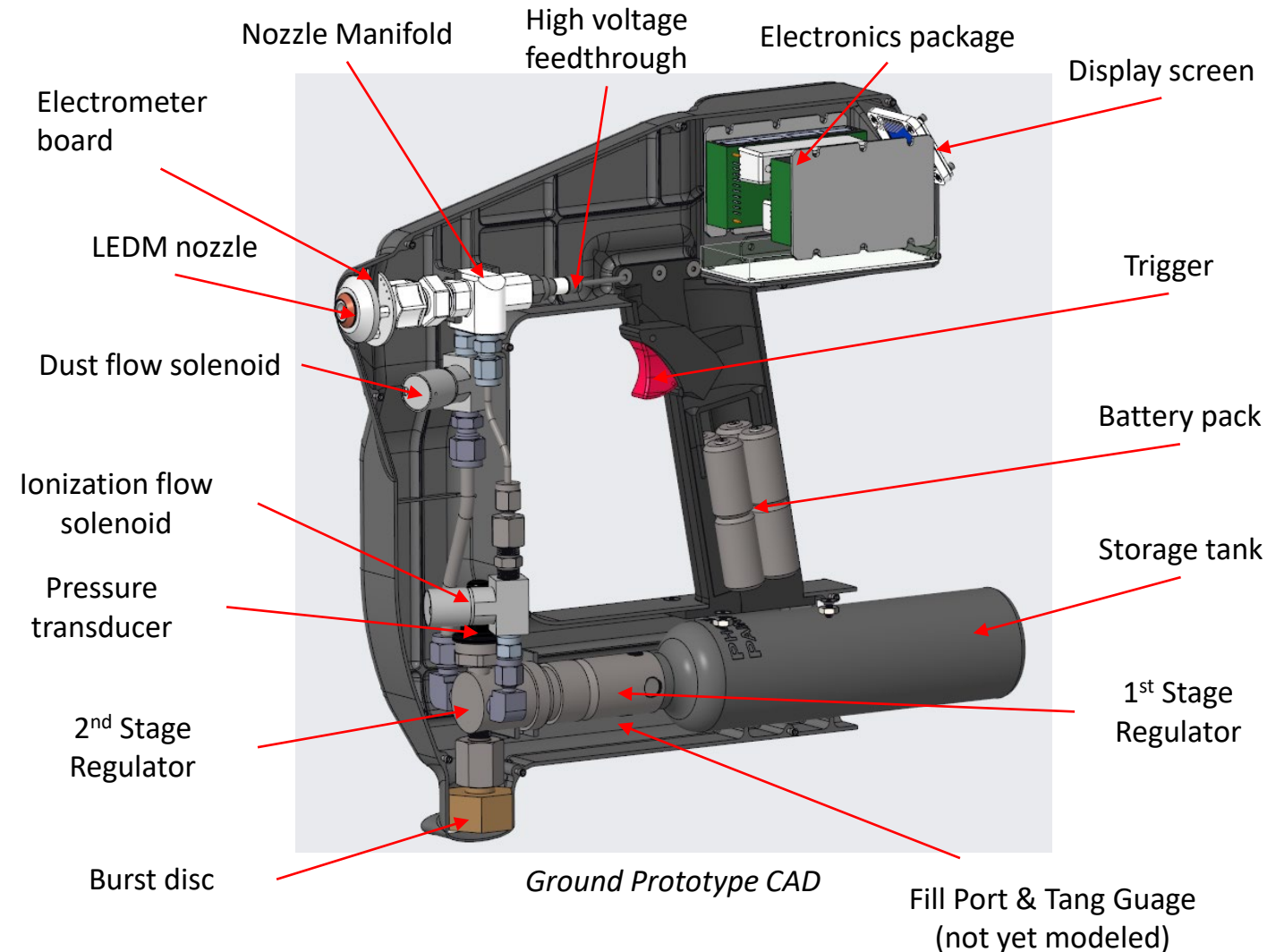
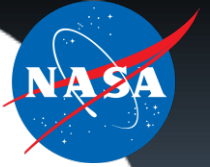


*Leg Simulator with ~2.3
grams removed*

LEDM Demo 2 Clearing a GoPro at GMRO's Big Bin



Ground Prototype



Tool Mass: 7.2 lbs.

Power: Battery powered.

Estimated battery life: 13 hours (for continuous use).

Gas: Nitrogen stored at 3000 psi with option of 4,500 psi

Gas amount per pulse @ 75 psid mode 1: 0.62 g.

Gas amount per pulse @ 75 psid mode 2: 0.85 g.

Maximum # of shots @ 75 psid mode 1: 85 shots.

Maximum # of shots @ 75 psid mode 2: 62 shots.

Discharge time scale: ~1 to 2 seconds.

Tool effective distance: 4" to 8".

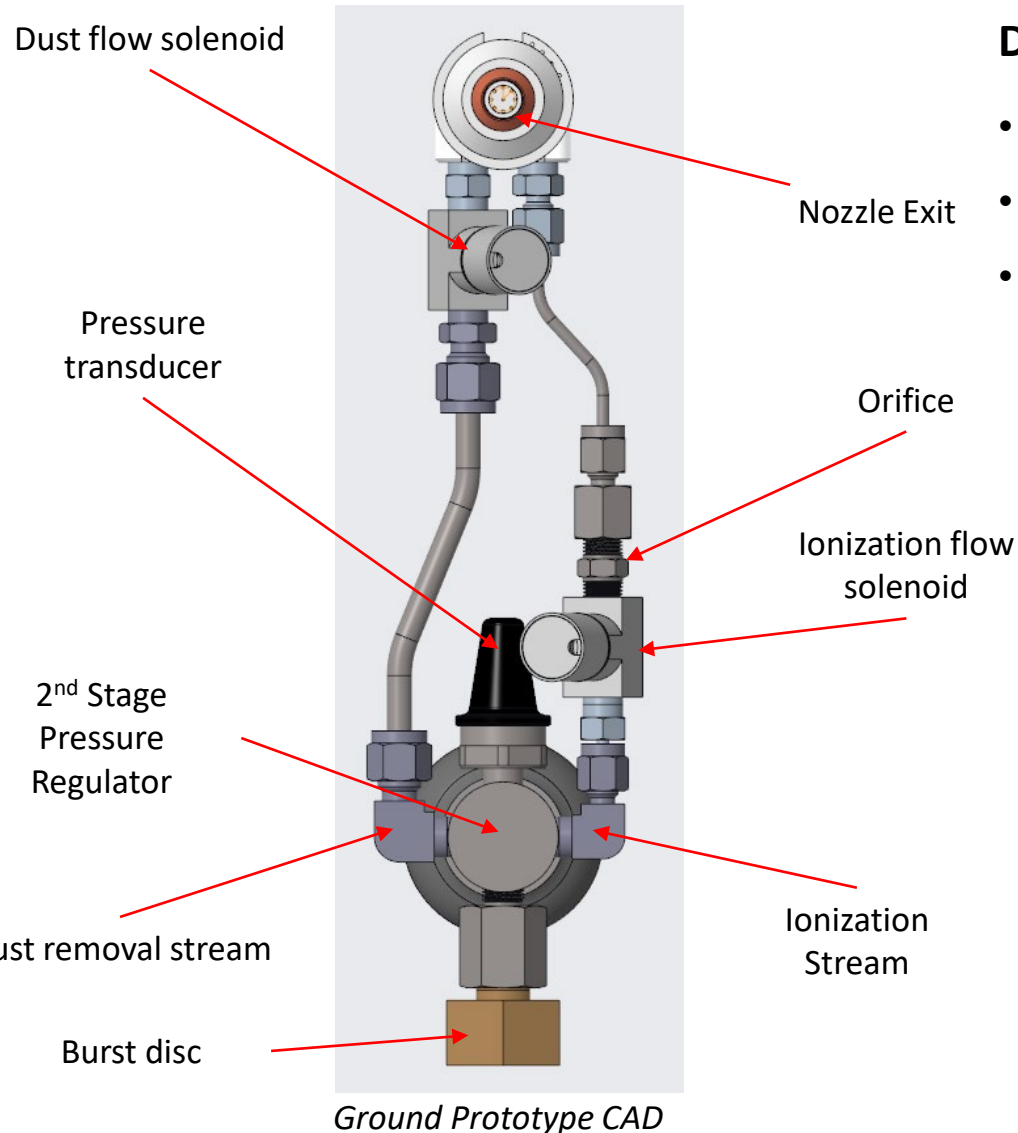
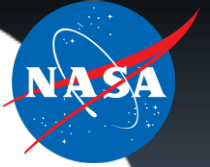
Surface potential neutralized in one pulse on insulators:
 ± 1200 V

Current TRL: 4

Changes from Demo 2 unit:

- Removed tank manifold and replaced with COTS pressure regulator.
- Added a dual gas stream nozzle manifold to enable fast dust removal and slower ionization gas flows.

Ground Prototype



Difficulties in Ionizing the high gas flow resulted in Demo 2 changes:

- Two separate flow streams for dust removal and ionization instead of one.
- Two solenoids to control the dust and ionization stream independently.
- Orifice in the ionization line to improve surface charge neutralization.

Operational Modes:

Power Off

Power On

- Electrometer Readings - Continuous
- Electrometer Zeroing - Selective

Dust Removal Only

- Single Shot – Trigger pressed and released
- Repetitive Shot – Trigger held down

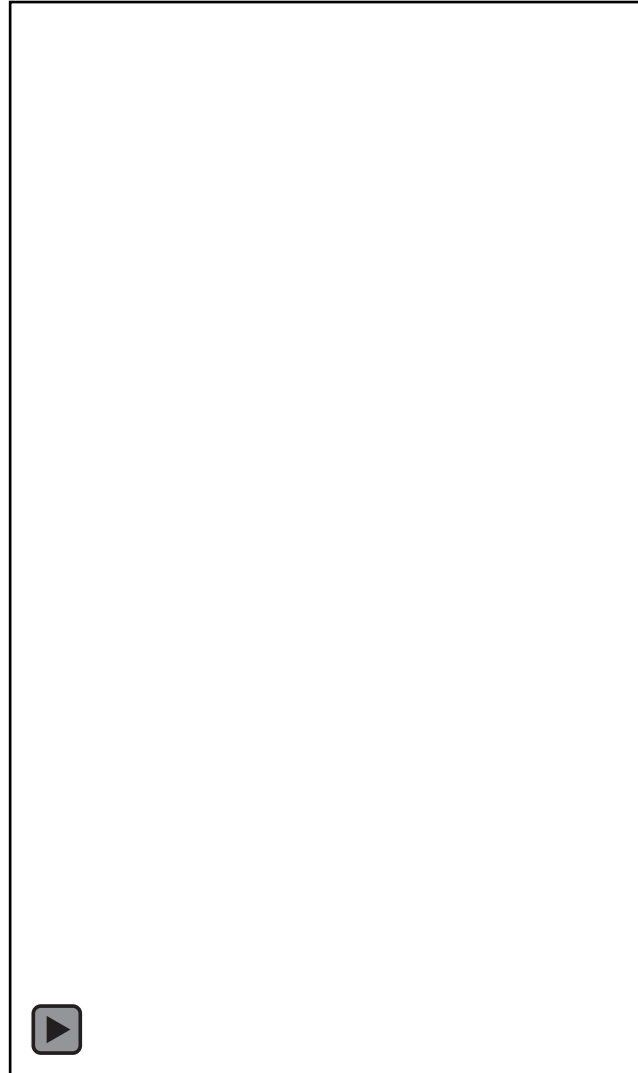
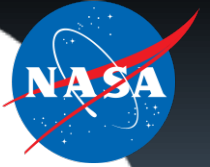
Charge Removal Only

- Single Shot – Trigger pressed and released

Dust/Charge Removal

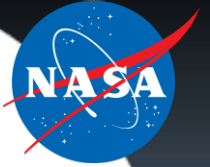
- Automated operation – Trigger pressed and released

Suited up LEDM Ground Prototype Handling at JSC's Neutral Buoyancy Lab

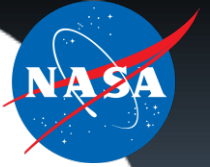


Video by NASA Johnson Spaceflight Center's EMU Team.

LEDM Ground Prototype Ionization



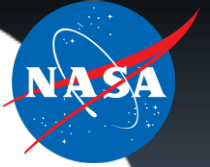
Future Plans



- Secure funding for FY26 for Ground Prototype (in progress)
 - Planned Environmental Testing at MSFC PLANET
 - Charge neutralization during dust operations
 - Neutralization of space charge environment
 - Dust testing on more relevant test articles
 - Further optimization of tool parameters
- Discussion and Development of Flight tool
 - Aggressive environmental campaign (JSC/KSC/MSFC)
 - Testing at NBL
 - GFE on Artemis III
 - Addition of data storage for Artemis III

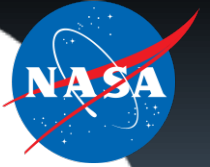


Any Questions?

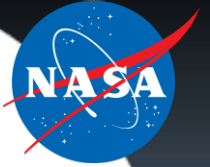


NASA Kennedy Space Center
Electrostatics and Surface Physics Lab
david.c.lund@nasa.gov

Backup



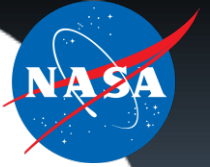
Air Ion Transportation



Air Ions are typically moved by two fundamental methods:

1. Electrostatic force from an electric field (attraction and repulsion).
 2. Mechanical force from being entrained in an airflow.
- **1st method** uses the electrostatic force developed by the electric field of the charged item itself to move (repel or attract) ions from the ionizer, whose field also moves the ions to the charged item.
 - This method requires to be placed near the item to be neutralized so that the electric field from the charged object can interact with the ionizer.
 - **2nd method** is to entrain the ions in a moving airflow and physically move them to the vicinity of the charged item where electrostatic forces take over to perform the neutralization.
 - This method typically allows the ionizer to be placed at a distance from the charged item, with the airflow from the ionizer or the ambient airflow directed onto the item.

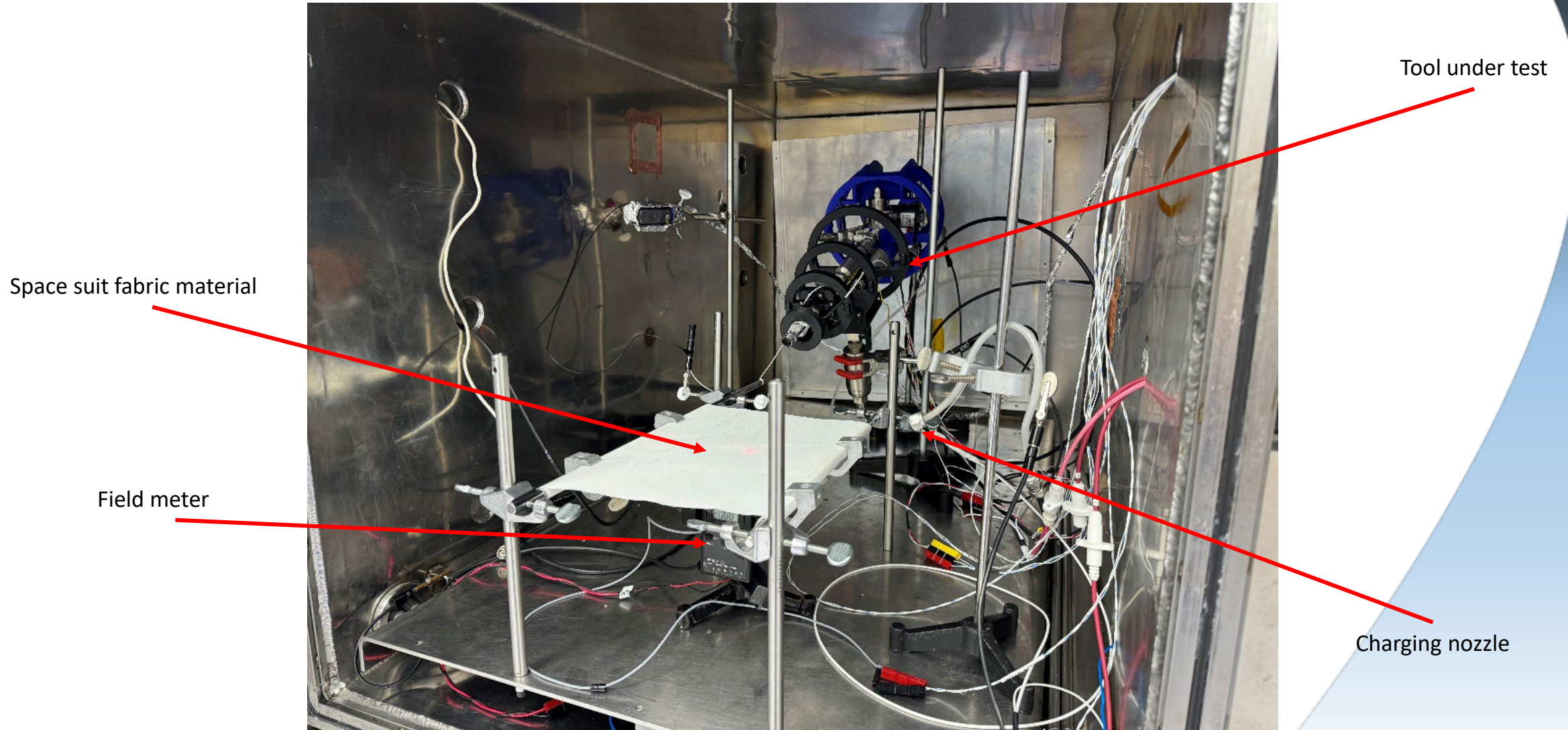
Dust Removal Test Result Summary



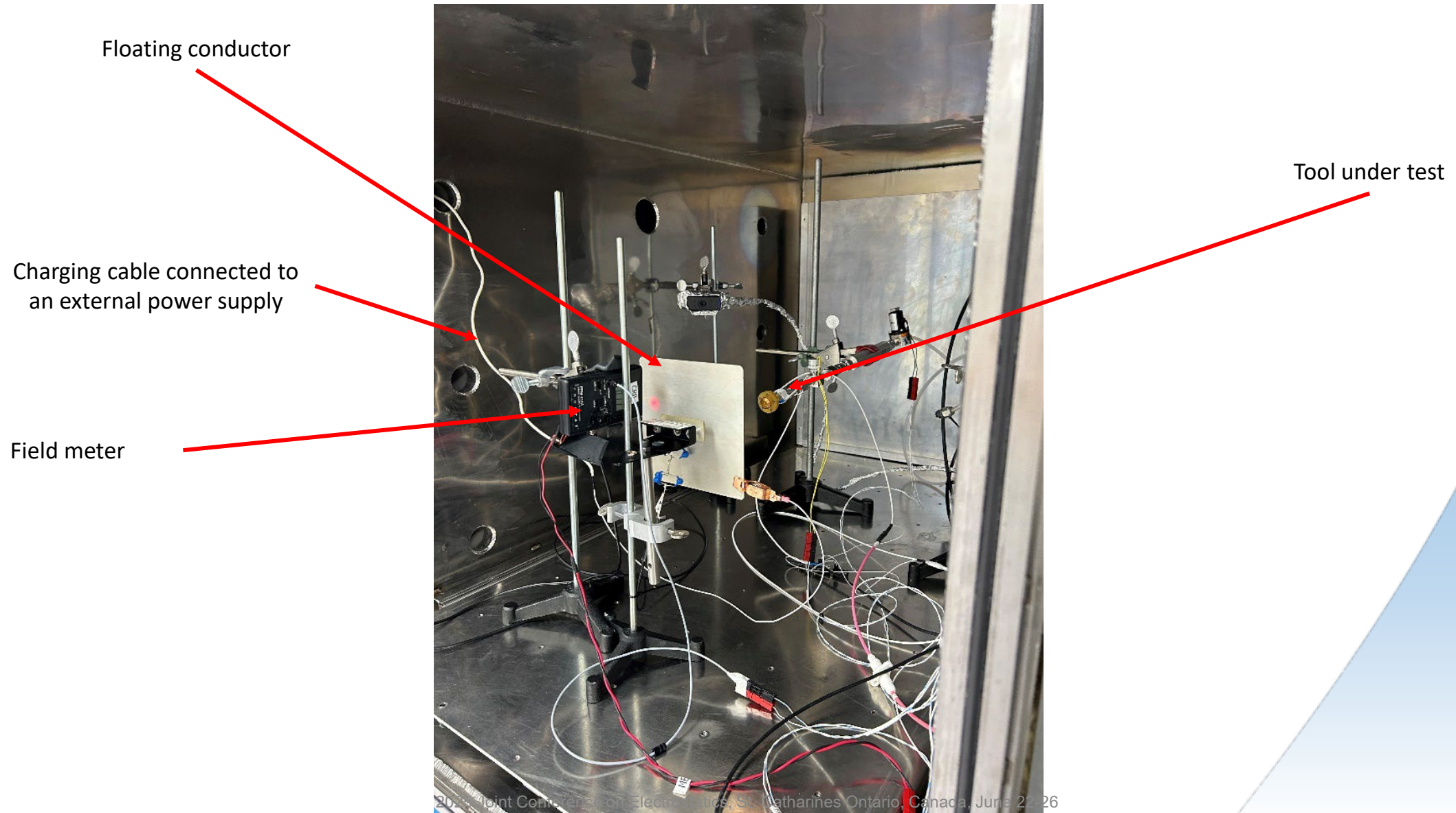
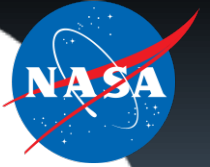
- Determined the impact of test parameters on dust removal efficiency.
 - Dust loading/concentration
 - Application method
 - Gravitational settling (sieve)
 - Mechanically pressed in
 - Tool's area of effectiveness
 - Distance between the nozzle to the target
 - Nozzle angle
 - Gas pressure
 - Simulant type
 - JSC-1
 - LHS-2
 - OPRH3N
 - Test article profile • Test article materials
 - Boots
 - Ortho-fabric
 - Gloves
 - Beta-cloth
 - Leg
 - Metal backed insulator
 - Flat panels
 - Bare metal



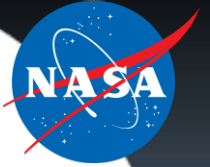
Charge Neutralization Test Setup (Insulator)



Charge Neutralization Test Setup (Conductor)

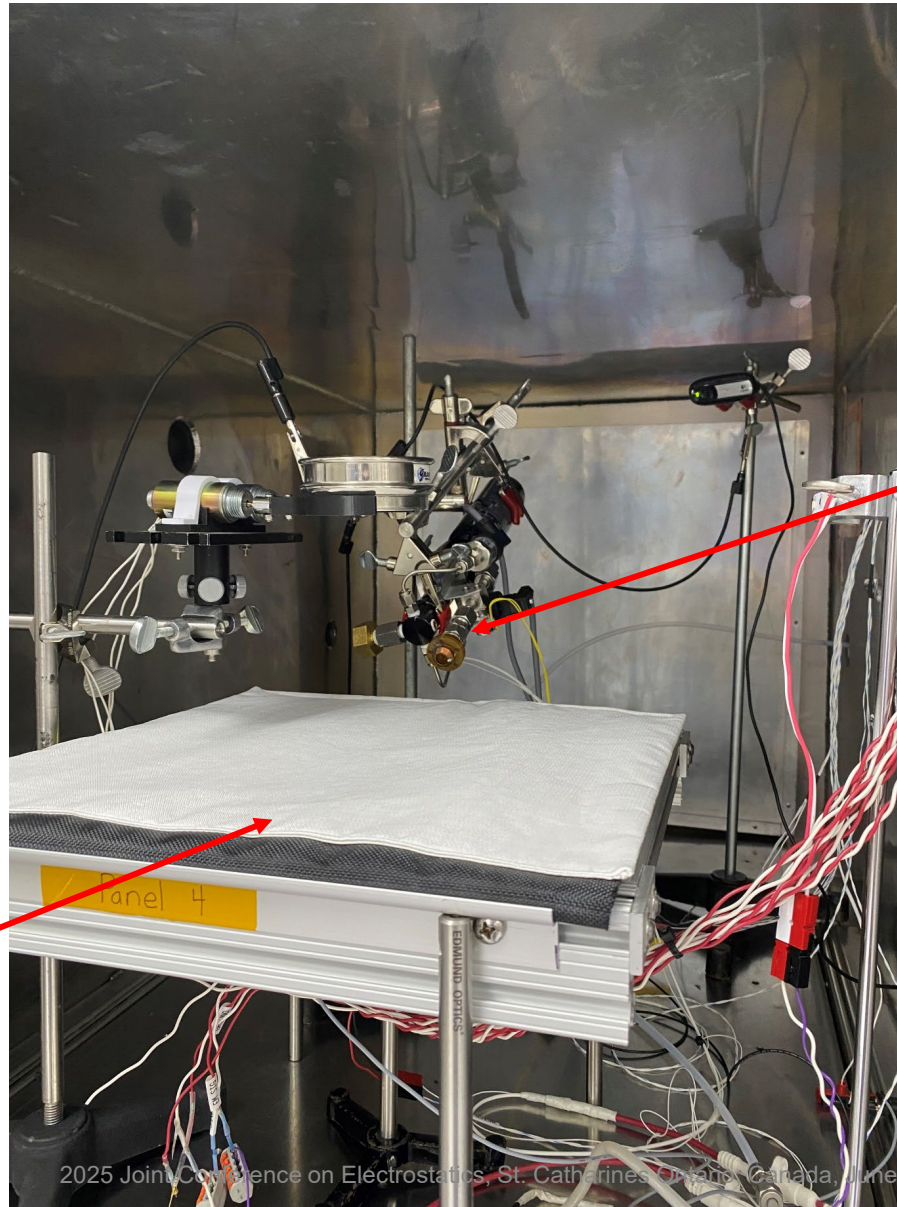


Dust Removal Test Setup Ortho fabric



Ortho fabric

Tool under test

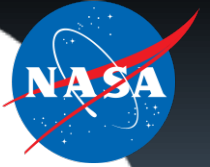


Demo 1 and Demo 2 KSC Testing Summary

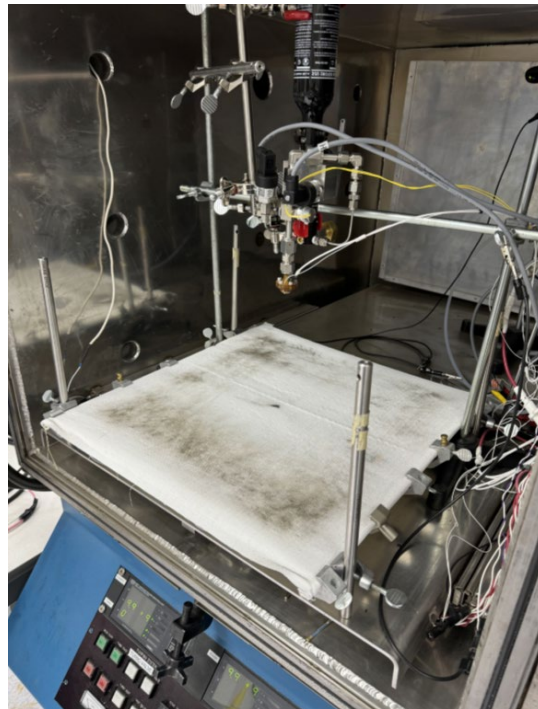
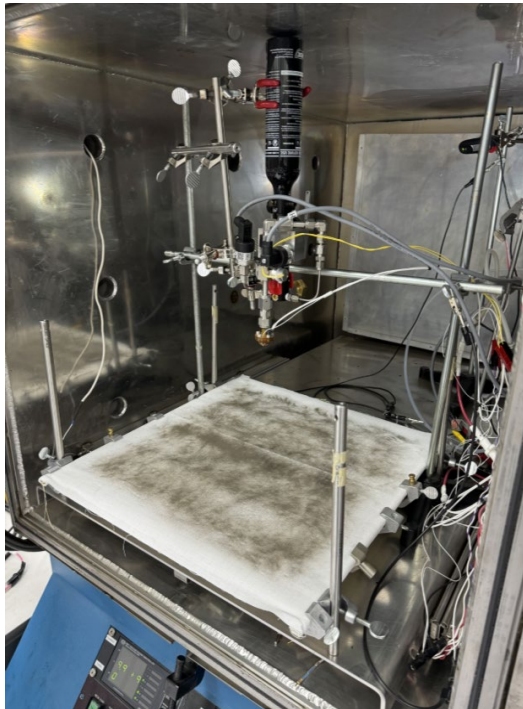
- COTS system metal plate charge removal testing (220)
- Demo 1 ortho fabric charge removal testing (630)
- Demo 1 ortho fabric and beta cloth dust removal testing (20)
- Demo 2 metal plate, ortho fabric, and beta cloth charge removal testing (400)
- Demo 2 metal backed insulator charge removal testing (20)
- Demo 2 ortho fabric dust removal testing (80)



Area of Effect Dust Testing

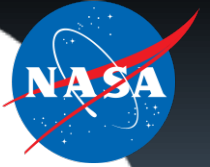


- 7-8 g of dust loading with seven distance/angle configurations tested for dust removal area of effect
 - Angles: 20, 45, and 90 deg
 - Distances: 4, 6, and 8 in
- Geometric patterns deduced from post-op imagery to characterize gas flow cone
 - Post-op images were separated into effective clearing regions to determine the most effective areas for dust removal
 - Dust removal efficiency also captured for correlation to area of effect



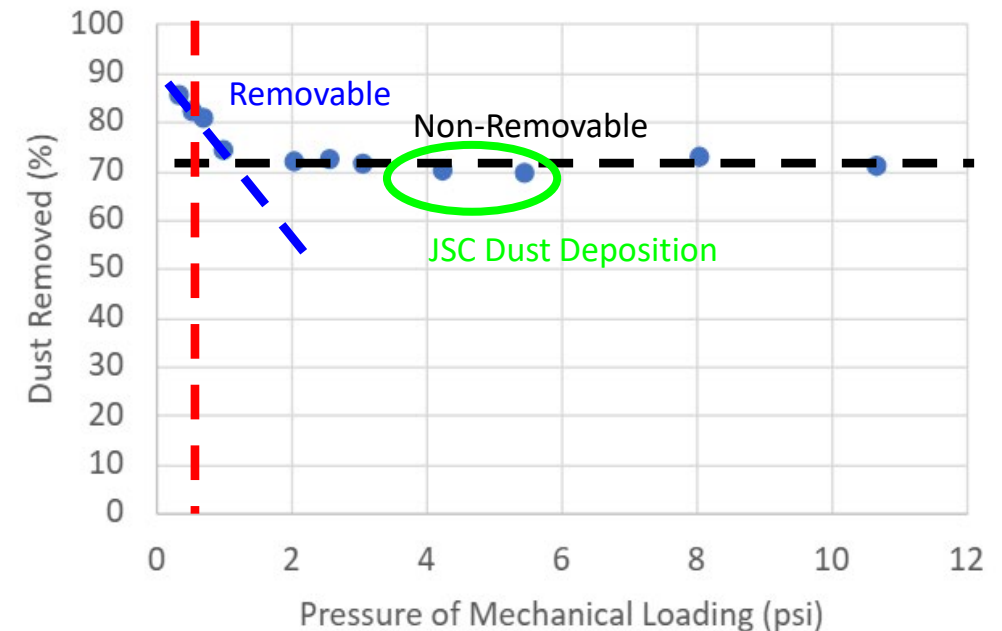
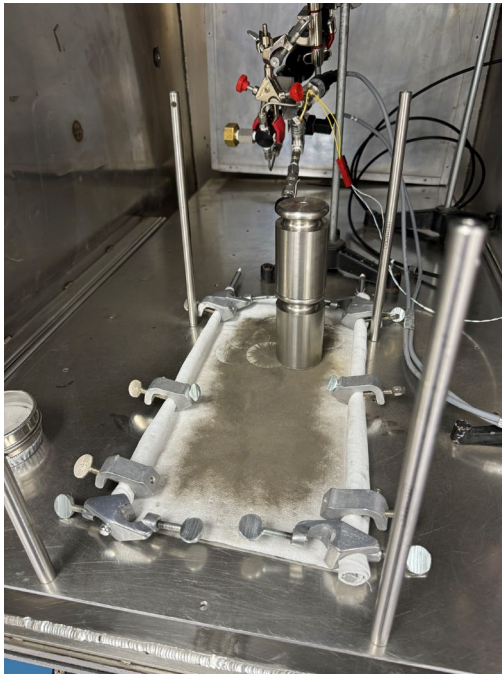
Distance (in)	Angle of Attack (deg)	Cleaned Area (in ²)	Dust Removed (%)
4	90	15.9	73.3
6	20	143.6	87.3
6	45	166.34	84.5
6	90	41.88	78.7
8	90	41.59	78.3

Mechanically Applied Dust Removal Testing

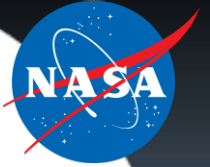


- Six grams of dust loaded onto a 14" x 6" area on an ortho fabric sample and mechanically pressed into the fabric with weights ranging from 0.44 – 45.59 lbs.
 - Weight application areas ranging from 1.18 – 4.27 in²
 - Each test conducted with a nozzle pressure of 60 psid (not 75 psid) and in a configuration 9 in away from the target with a 20 deg angle of attack
 - Excess dust not pressed into the fabric was removed before testing

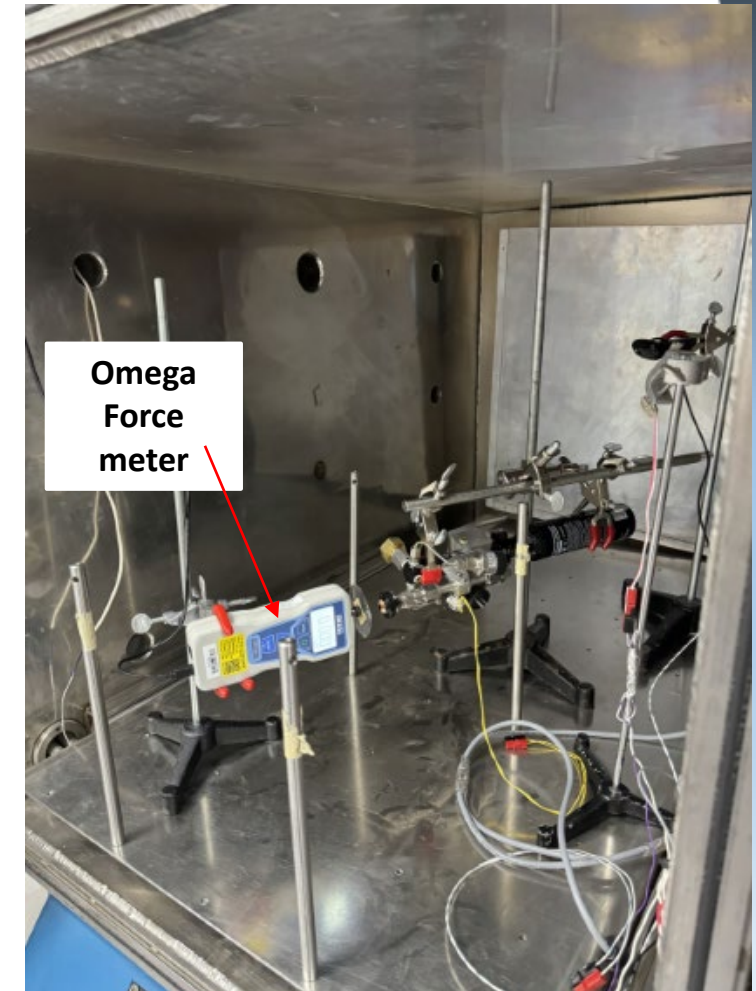
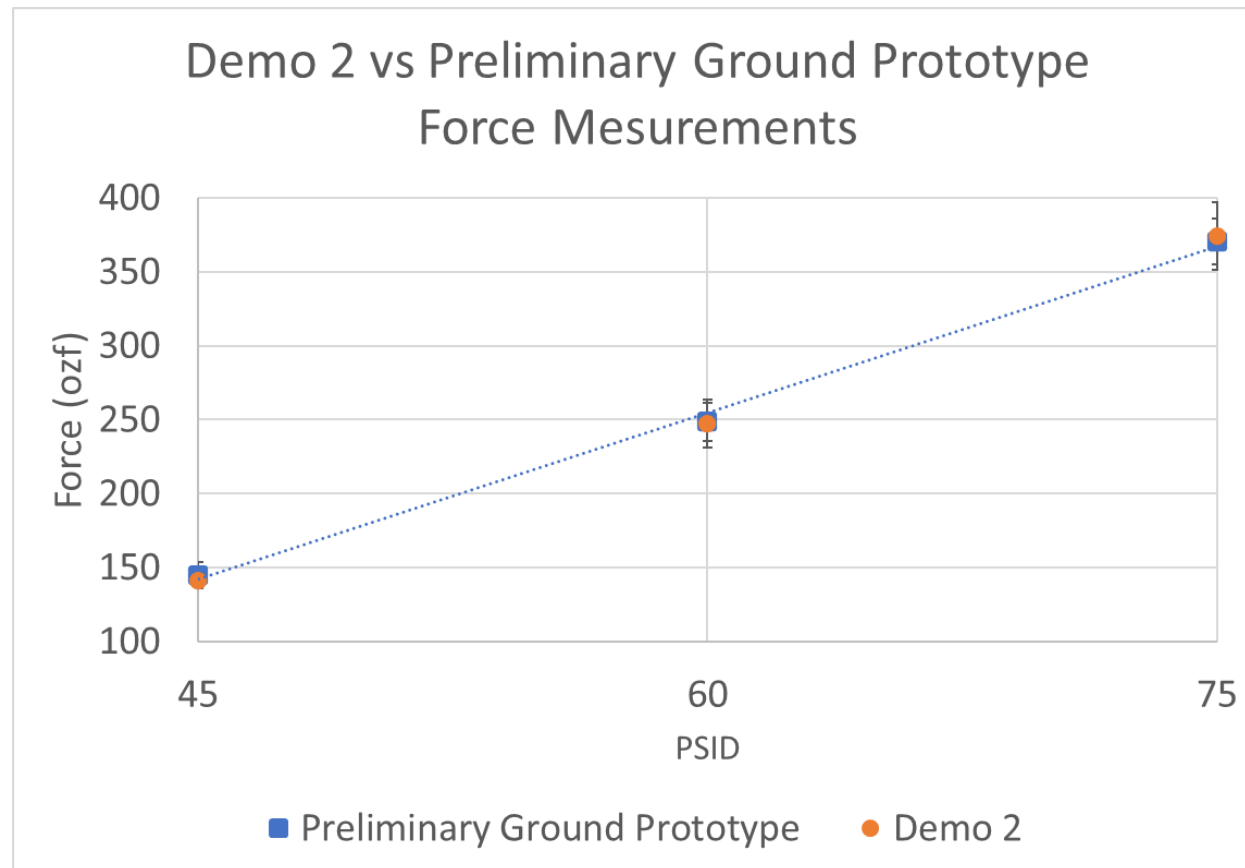
- **A 419 lb. astronaut standing with two boots on the lunar surface applies ~0.578 psi of pressure**



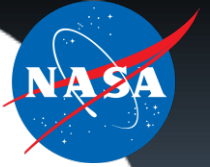
Preliminary Ground Prototype Force Measurements



- **New designs required Force measurement testing to ensure the dust removal efficiency would remain unaffected.**
 - Verified changing the flow path from a straight path (Demo 2) to a 90° angle (Preliminary Ground Prototype) would not change dust removal force



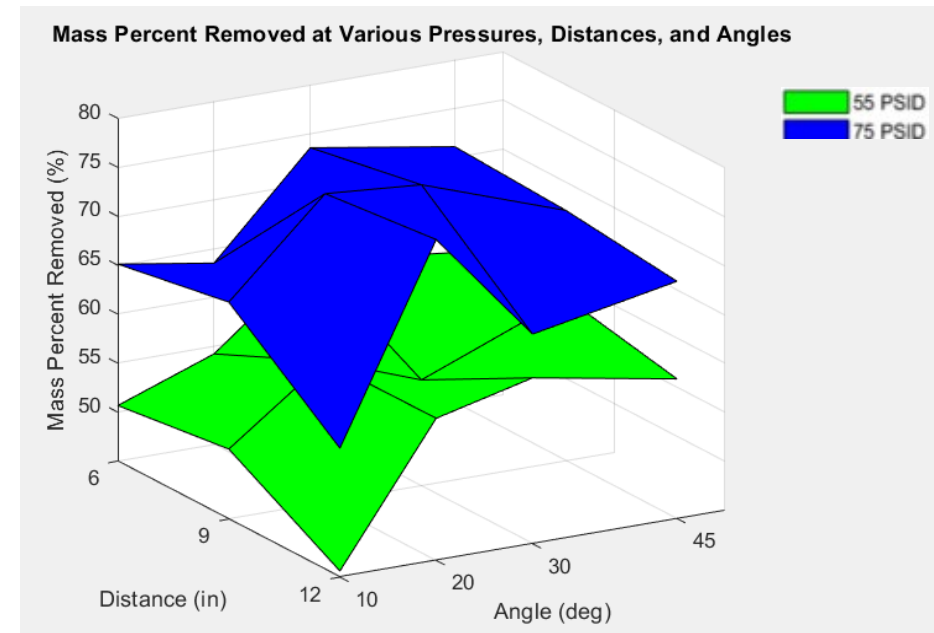
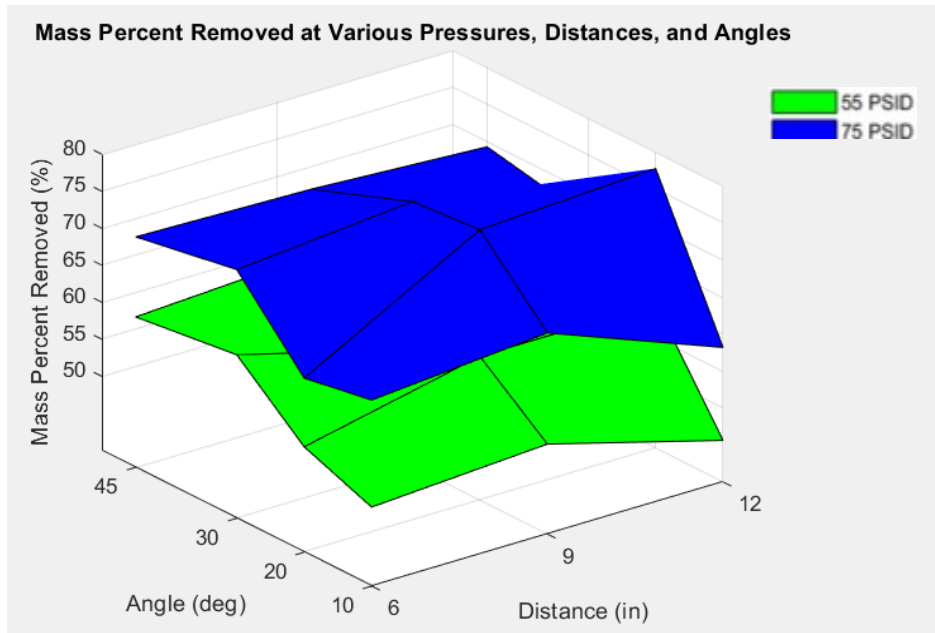
Variable Distance, Angle, and Pressure Dust Testing



24 Test Combinations

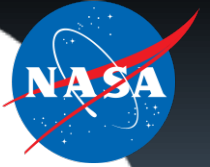
Pressure (psid)	Distance (in)	Angle (deg)
55	6	10
75	9	20
-	12	30
-	-	45

75 PSID, 9 inches, 10 degrees



***Area of effect calculation not taken into consideration for dust removal efficiency percentage**

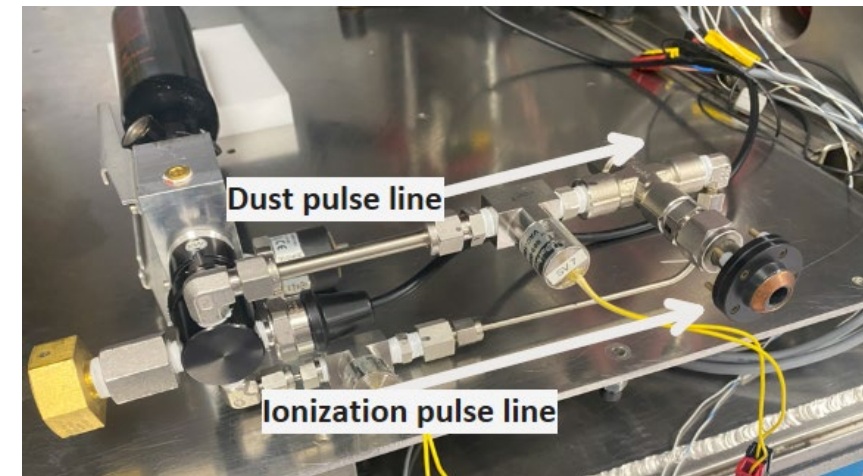
Preliminary Ground Prototype Shot Count



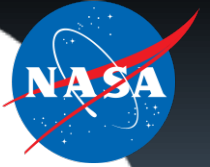
3,000 psi and 13 in³ COTS tank

- ♦ Dust removal only shots at 75 psid: 85
- ♦ Combination (dust & ionization) shots at 75 psid: 62
- ♦ Methods to increase shot count include:
 - Refill tanks in situ
 - Switch out tanks
 - Use of a Larger overall tank
 - Use of a High-pressure tank (e.g. COPV)
 - Decreased gas pulse duration
 - Lower overall nozzle pressure

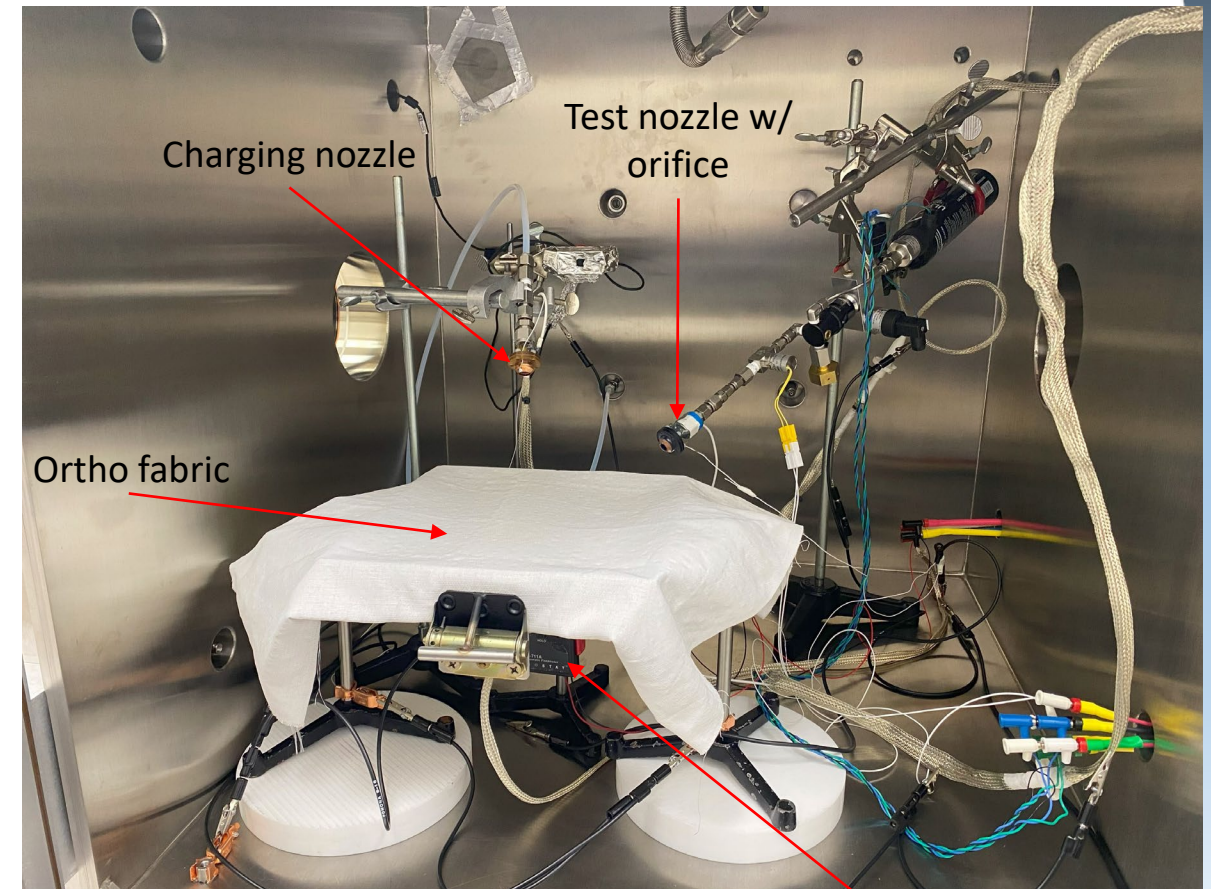
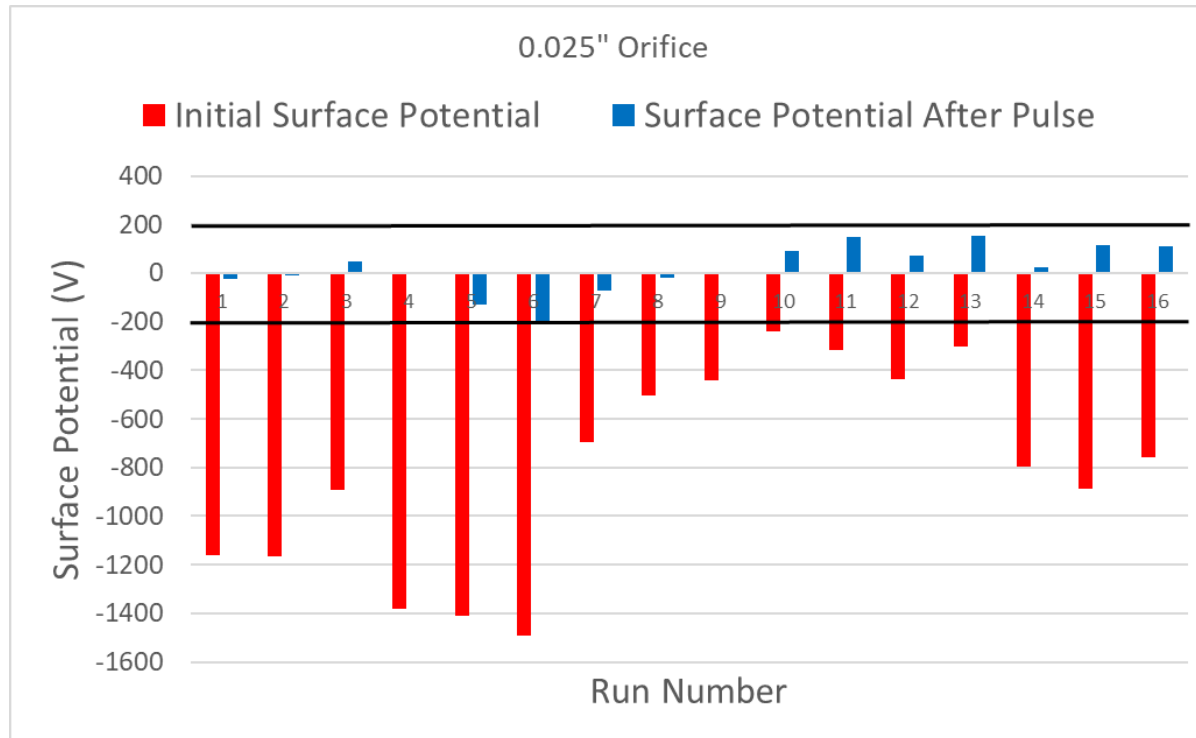
Nozzle Pressure (PSID)	Dust Pulse Duration (ms)	Ionization Pulse Duration (ms)	Shot Count
75	400	800	62
75	400	-	85
55	400	800	77
55	400	-	113
45	400	800	99
45	400	-	152



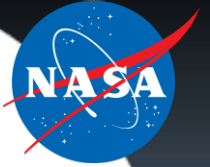
Gas Flow Reduction for Charge Neutralization



- Tested 3 orifice sizes to reduce the gas flow for charge neutralization. [0.016" 0.025" 0.036"]
- 0.025" opening provided the best surface potential reduction.
- Average initial surface potential: **-850V**
- Average surface potential reduction: 800V

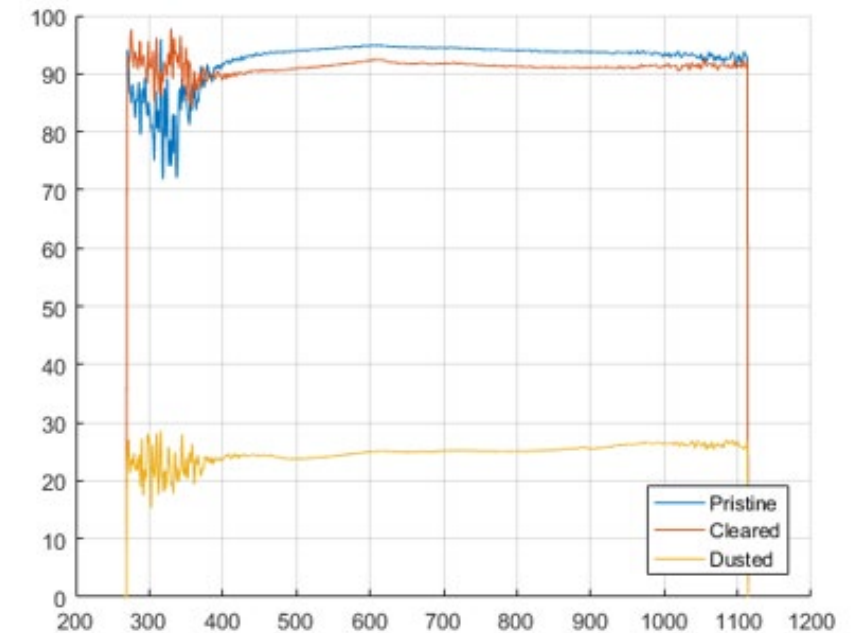


LEDM Test on Solar Cell Glass

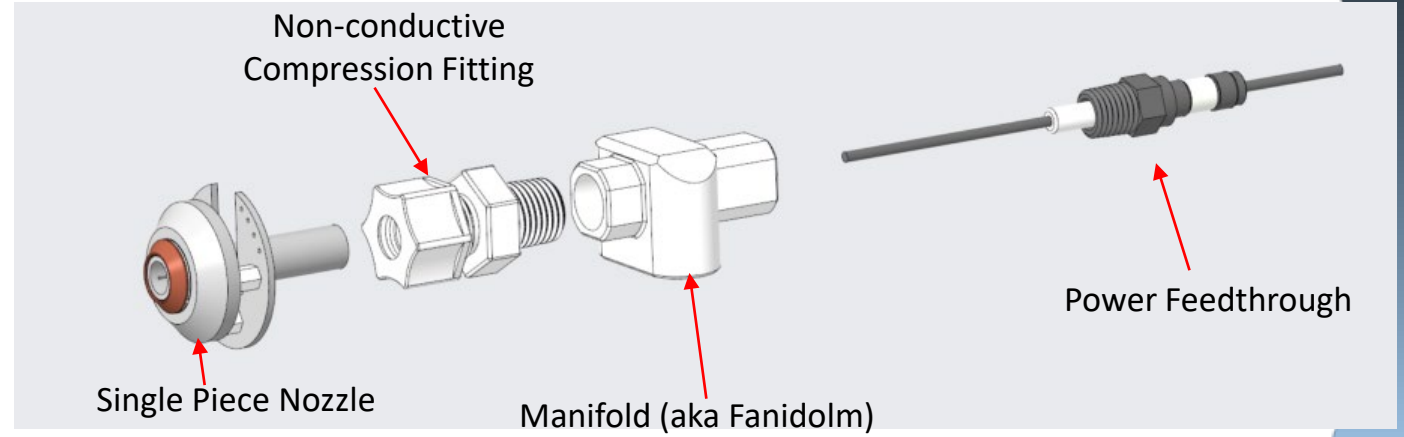
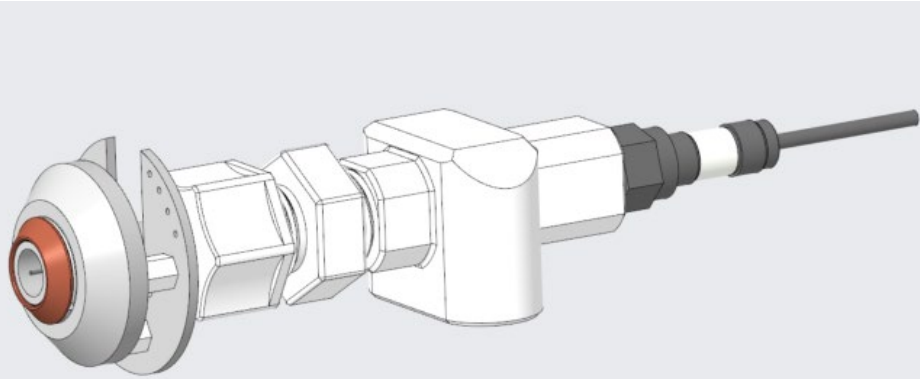


LEDM removing LHS-1 lunar simulant from solar cell cover glass 6 inches away and 19° angle of attack loaded with 4 mg/cm² of simulant under high vacuum conditions

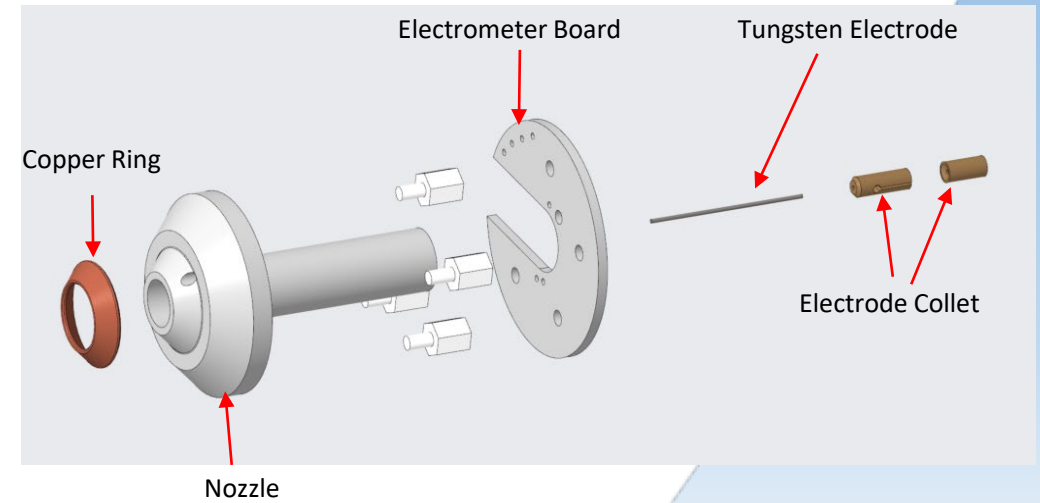
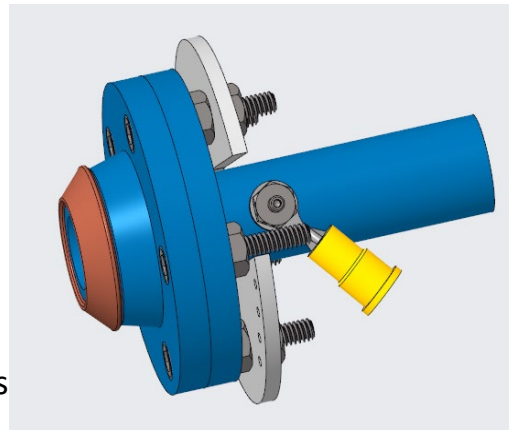
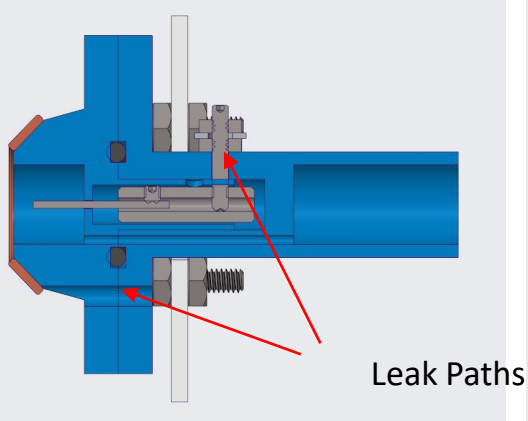
Transmittance before dust deposition and after dust removal



New Single Piece Nozzle Design



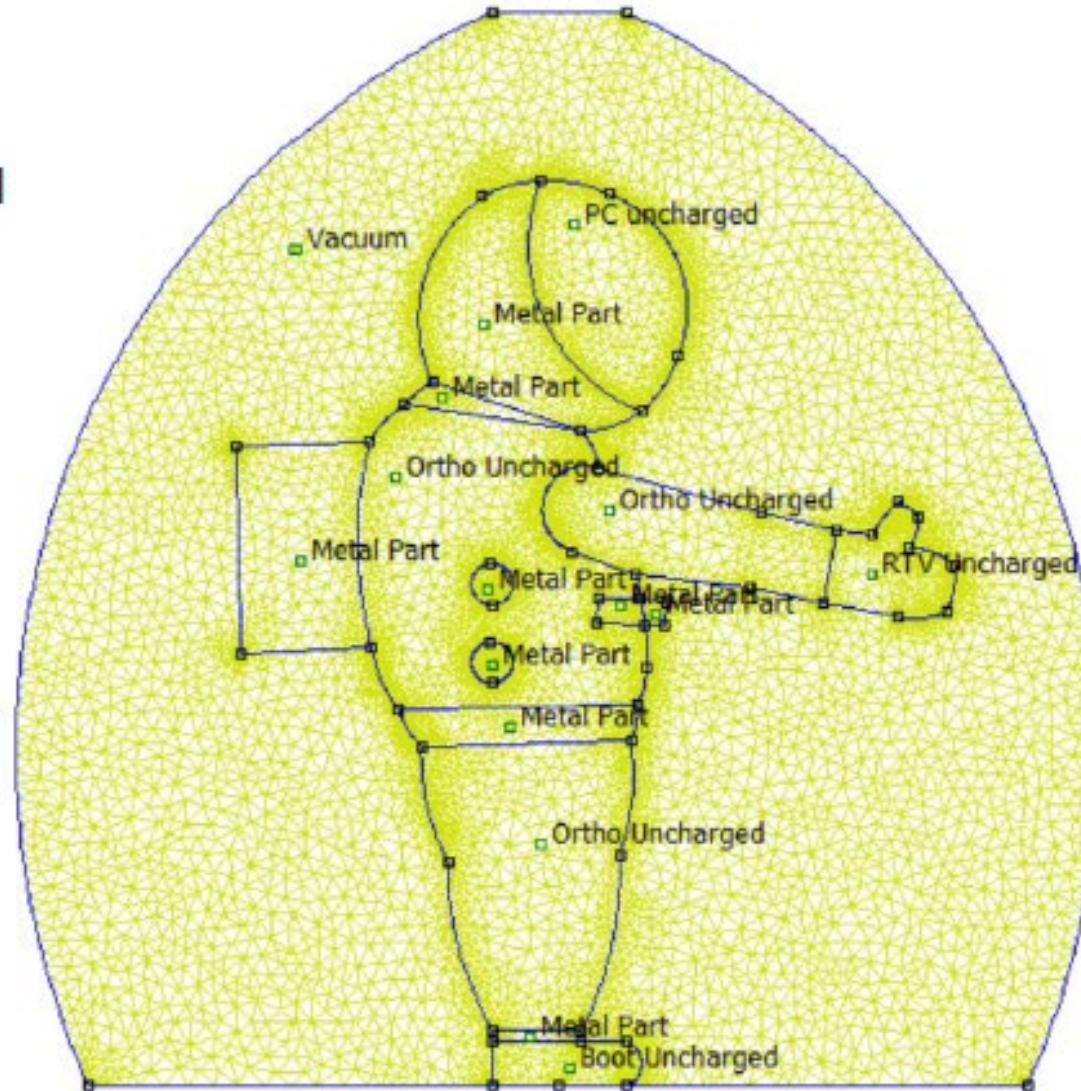
Previous Two Piece Nozzle Design



FEMM Modelling

Modelling is useful for exploring potential hazards

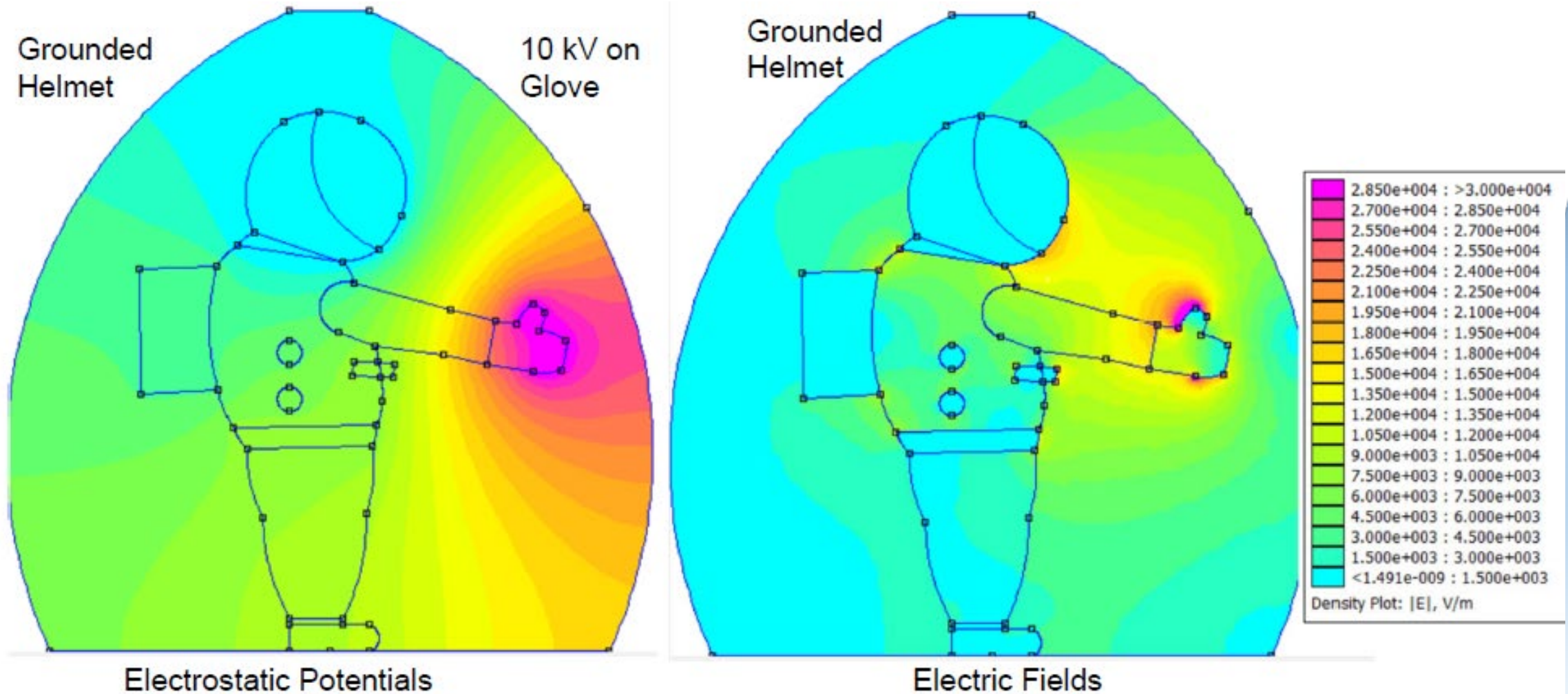
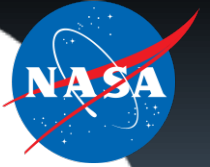
- O₂ leak locations
- Dust deposition



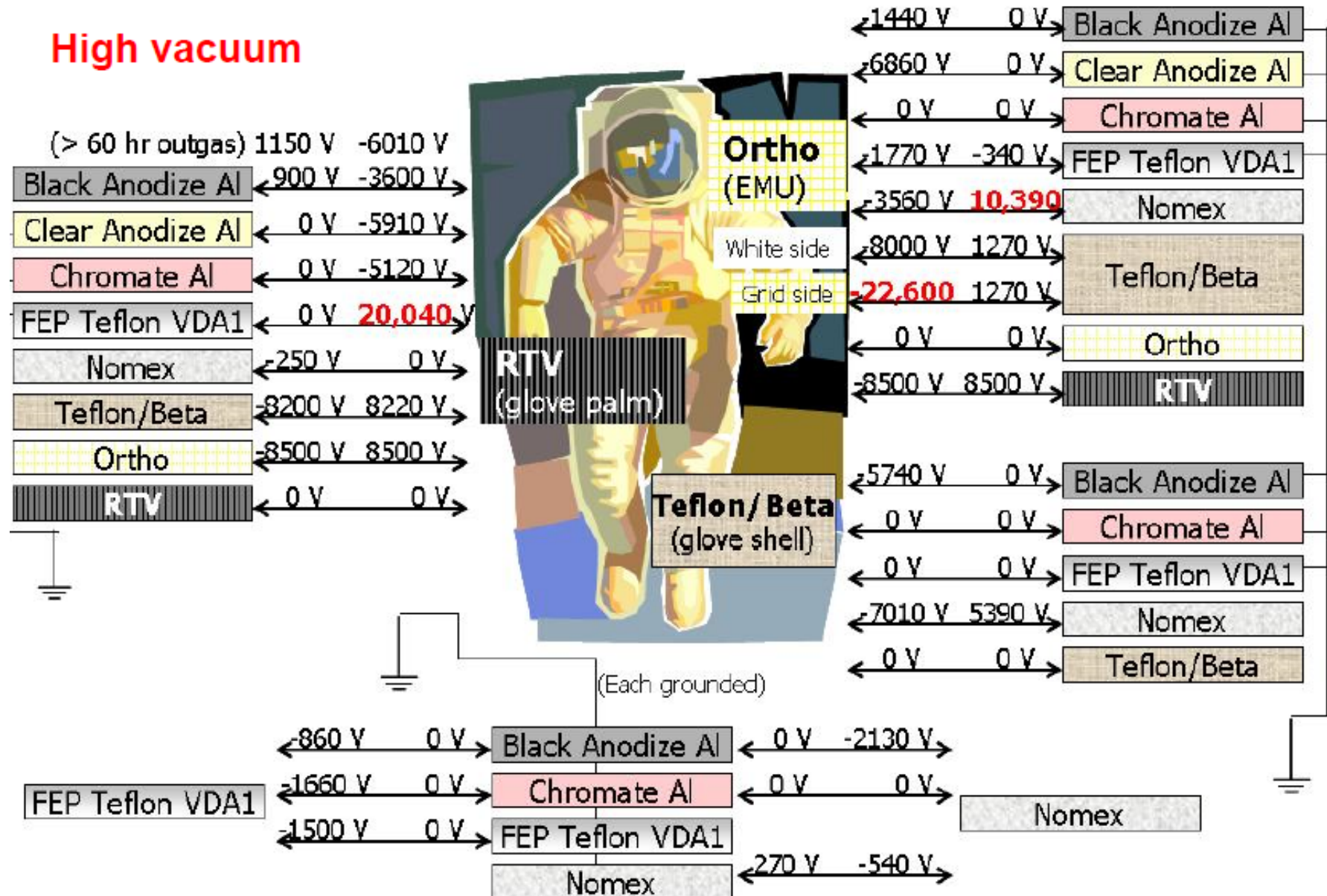
Many models can be used

- FEMM
- COMSOL
- EMA-3D

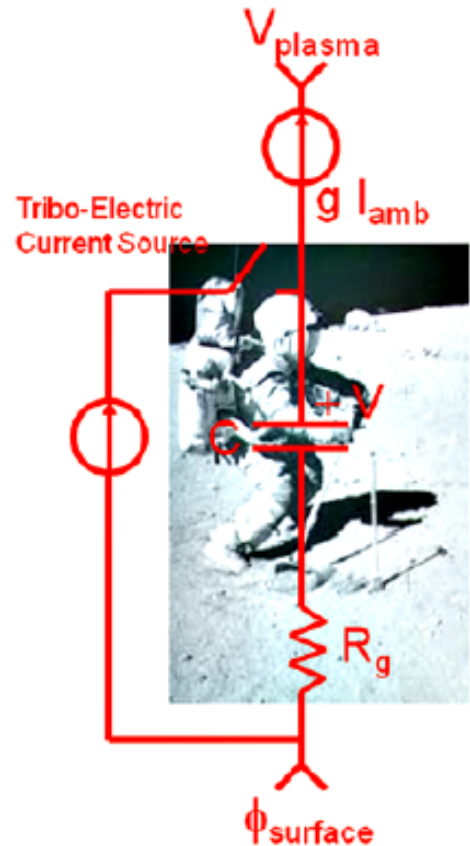
FEMM Modelling potentials and fields



High vacuum



Charge Equivalent Circuit



Farrell et al, 2008
Jackson et al., 2011

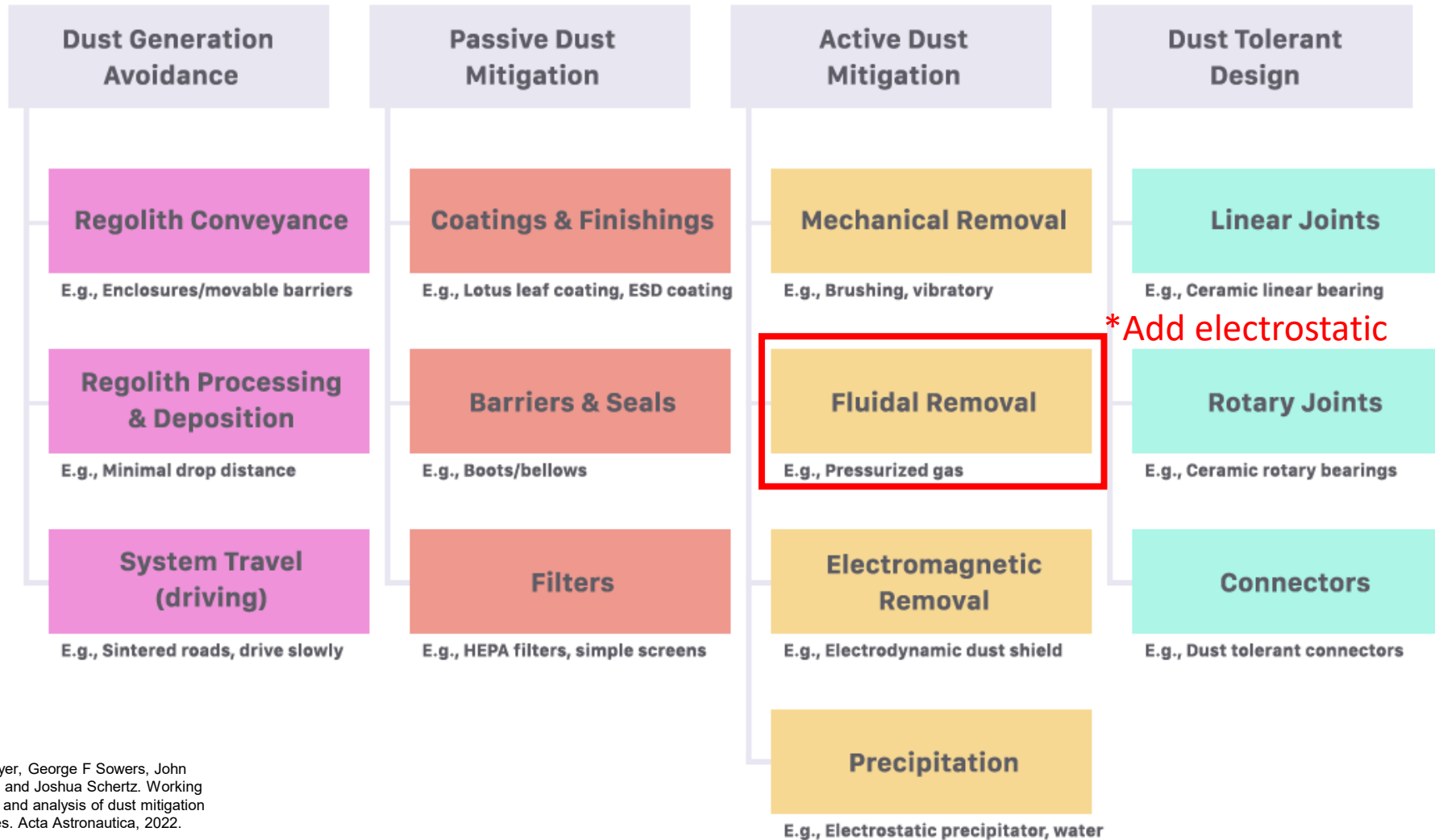
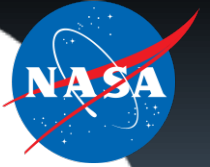
On surface, now add dynamic terms to current balance:

- Moving over surface creates a tribo-electric source of charge, $S(t)$
- Surface 'ground', but the Moon is a very poor conductor (in shadowed regions can be as low as 10^{-17} S/m) [Carrier et al., 1991]
- On dayside, photoelectrons and solar wind ions provide a good ground. The medium is conductive.
- **Problem areas:** Nightside and shadow – no photoelectron currents, and have reduced plasma currents

$$S(t) + I_{\text{ground}} + I_{\text{photoelec}} + I_{\text{elec}} + I_{\text{ion}} + I_{\text{secondary elec}} = dQ/dt$$

- *Ground to the local plasma, and not to 'surface' ground*

Dust Mitigation Taxonomy



Kevin M Cannon, Christopher B Dreyer, George F Sowers, John Schmit, Thao Nguyen, Keoni Sanny, and Joshua Schertz. Working with lunar surface materials: Review and analysis of dust mitigation and regolith conveyance technologies. Acta Astronautica, 2022.

Surface Plasma Estimates



Table 1

Electron, ion and secondary electron currents for various lu regions.at the Moon

Current	Day	Term	Night	Crater
J_{e-env} (A/m ²)	1×10^{-6}	3.52×10^{-8}	4×10^{-10}	5.1×10^{-10}
J_{i-env} (A/m ²)	3.2×10^{-7}	3.52×10^{-8}	4×10^{-10}	1.6×10^{-11}
J_{s-env} (A/m ²)	0	0	4×10^{-11}	5.1×10^{-10}
J_{p-env} (A/m ²)	4×10^{-6}	0	0	0

$\sim 5 \mu\text{A/m}^2$

$\sim 0.8 \text{ nA/m}^2$

Jackson et al., 2015

