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Satellite Survivability in a Harsh Space Environment: A Materials Perspective

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Satellite Survivability in Space: A Materials Perspective

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To paraphrase Douglas Adams,

"Space is [harsh]. Really [harsh]. You just won't believe how vastly, hugely, mind-bogglingly [harsh] it is.

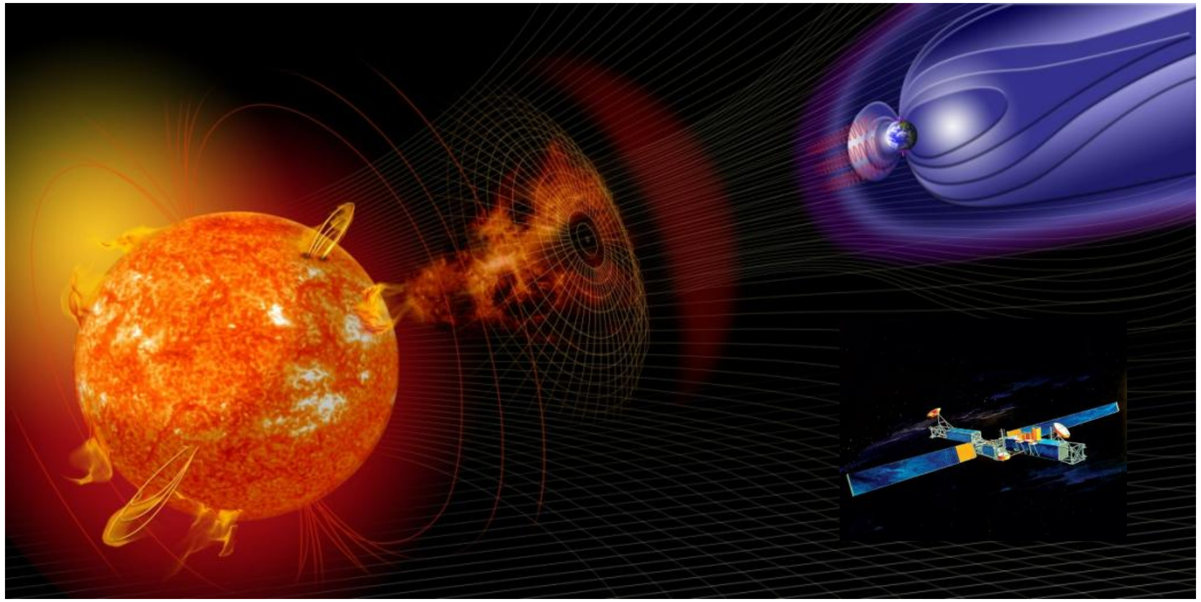
I mean, you may think it's a long way down the road to the chemist, but that's just peanuts to space."

D. Adams--*Hitchhiker's Guide to the Galaxy*

Bottom line for the *USU Materials Physics Group*:

Interactions with this harsh space environment can modify materials and cause unforeseen and detrimental effects to spacecraft. Therefore, we:

- **simulate the space environments,**
- **characterize their effects on materials properties,**
- **use these results to predict and mitigate space environment effects,**
- **work to understand the materials physics involved at the atomic scale to**
- **extend our work to more diverse problems and materials.**



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Spacecraft/Environment Interactions

- The Sun gives off high energy charged particles, with dynamic fluxes.
- Particles interact with the dynamic Earth's atmosphere and magnetic field in interesting and dynamic ways.
- Dynamics of the space environment and satellite motion lead to dynamic spacecraft interactions
- High energy particles deposit charge and energy into spacecraft surfaces
- Materials in spacecraft can modify the local space environment
- Materials properties evolve in response to interactions with the environment
- Evolving mission objectives, complexity, sensitivity, size

Dynamic Space Environments:

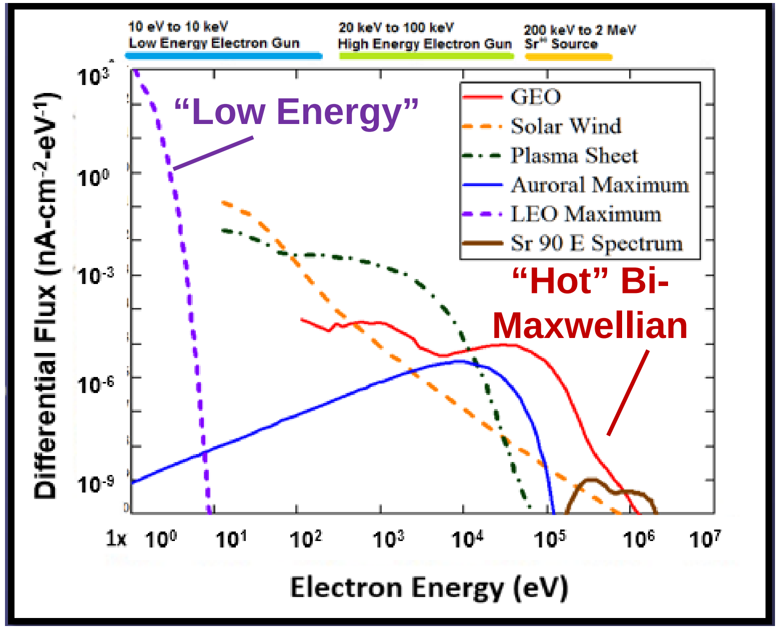
- Solar Wind, Solar Flares, CME, Solar Cycle
- Dynamic magnetic fields
- Orbital eclipse, rotational eclipse

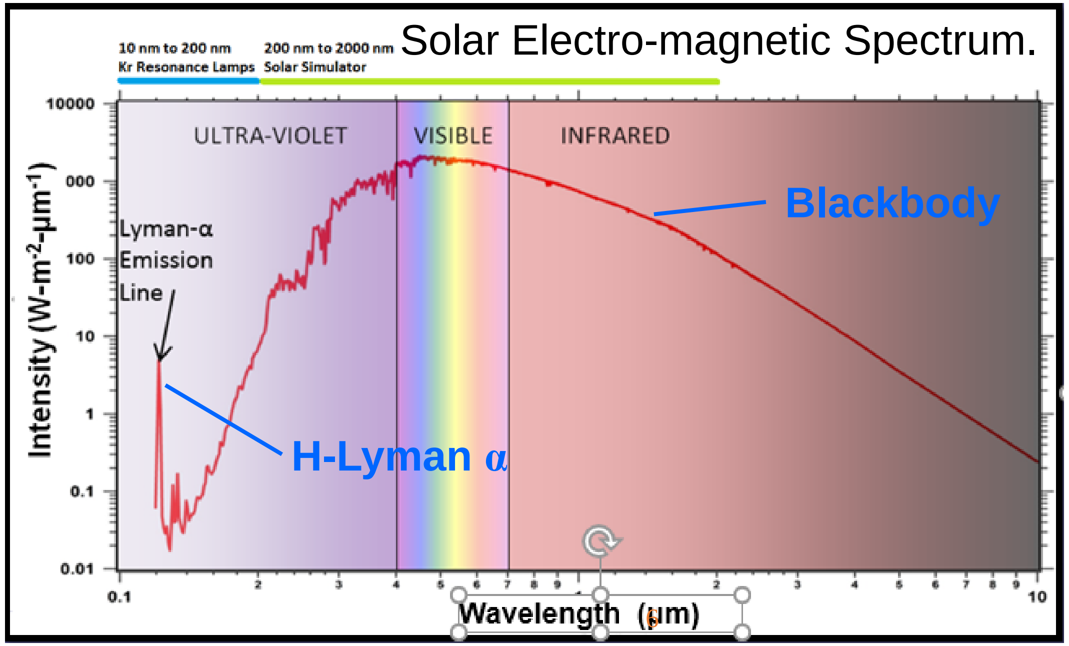
Dynamic Fluxes:

- Electrons, e^-
- Ions, I^+
- Photons, γ
- Particles, m

The Space Environment

Typical Space Electron Flux Spectra



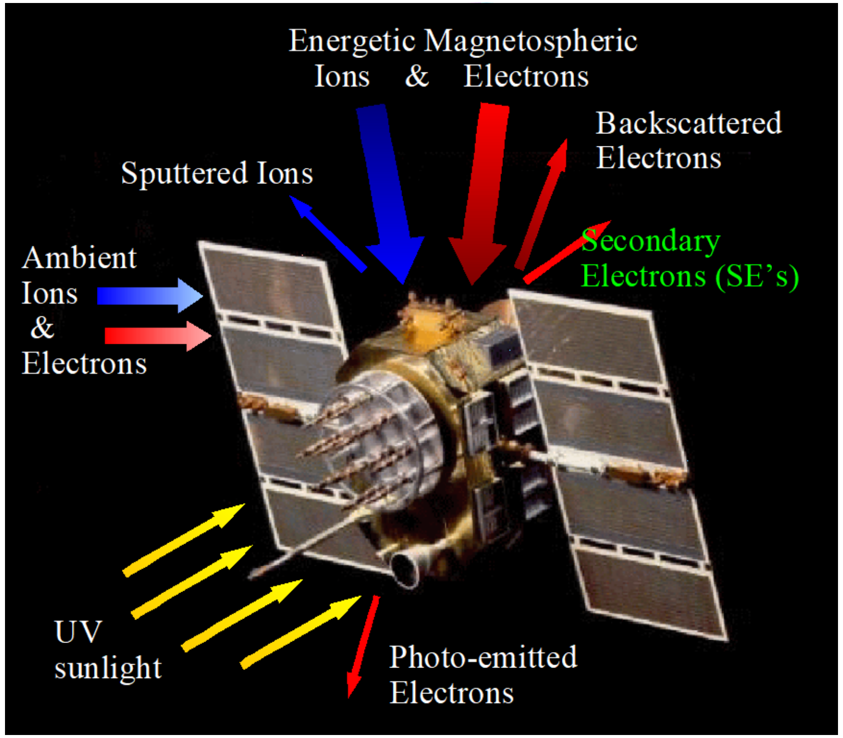


Primary Motivation For Our Research—Spacecraft Charging

Our concern for spacecraft charging is caused by plasma environment electron, ion, and photon-induced currents. Charging can cause performance degradation or complete failure.

Majority of all spacecraft failures and anomalies due to the space environment result from plasma-induced charging

- *Single event interrupts of electronics*
- *Arcing*
- *Sputtering*
- *Enhanced contamination*
- *Shifts in spacecraft potentials*
- *Current losses*

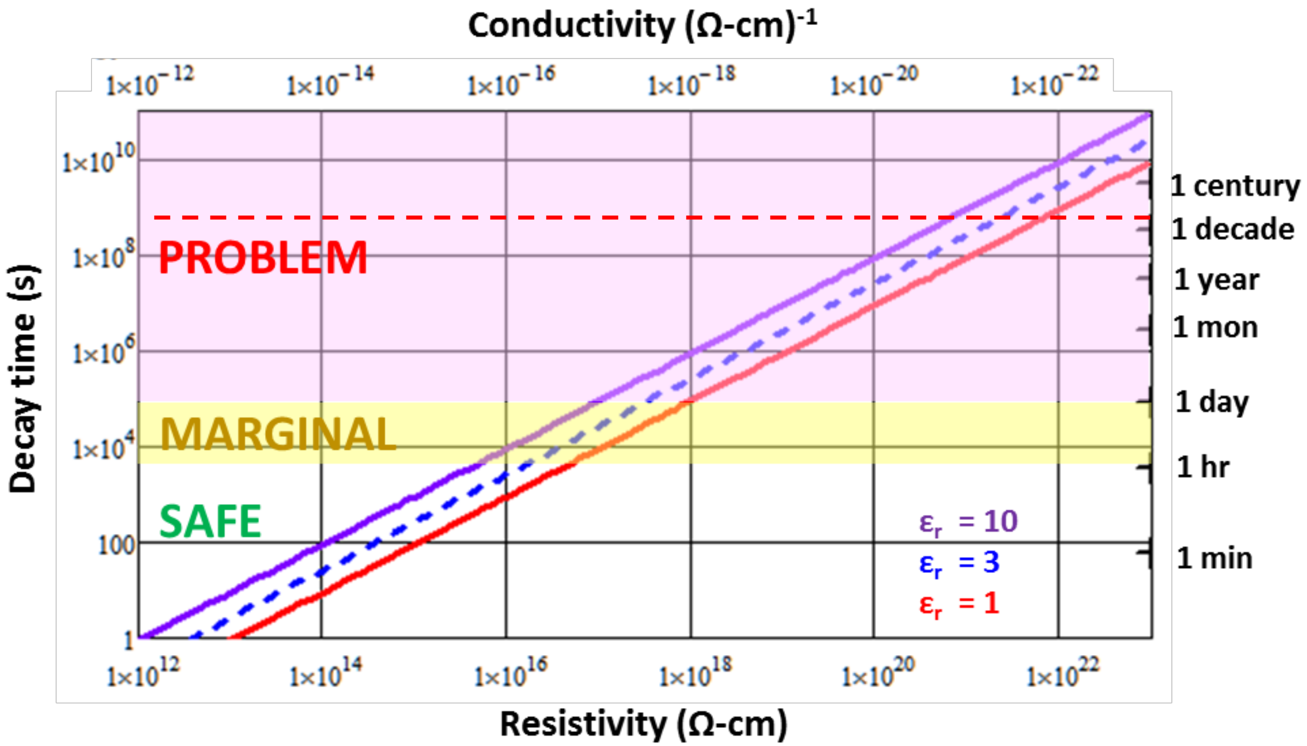


Incident and Emitted Currents that Result in Spacecraft Charging

Spacecraft adopt potentials in response to interaction with the plasma environment.

- **Incident fluxes and electron emission govern amount of charge accumulation**
- **Resistivity governs:**
- *Where charge will accumulate*
- *How charge will redistribute across spacecraft*
- *Time scale for charge transport and dissipation*

Critical Time Scales and Bulk Resistivities



Corresponding Decay Times (ε_r=1)

500 yr → $\rho \bullet \varepsilon_o$ ~$1 \bullet 10^{23}$ Ω-cm

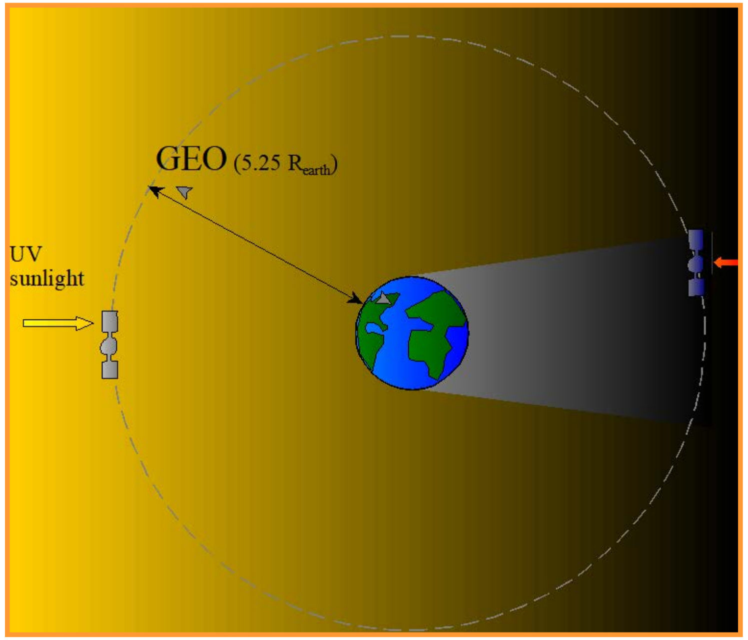
15 yr → $\rho \bullet \varepsilon_o$ ~$5 \bullet 10^{21}$ Ω-cm

1 yr → $\rho \bullet \varepsilon_o$ ~$4 \bullet 10^{20}$ Ω-cm

1 day → $\rho \bullet \varepsilon_o$ ~$1 \bullet 10^{18}$ Ω-cm

1 hr → $\rho \bullet \varepsilon_o$ ~$4 \bullet 10^{16}$ Ω-cm

1 min → $\rho \bullet \varepsilon_o$ ~$1 \bullet 10^{15}$ Ω-cm



Decay time vs. resistivity base on simple capacitor model.

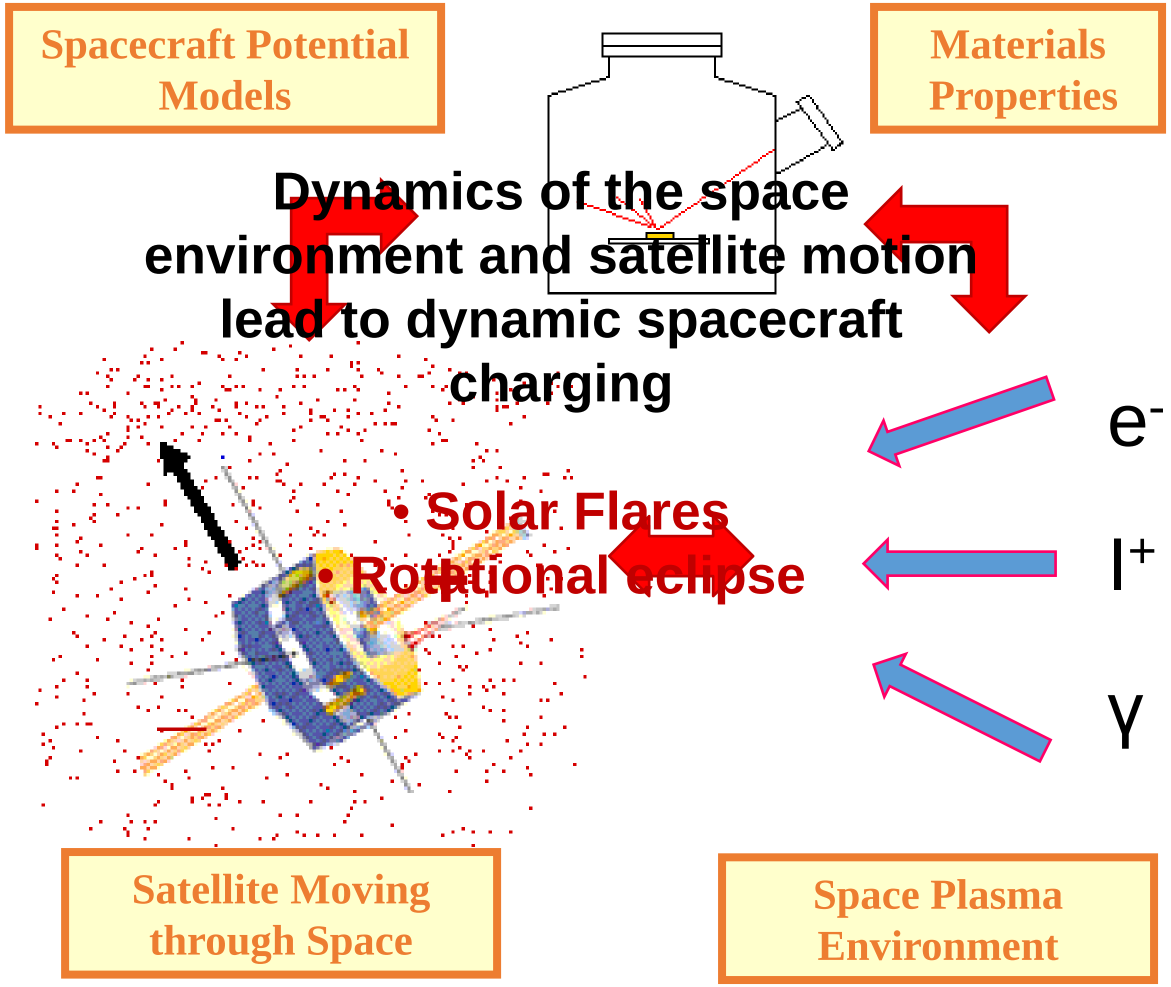
$$\tau = \rho\, \varepsilon_r\, \varepsilon_o$$

Where Materials Testing Fits into the Solution

Charge Accumulation
- Electron yields
- Ion yields
- Photoyields
- Luminescence

Charge Transport
- Conductivity
- Radiation Induced Conductivity
- Permittivity
- Electrostatic breakdown
- Penetration range

ABSOLUTE values as functions of materials species, flux, fluence, energy, and temperature.



Complex dynamic interplay between space environment, satellite motion, and materials properties

Dale Ferguson's "New Frontiers in Spacecraft Charging"

#1 Non-static Spacecraft Materials Properties
#2 Non-static Spacecraft Charging Models

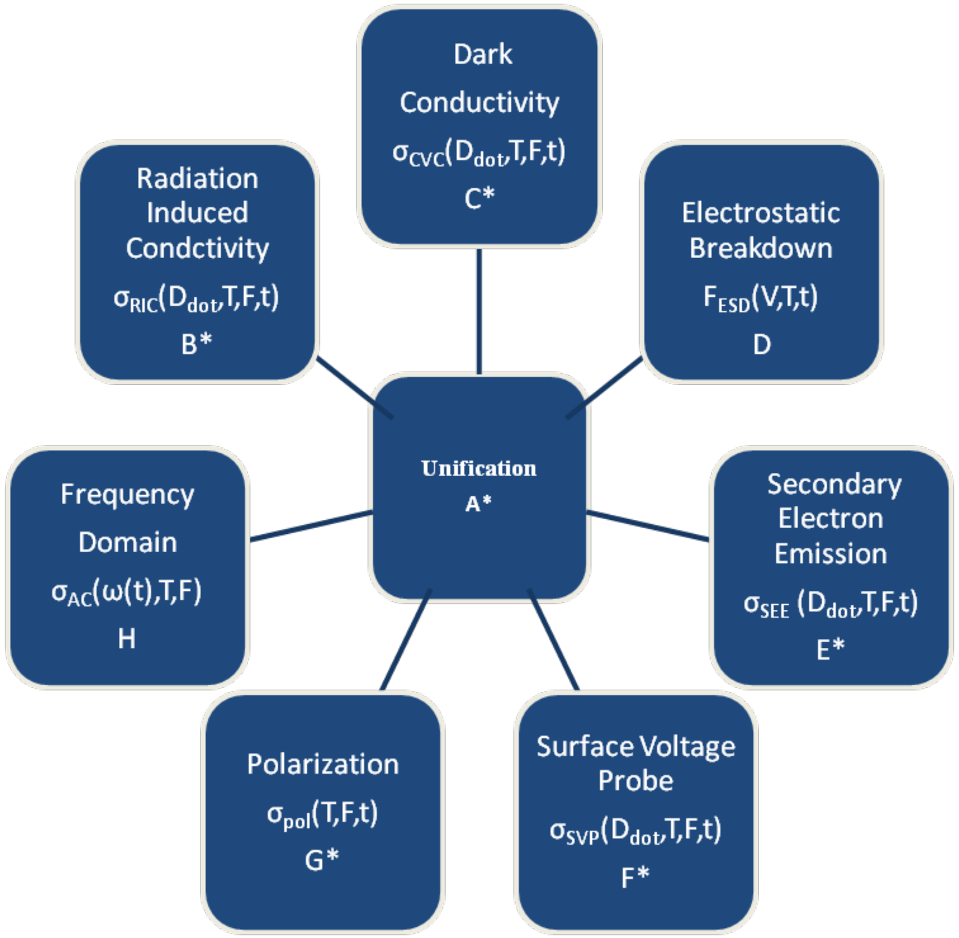
These result from the complex dynamic interplay between space environment, satellite motion, and materials properties

Specific focus of our work is the change in materials properties as a function of:

- Time (Aging), t
- Temperature, T
- Accumulated Energy (Dose), D
- Dose Rate, Ď
- Radiation Damage
- Accumulated Charge, ΔQ or ΔV
- Charge Profiles, Q(z)
- Charge Rate (Current), Ǫ
- Conductivity Profiles, σ(z)

A Materials Physics Approach to the Problem

Measurements with many methods…



Interrelated through a…

Complete set of dynamic transport equations

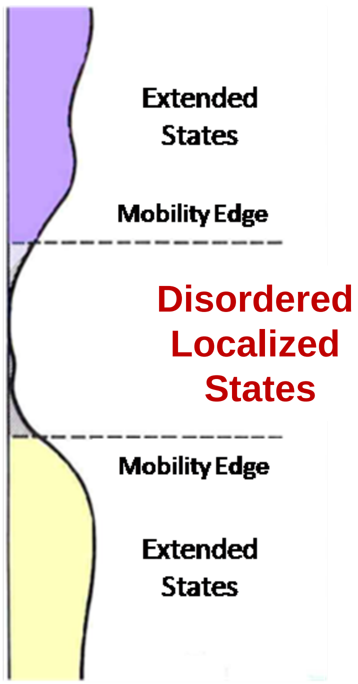
$$J = q_e n_e(z,t)\mu_e F(z,t) + q_e D \frac{dn_{tot}(z,t)}{dz}$$

$$\frac{\partial}{\partial z} F(z,t) = q_e n_{tot}/\epsilon_0 \epsilon_r$$

$$\frac{\partial n_{tot}(z,t)}{\partial t} - \mu_e \frac{\partial}{\partial z}[n_e(z,t)F(z,t)] - q_e D \frac{\partial^2 n_e(z,t)}{\partial z^2} = N_{ex} - \alpha_{er}\, n_e(z,t) n_{tot}(z,t) + \alpha_{et}\, n_e(t)[N_t(z) - n_t(z,t)]$$

$$\frac{dn_h(z.t)}{dt} = N_{ex} - \alpha_{er}\, n_e(z,t) n_h(z,t)$$

$$\frac{dn_t(z,\varepsilon,t)}{dt} = \alpha_{et} n_e(z,t)[N_t(z,\varepsilon) - n_t(z,\varepsilon,t)] - \alpha_{te} N_e \exp\left[-\frac{\varepsilon}{kT}\right] n_t(z,\varepsilon,t)$$



…written it terms of spatial and energy distribution of electron trap states

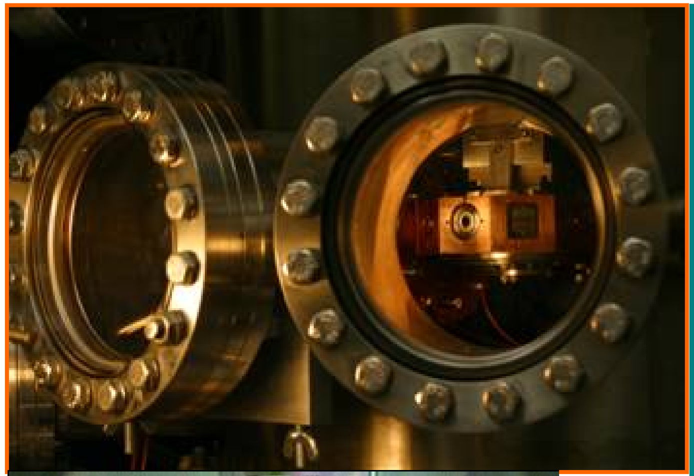
Materials Physics Group Measurement Capabilities

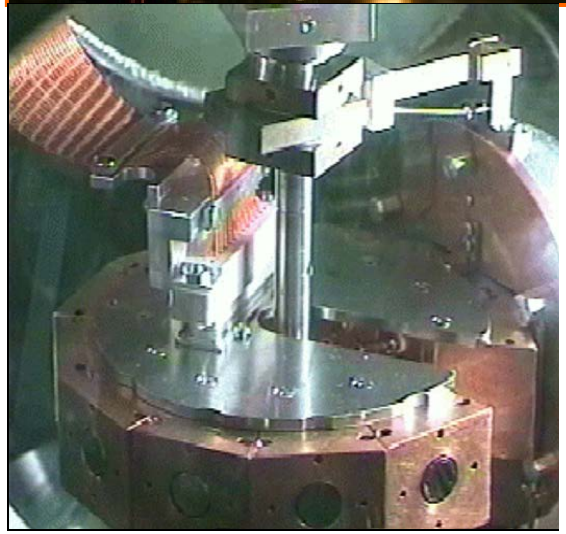
Electron Emission / **Ion Yield**

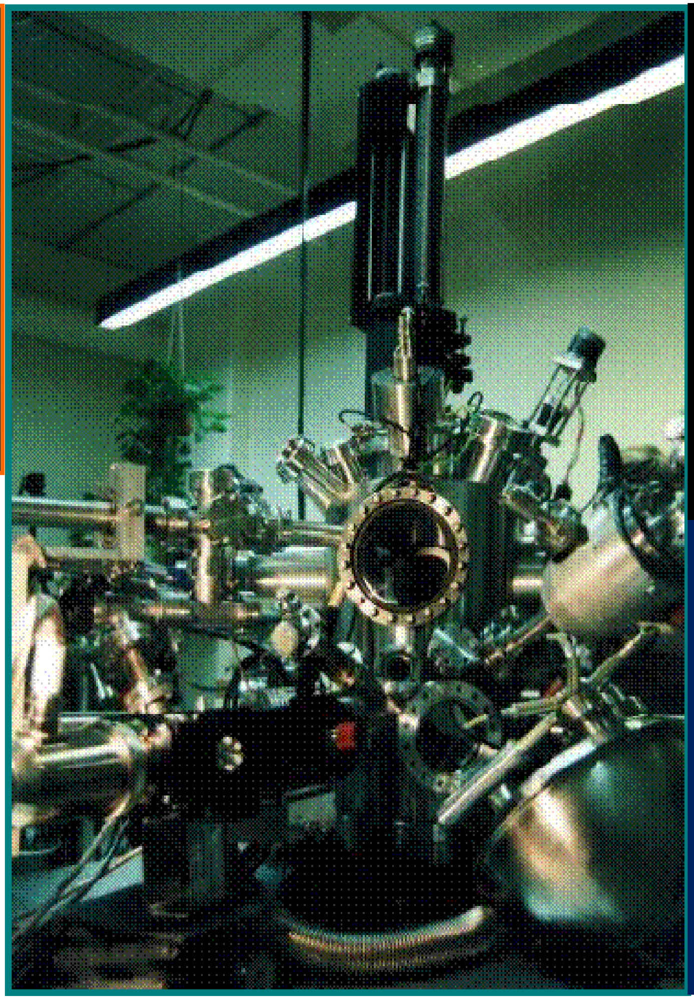
Photoyield / **Luminescence**

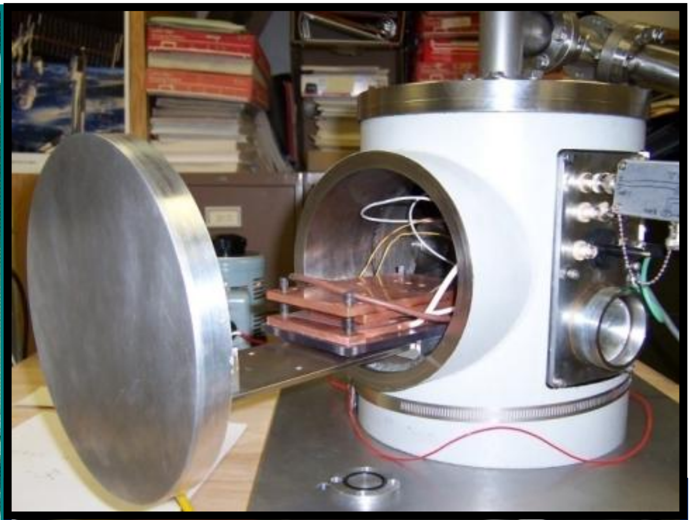
Conductivity / **Electrostatic Discharge**

Radiation Induced Cond. / **Radiation Damage**









Dependence on: Press., Temp., Charge, E-field, Dose, Dose Rate

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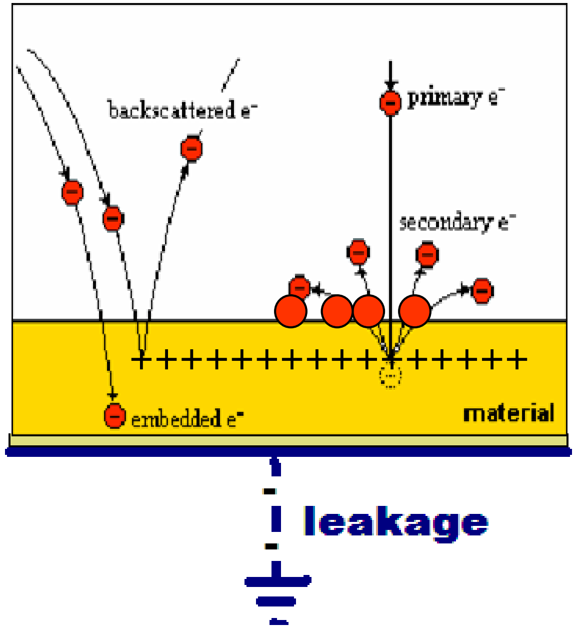
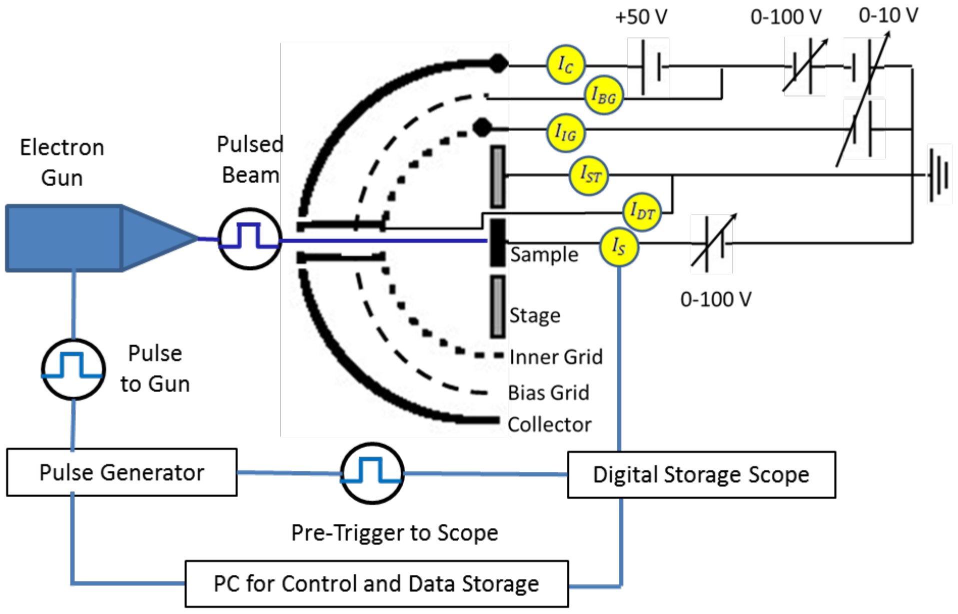
Electron Yields Determine Charge Accumulation

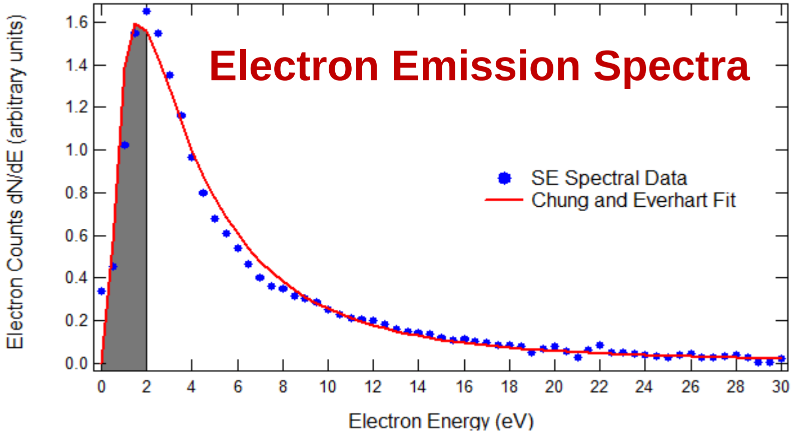
Electron yields characterize a material's response to incident charged particles.

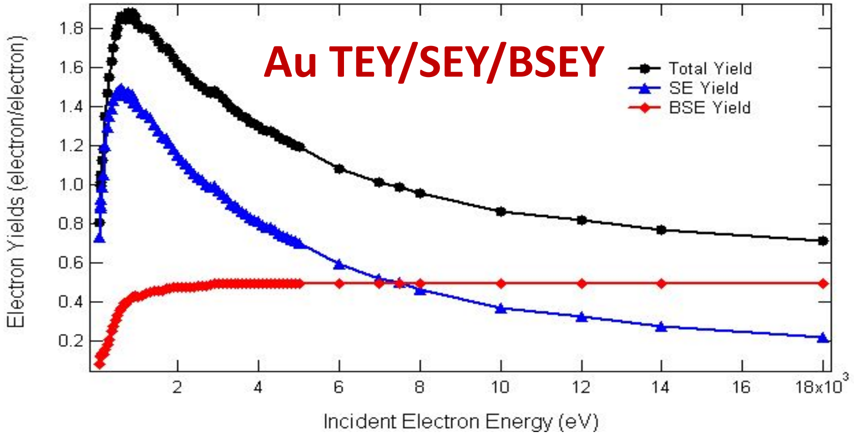
$$Yield = \sigma = \frac{e^-_{out}}{e^-_{in}}$$

- **Can be 0<σ>>1**
- **Leading to + or - charging**
- **Depends on material**
- **Incident electron energy**
- **Temperature**
- **Charge**
  - ➢ **Grounded conductors replenish net emitted charge in <ps**
  - ➢ **Yields of insulators change as charge accumulates in sample.**
  - ➢ **Intrinsic yield is zero charge yield**

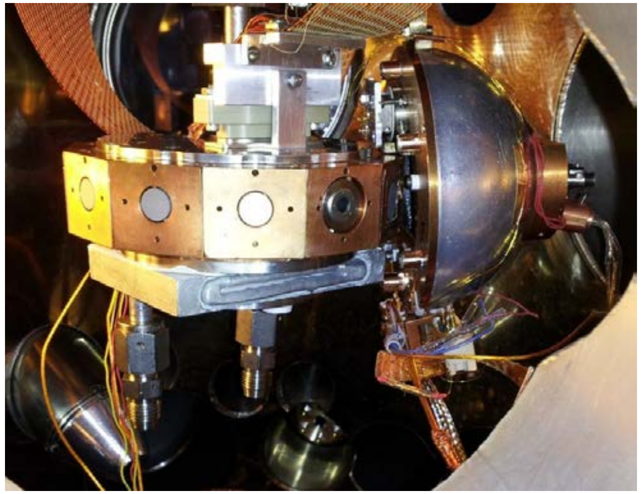


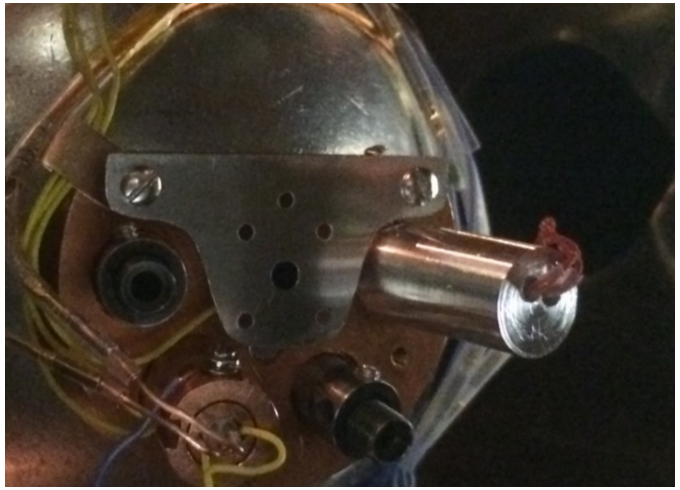


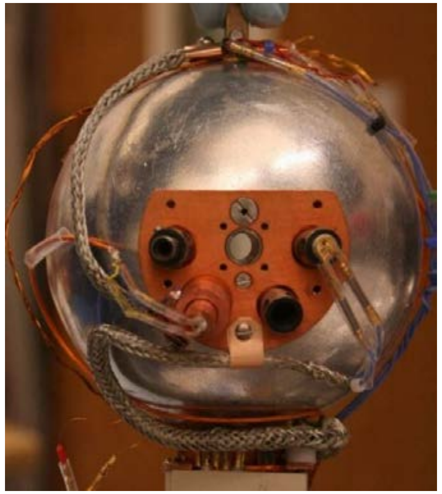




Hemispherical Grid Retarding Field Analyzer Electron Emission Detector



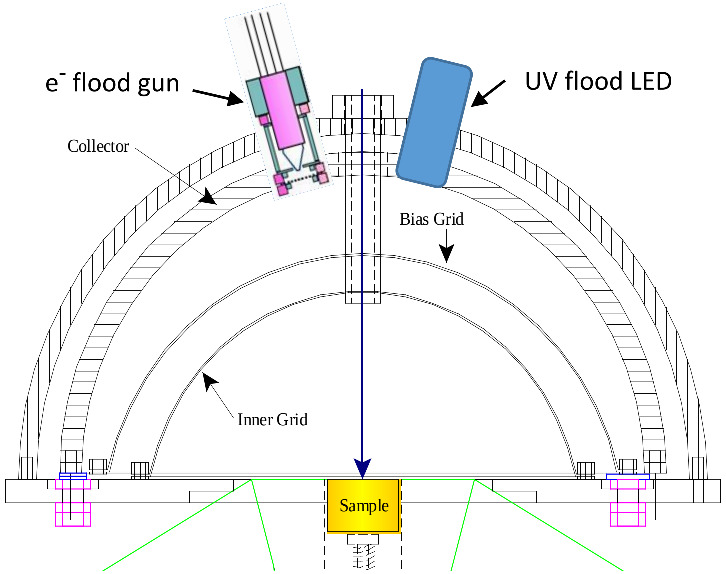




- o **10 eV to ~~30~~ 100 keV incident electrons**
- o **fully enclosed HGRFA for emission electron energy discrimination.**
- o **Precision absolute yield by measuring all currents**
  - o **~1-2% accuracy with conductors**
  - o **~2-5% accuracy with insulators**
- o ***in situ* absolute calibration**
- o **multiple sample stage**
- **~~~100~~ 40 K < T < 400 K**
- **reduced S/N**

Enhanced Low Fluence Methods for Insulator Yields

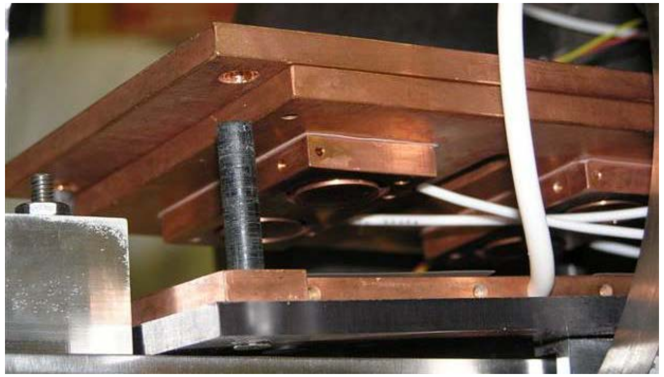
- o **low current (<1 nA-mm^{-2}), pulses (<4 μs) with <1000 e$^-$-mm^{-2}**
- o **Point-wise yield method charge with <30 e$^-$-mm^{-2} per effective pulse**
- o **neutralization with low energy (~5 eV) e$^-$ and UV**
- o ***in situ* surface voltage probe**

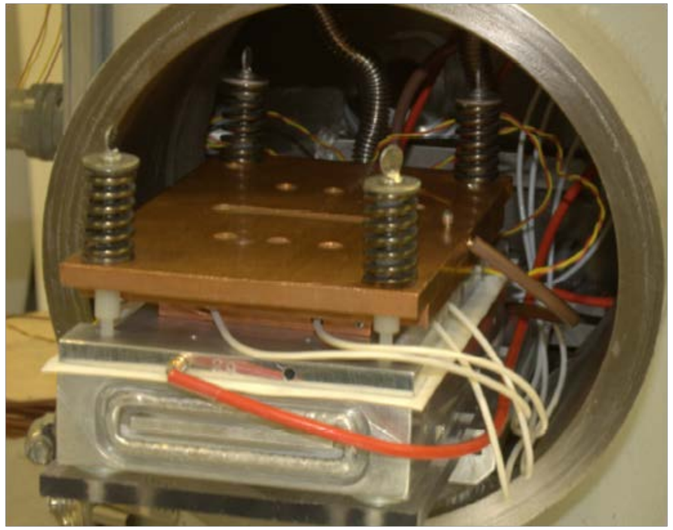


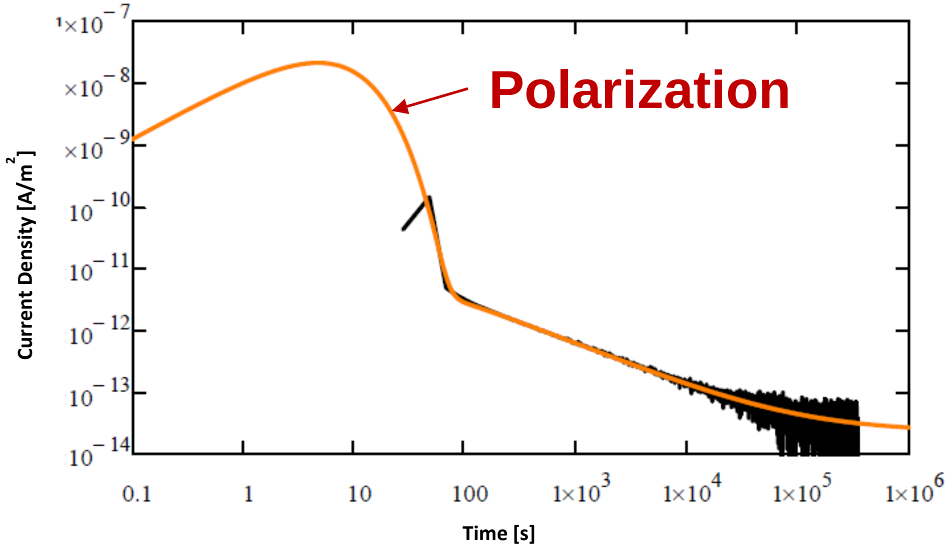
Constant Voltage Conductivity

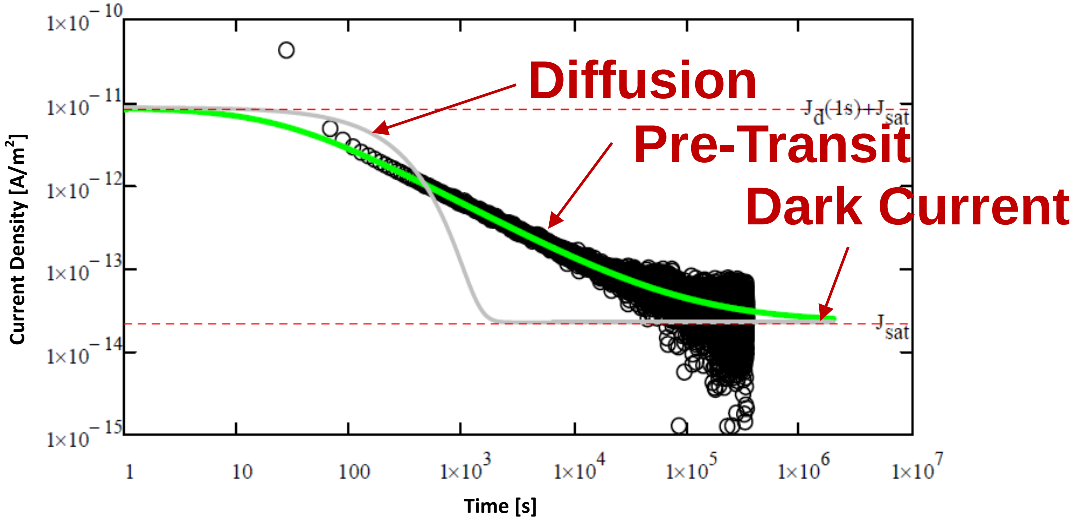
Constant Voltage Chamber configurations inject a continuous charge via a biased surface electrode with no electron beam injection.

- Time evolution of resistivity
- $<10^{-1}$ s to $>10^{6}$ s
- ±200 aA resolution
- $>5\cdot10^{22}$ Ω-cm
- ~100 K <T< 375 K







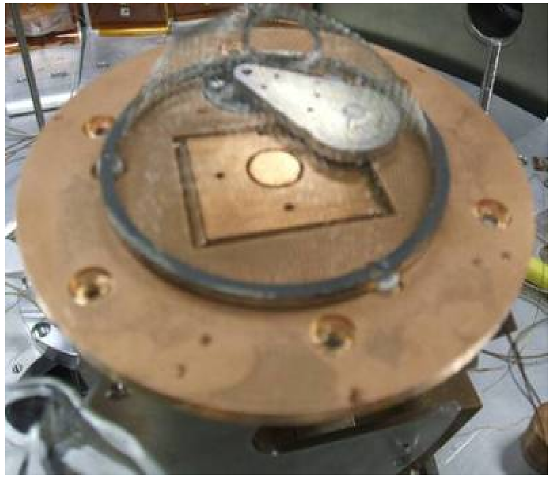


Surface Voltage Charging and Discharging

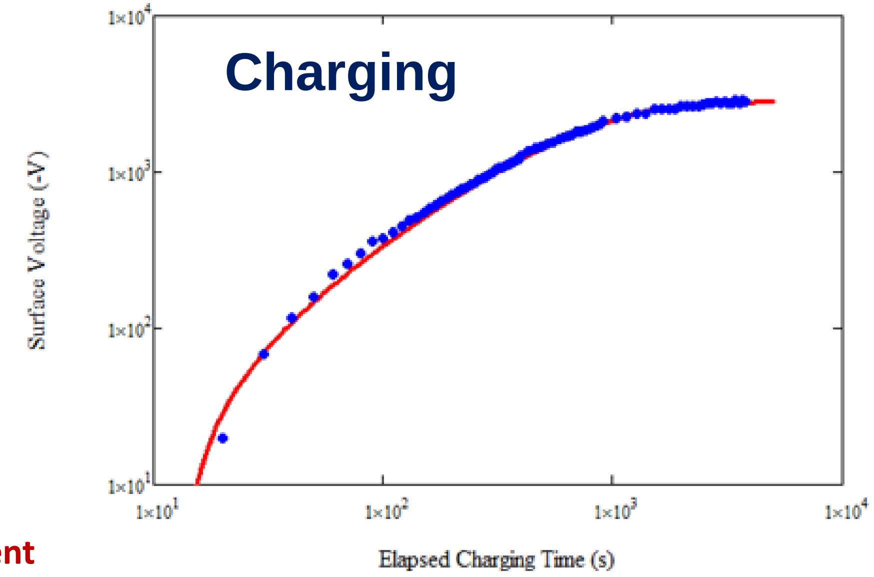
- Uses pulsed non-penetrating electron beam injection with no bias electrode injection.
- Fits to exclude AC, polarization, transit and RIC conduction.
- **Yields N_T, E_d, α, ε_{ST}**

$$\sigma(t)=\sigma_o\left\{1+\left[\frac{\sigma^o_{diffusion}}{\sigma_o}\right]t^{-1}+\left[\frac{\sigma^o_{dispersive}}{\sigma_o}\right]t^{-(1-\alpha)}\right\}$$

Instrumentation

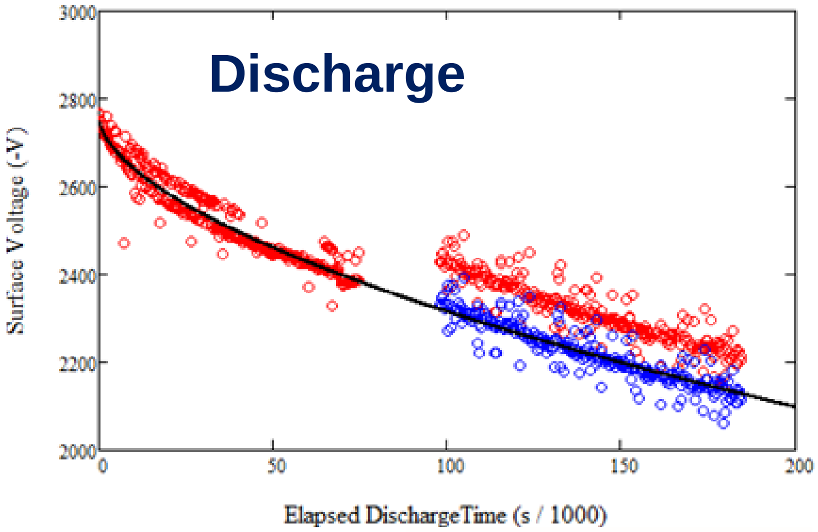


Second generation under development



Charging

$$V_s(t)=\frac{\left[\frac{q_e n_t^{max}}{\varepsilon_o\varepsilon_r}\left[1-Y(E_b)\right]\right]\left[R(E_b)D\left(1-\frac{R(E_b)}{2\,D}\right)\right]\left[\frac{\tau_Q}{t}\right]\left[1-e^{-\left(\frac{t}{\tau_Q}\right)\left\{1+\left(\frac{t\,\sigma_o}{\varepsilon_o\varepsilon_r}\right)\left[1+\frac{\sigma^o_{diffusion}}{\sigma_o}(t^{-1})+\frac{\sigma^o_{dispersive}}{\sigma_o}(t^{-(1-\alpha)})\right]\right\}^{-1}}\right]}{\left\{1+\left(\frac{t\,\sigma_o}{\varepsilon_o\varepsilon_r}\right)\cdot\left[1+\frac{\sigma^o_{diffusion}}{\sigma_o}(t^{-1})+\frac{\sigma^o_{dispersive}}{\sigma_o}(t^{-(1-\alpha)})\right]\right\}}$$

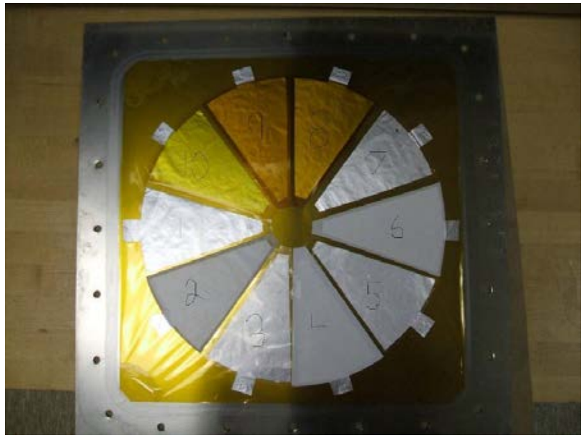


Discharge

$$V(t)=V_o\,e^{-t\sigma(t)/\epsilon_o\epsilon_r}\approx V_o\left[1-\left(\frac{\sigma_o\,t}{\epsilon_o\epsilon_r}\right)\left\{1+\left[\frac{\sigma^o_{diffusion}}{\sigma_o}\right]t^{-1}+\left[\frac{\sigma^o_{dispersive}}{\sigma_o}\right]t^{-(1-\alpha)}\right\}\right]$$

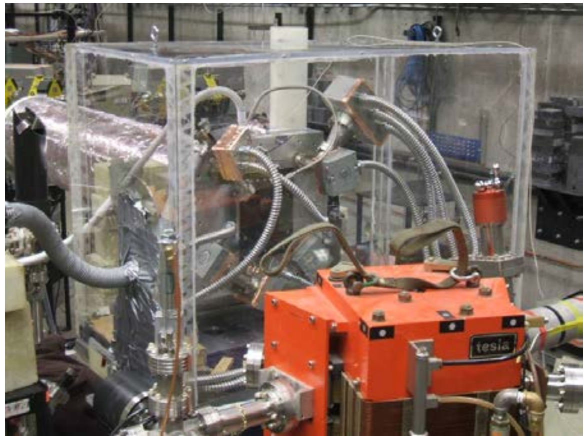
Radiation Induced Conductivity Measurements

RIC chamber uses a combination of charge injected by a biased surface electrode with simultaneous injection by a pulsed penetrating electron.

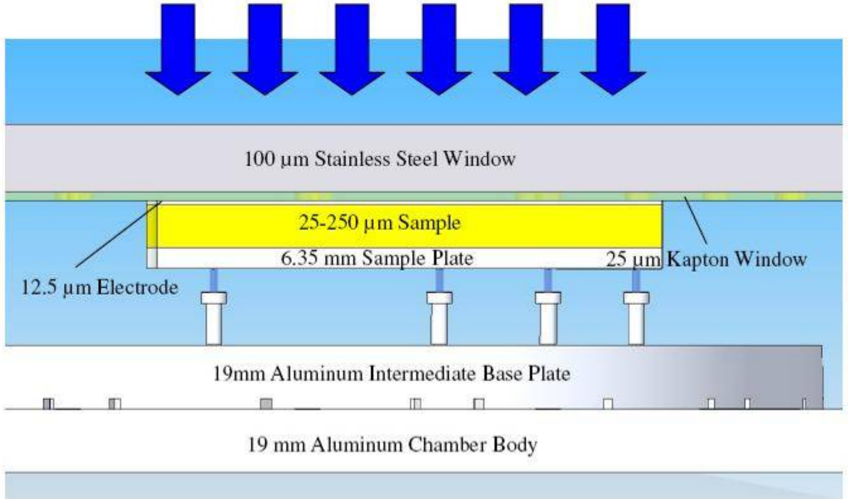


Top view of samples on window

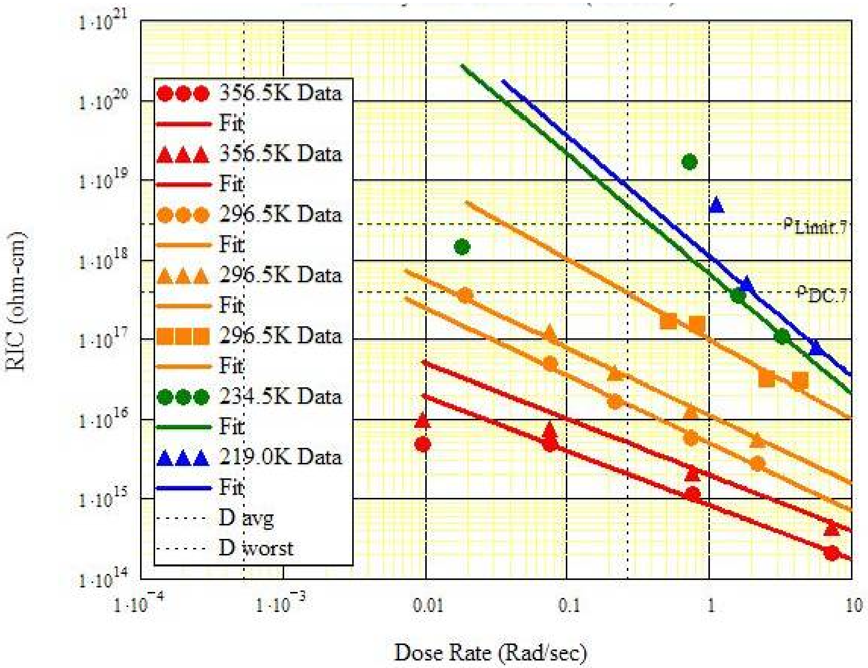
IAC Accelerator and RIC Chamber



RIC Chamber at IAC



Sample stack cross section



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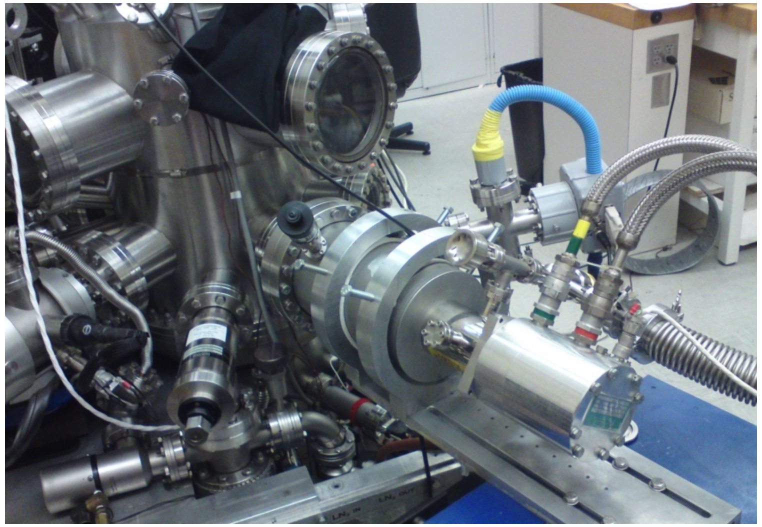
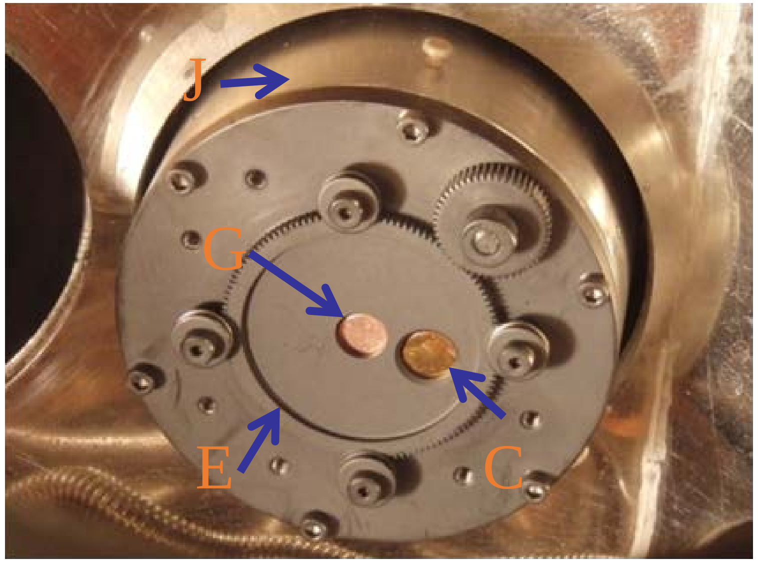
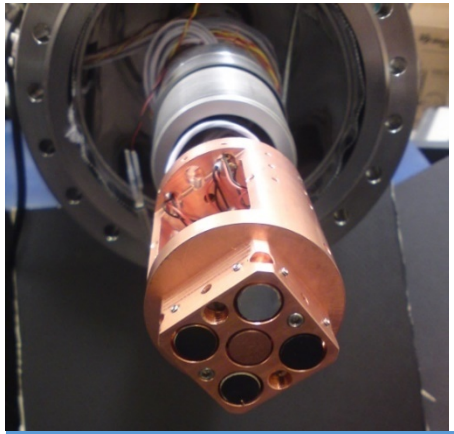
Low Temperature Cryostat





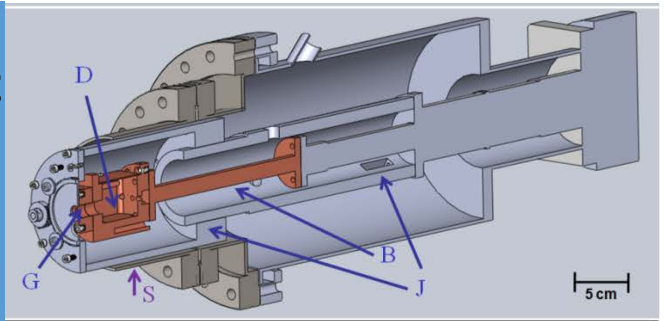


Used with:

- Constant Voltage Conductivity
- RIC
- Cathodoluminescence
- Arcing
- TE/SE/BSE Yields
- Surface Voltage Probe
- Photoyields and Ion Yields

Closed Cycle He Cryostat

- 35 K< T< 350 K
- ±0.5 K for weeks
- Multiple sample configurations



Radiation Sources
A Electron Gun

Sample Mount
B Sample Pedestal
C Sample
D Sample Mount
E Sample Mask Selection Gear
F Interchangeable Sample Holder
G *In situ* Faraday Cup
H Spring –Loaded Electrical Connections
I Temperature Sensor
J Radiation Shield

Analysis Components
K UV/Vis/NIR Reflectivity Spectrometers
L CCD Video Camera (400-900 nm)
M InGaAs Video Camera (800-1200 nm)
N InSb Video Camera (1000-5000 nm)
O SLR CCD Camera (300-800 nm)
P Fiber Optic Discrete Detectors
Q Collection Optics

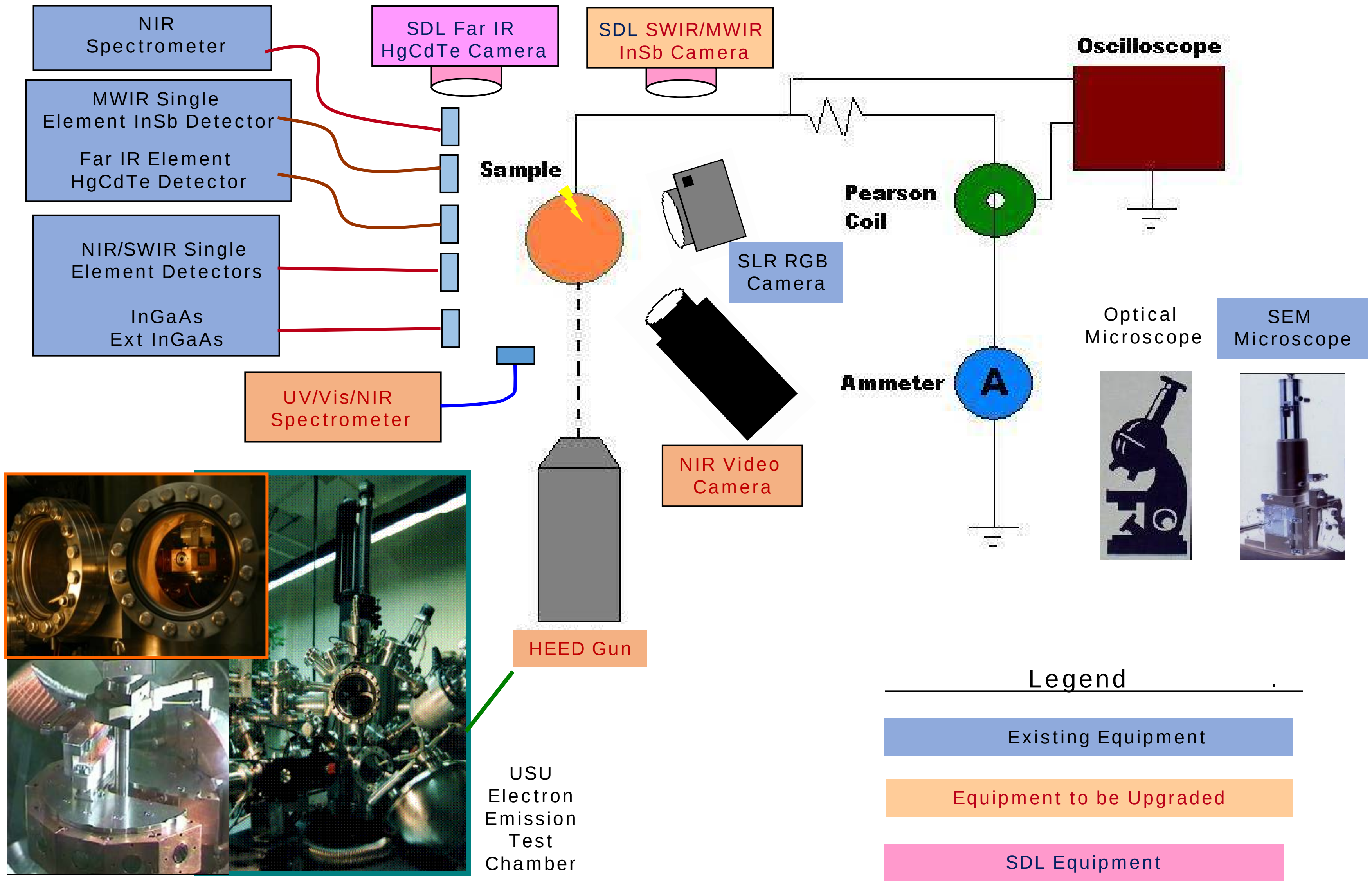
Instrumentation (Not Shown)
Data Acquisition System
Temperature Controller
Electron Gun Controller
Electrometer
Oscilloscope

Chamber Components
R Multilayer Thermal Insulation
S Cryogen Vacuum Feedthrough
T Electrical Vacuum Feedthrough
U Sample Rotational Vacuum Feedthrough
V Turbomolecular/Mech. Vacuum Pump
W Ion Vacuum Pump
X Ion/Convectron Gauges – Pressure
Y Residual Gas Analyzer – Gas Species

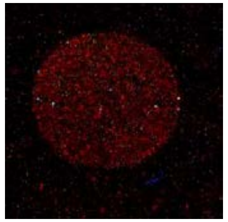
Cathodoluminescence & Induced ESD Measurements—Arc/Glow/Flare Testing

Luminescence/Arc/Flare Test Configuration

- Absolute spectral radiance
- ~200 nm to ~5000 nm
- 4 cameras (CCD, iiCCD, InGaAs, InSb)
- Discreet detectors filters
- 2 Spectrometers (~200 nm to ~1900 nm)
- e^- at ~1 pA/cm^2 to ~10uA/cm^2 & ~10 eV to 50 keV
- 35 K< T< 350 K
- Multiple sample configurations to ~10x10cm



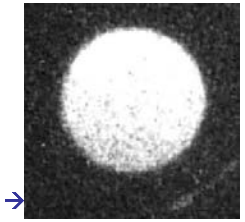
Electron-Induced Luminescence



Kapton XC

500 nA/cm^2
22 keV
150 K

← SLR   NIR Video 33 ms exp. →



"Flare"

M55J

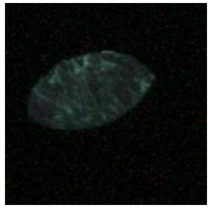
1 nA/cm^2
22 keV
100 K

Sustained Glow

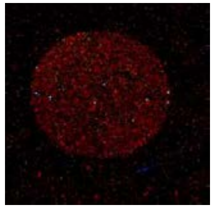
"Flare"

IEC Shell Face Epoxy Resin with Carbon Veil

1 nA/cm^2
22 keV
100 K

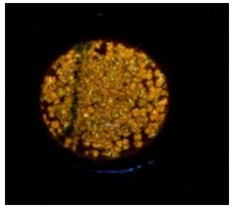


Sustained Glow



Sustained Glow

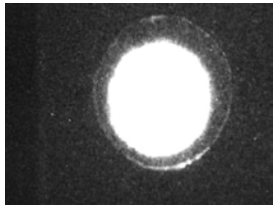
1 nA/cm^2
22 keV
100 K



Sustained Glow

Kapton E

500 nA/cm^2
22 keV
150 K

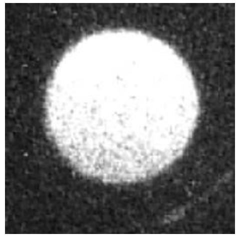


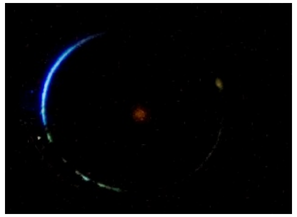
NIR Video

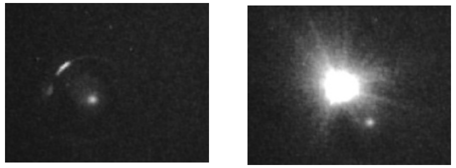
5 uA/cm^2
22 keV
150 K

Diversity of Optical Emission Phenomena in Time Domain

Ball Black Kapton Runs 131 and 131A	22 keV 135 K	110 or 4100 uW/cm^2 5 or 188 nA/cm^2







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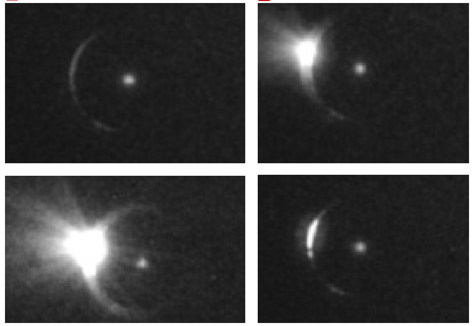


3 4

Surface Glow

Relatively low intensity
Always present over full surface when e-beam on
May decay slowly with time

Edge Glow

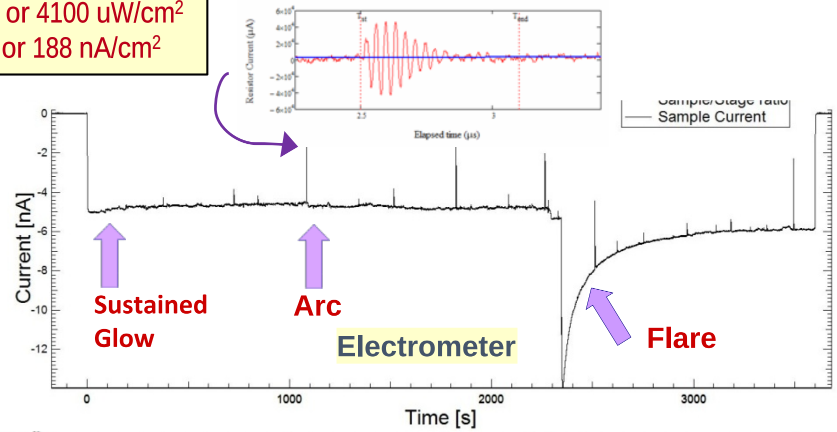
Similar to Surface Glow, but present only at sample edge

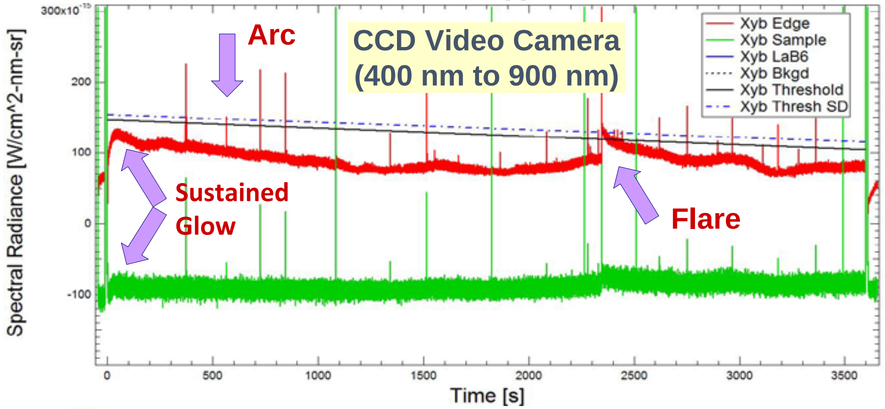
"Flare"

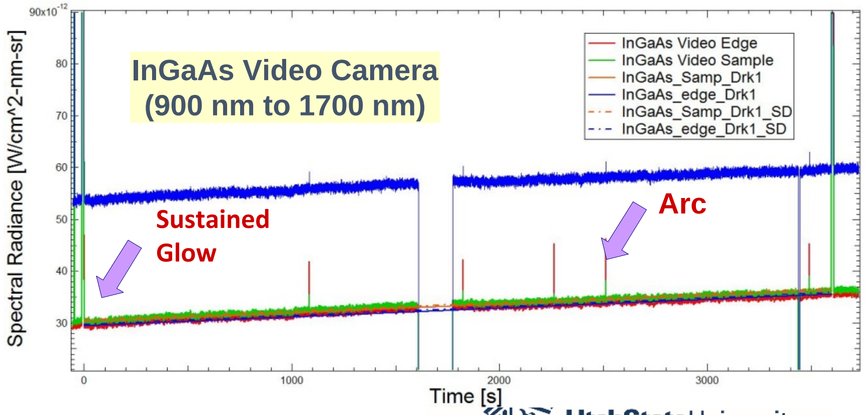
2-20x glow intensity
Abrupt onset
2-10 min decay time

Arc

Relatively very high intensity
10-1000X glow intensity
Very rapid <1 us to 1 s







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Risk Due to Electron-Induced Luminescence

Statement of Risk

Critical JWST structural and materials and optical coatings were found to glow at potentially unacceptable levels under electron fluxes typical of storm conditions in the L2 environment.

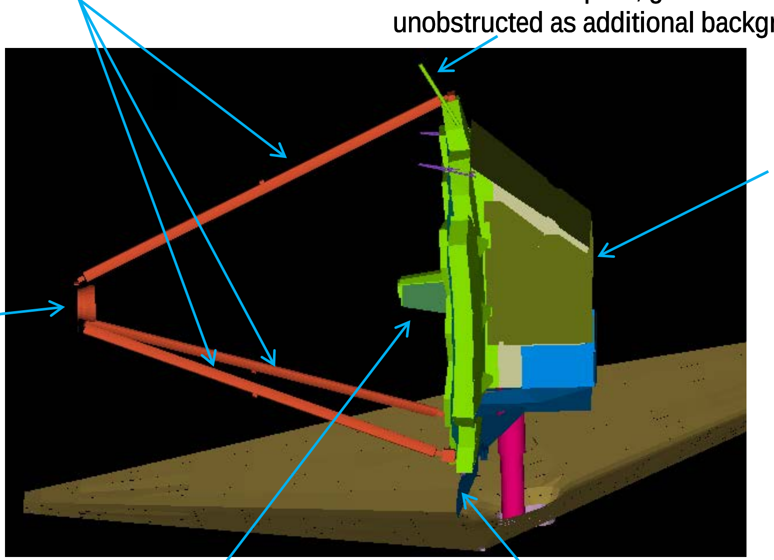
Preliminary results of Vis/NIR glow at <0.2 nA/cm^2 show

Intensity is:

- **visible with eye, SLR camera & NIR video camera**
- **estimated to exceed acceptable 2 µm stray light intensity into NIRCam**
- **Absolute sensitivity <20% of zodiacal background**

Glow spectra:

- **has been measured from ~250 nm to >1700 nm**
- **may well extend to much higher wavelengths**



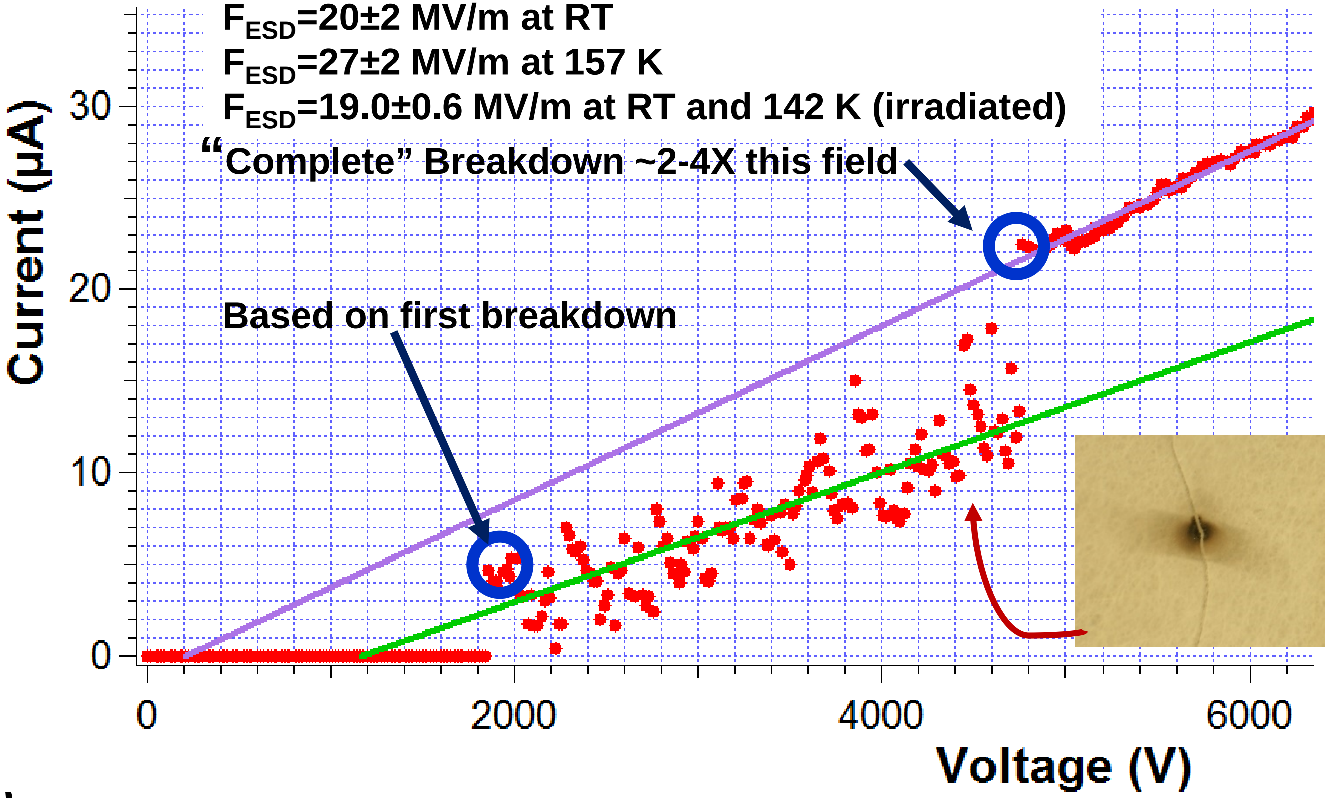
F_{ESD} Breakdown: Dual (Shallow and Deep) Defect Model

Yields:

Ratio of Defect energy to Trap density, $\Delta G_{def}/N_T$

Separate these with T dependence

ΔG_{def} =0.97 eV
$N_T = 1\cdot 10^{17}$ cm^{-3}



Breakdown field measurements:

$$N_{def}\ \Delta G_{def} = \frac{\varepsilon_0 \varepsilon_r}{2}\cdot (F_{ESD})$$

Endurance time measurements:

$$t_{en}(F,T) = \left(\frac{h}{2k_bT}\right)\exp\left[\frac{\Delta G_{def}(F,T)}{k_bT}\right]\mathrm{csch}\left[\frac{F^2\varepsilon_0\varepsilon_r}{2k_BT\ N_{def}(F,T)}\right]$$

A Path Forward for Dynamic Materials Issues

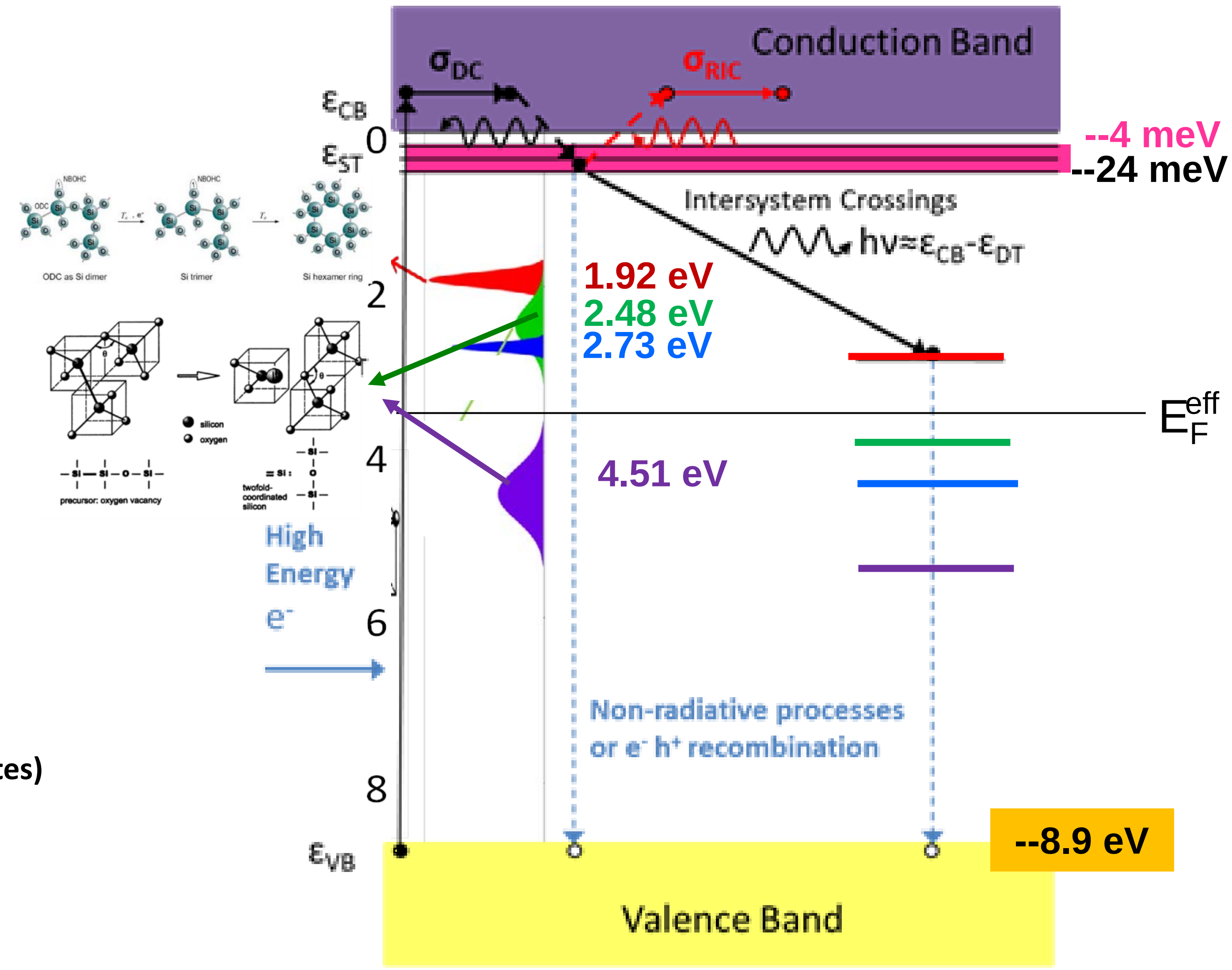
For dynamic materials issues in spacecraft charging:

• **Synthesis of results** from different studies and techniques

• Development of **overarching theoretical models**

allow extension of measurements made over limited ranges of environmental parameters to make predictions for broader ranges encountered in space.

- Energy Diagram incorporates information from:
- Optical transmission (CB-VB gap)
- Conductivity (shallow trap distribution, rates)
- Surface Decay (shallow trap distribution, recombination)
- RIC (shallow trap distribution & occupation, rates)
- Electrostatic discharge (shallow trap distribution & occupation, rates)
- Cathodoluminescence (deep trap distribution, defect types, trap occupation, rates, relaxation)
- Optical & Thermal Stimulated CL (deep trap distribution, trap occupation, rates, relaxation)



A Puzzle from Solar Probe Plus: Temperature and Dose Effects

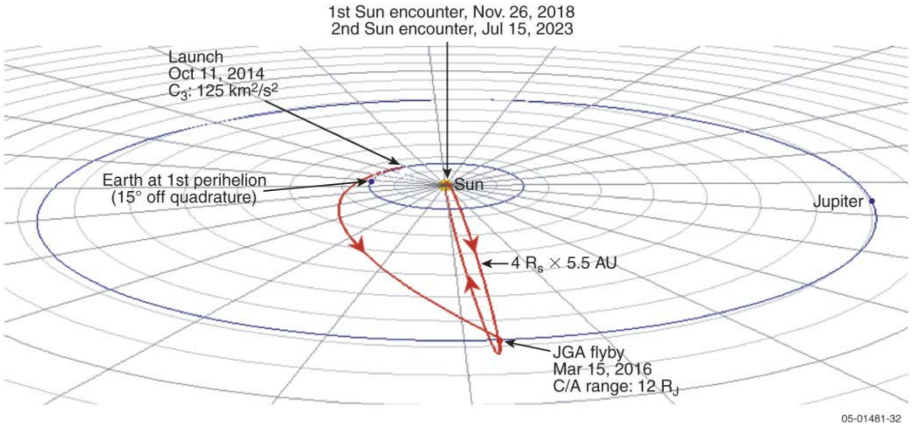


Figure 4-1. Solar Probe mission summary.

WideTemperature Range

<100 K to >1800 K

Wide Dose Rate Range

Five orders of magnitude variation!

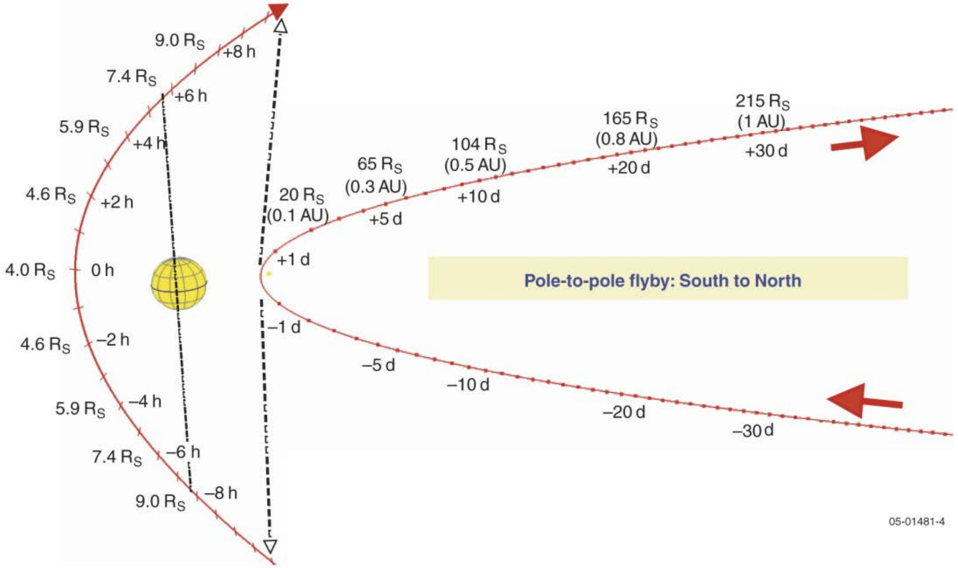


Figure 4-2. Solar encounter trajectory and timeline. Science operations begin at perihelion –-5 days (65 R_S) and continue until perihelion +5 days.

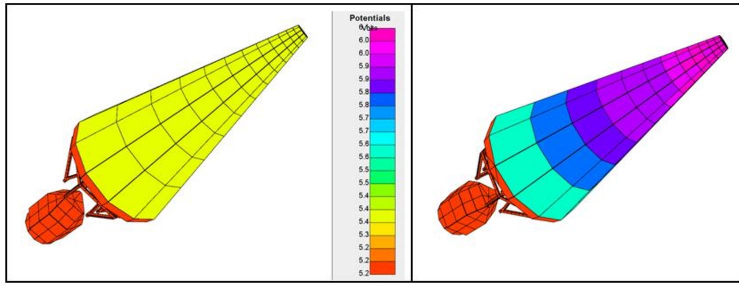
Wide Orbital Range

Earth to Jupiter Flyby

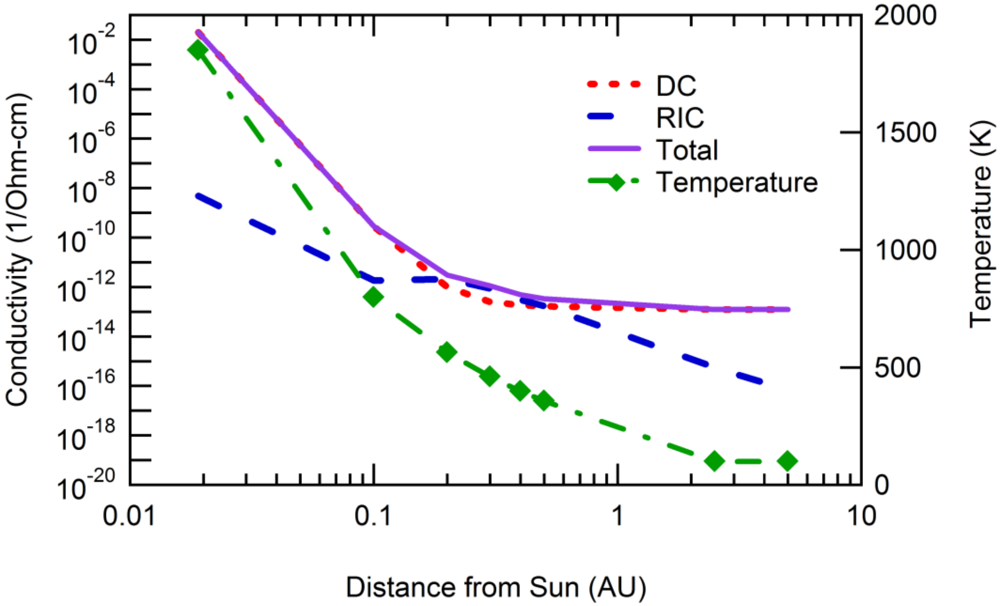
Solar Flyby to 4 R_s

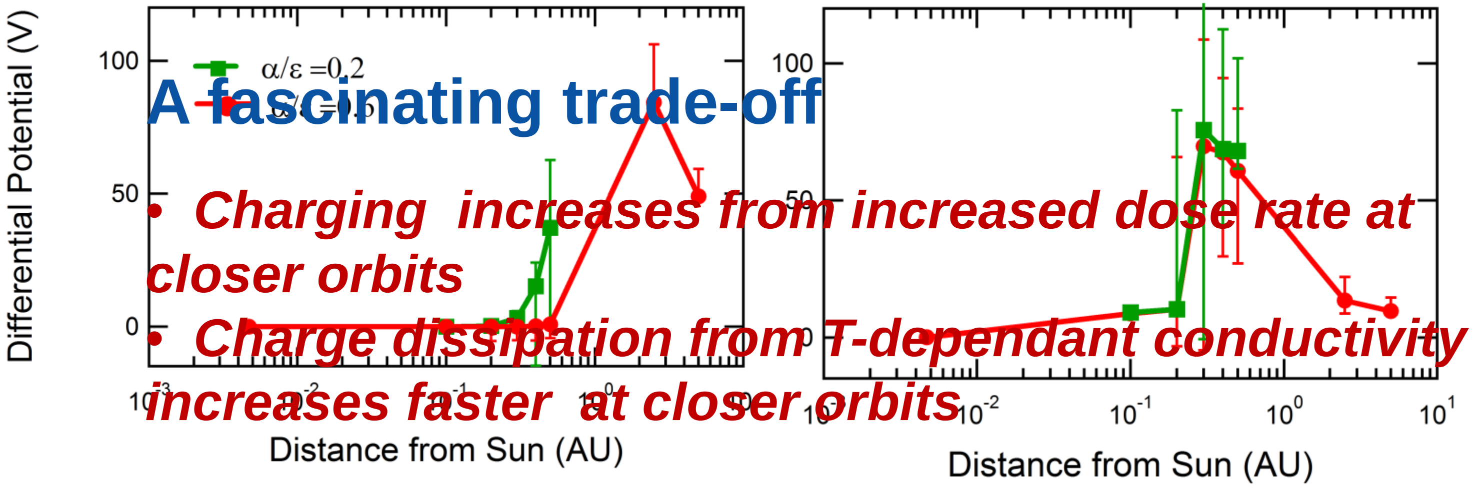
Charging Study by Donegan, Sample, Dennison and Hoffmann

Charging Results: Temperature and Dose Effects



Modeling found a peak in charging a ~0.3 to 2 AU





A fascinating trade-off

- *Charging increases from increased dose rate at closer orbits*
- *Charge dissipation from T-dependant conductivity increases faster at closer orbits*

General Trends

- ***Dose rate decreases as*** $\sim r^{-2}$
- ***T decreases as*** $\sim e^{-r}$
- σ_{DC} ***decreases as*** $\sim e^{-1/T}$
- σ_{RIC} ***decreases as*** $\sim e^{-1/T}$
- ***and decreases as*** $\sim r^{-2}$

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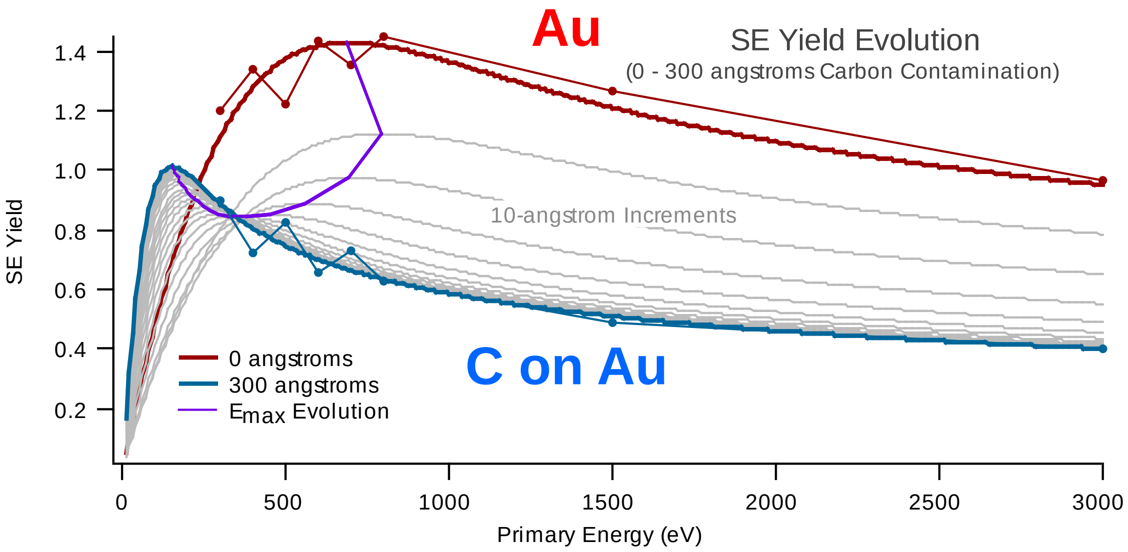
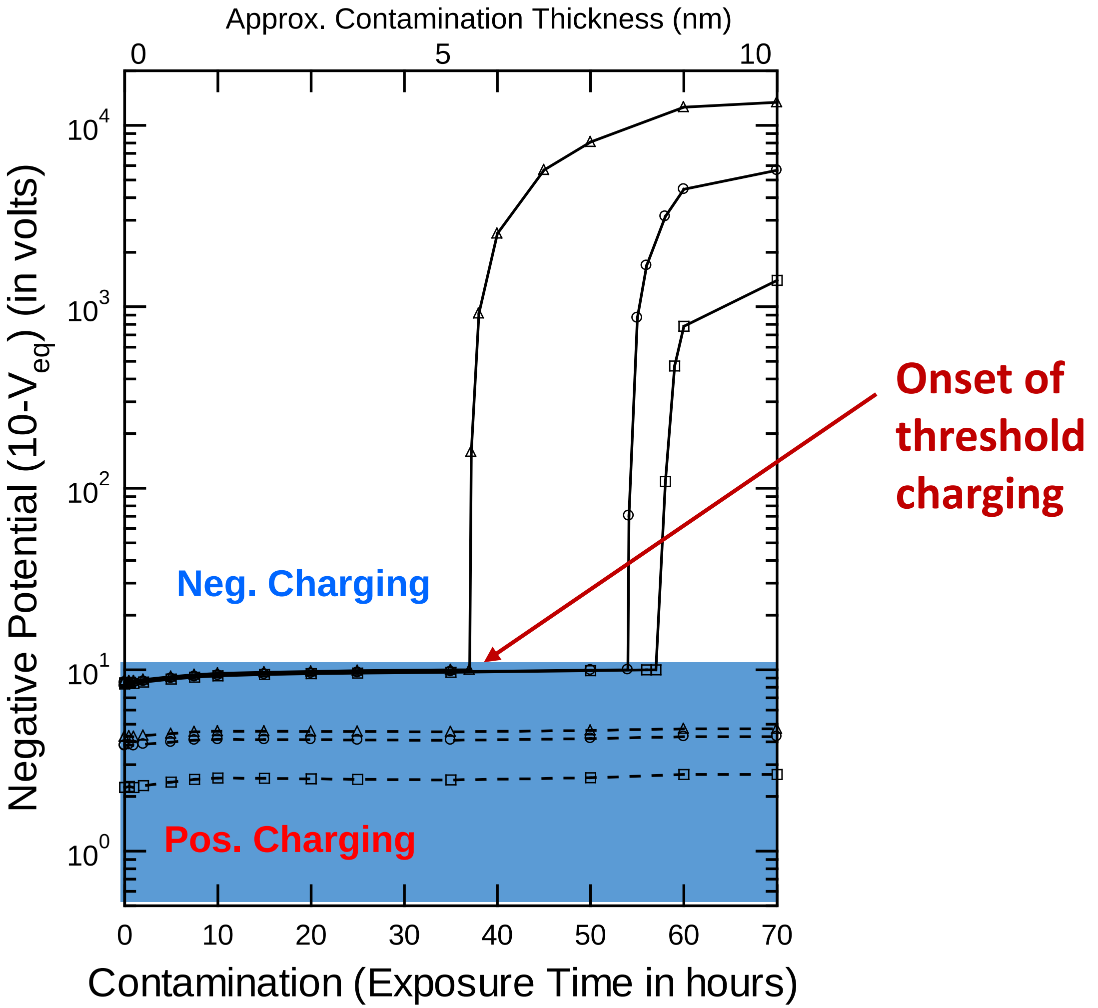
Utah State University — Materials Physics Group

Charging: Evolution of Contamination and Oxidation

"All spacecraft surfaces are eventually carbon…"
--C. Purvis

This led to lab studies by Davies, Kite, and Chang





Environmental Changes: Reflectivity as a Feedback Mechanism

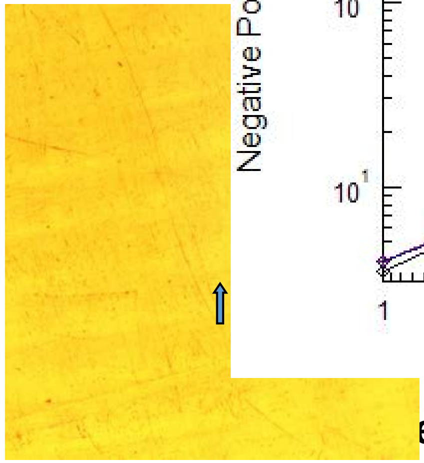
Reflectivity changes with surface roughness and contamination

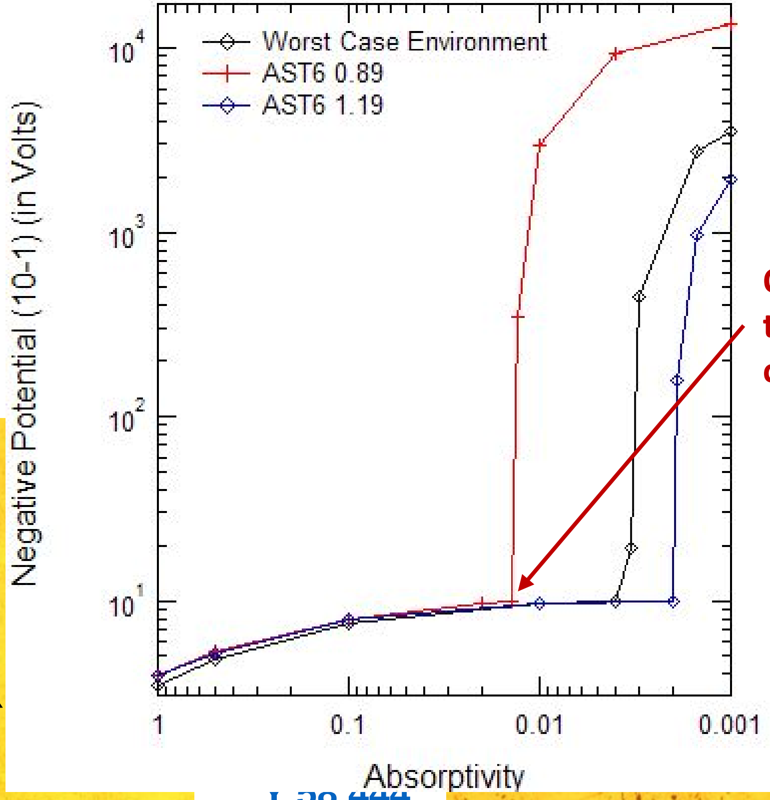
Reflect→Charging→Contamination

Reflect→Emissivity→Temp→Contamination

Charging→ Reflectivity

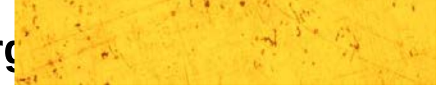
Radiation → Reflect→Emissivity→Temp→Contamination





Onset of threshold charging

eshold Charg



Before Zoomed Images **After**

See Lai & Tautz, 2006 & Dennison 2007

JWST Structure: Charging vs. Ablation

Temperature Effects on Materials Properties

Strong T Dependence for Insulators

Charge Transport

- **Conductivity**
- **RIC**
- **Dielectric Constant**
- **ESD**

Examples:

IR and X-Ray Observatories
JWST, WISE, WMAP, Spitzer, Herscel, IRAS, MSX, ISO, COBE, Planck

Outer Planetary Mission
Galileo, Juno, JEO/JGO. Cassini, Pioneer, Voyager,

Inner Planetary Mission
SPM, Ulysses, Magellan, Mariner

Radiation Effects

Large Dosage ($>10^8$ Rad)

Medium Dosage ($>10^7$ Rad)

Low Dose Rate ($>10^0$ Rad/s)

“…Earth is for Wimps…” H. Garrett

“…auroral fields may cause significant surface charging…” H. Garrett

Examples: RBSP, MMS, JUNO, JGO/JEO

Examples: RBSP, MMS, JUNO, JGO/JEO

Radiation induced Conductivity (RIC)

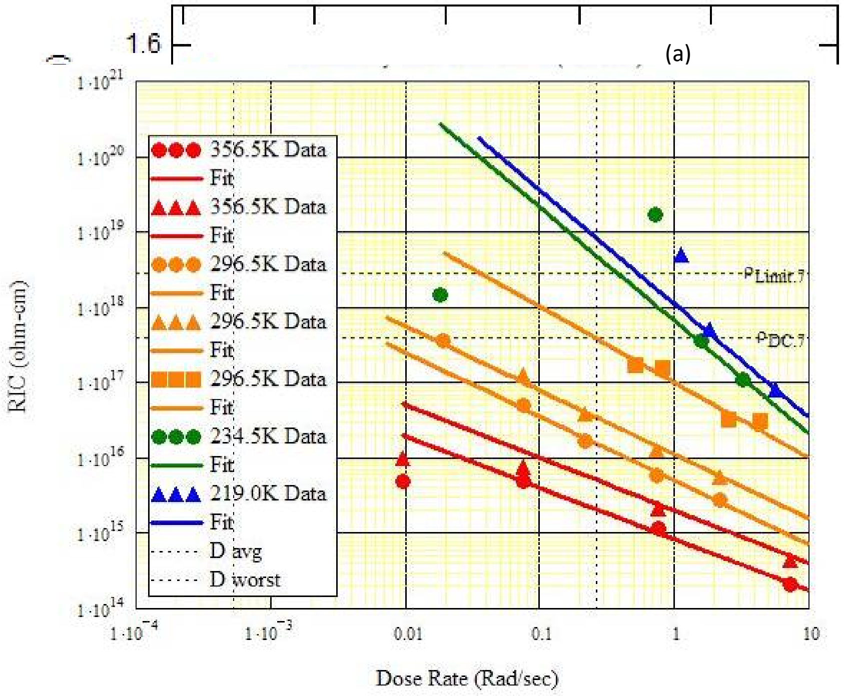
Temperature dependent

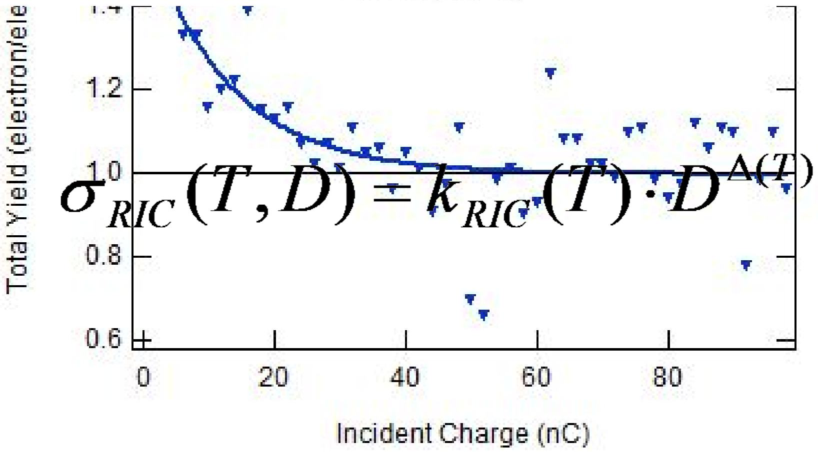
Mechanical Modification of Electron Transport and Emission Properties

Examples: RBSP, JUNO, JGO/JEO

Caused by bondbreaking and trap creation

Mechanical and Optical Materials Damage

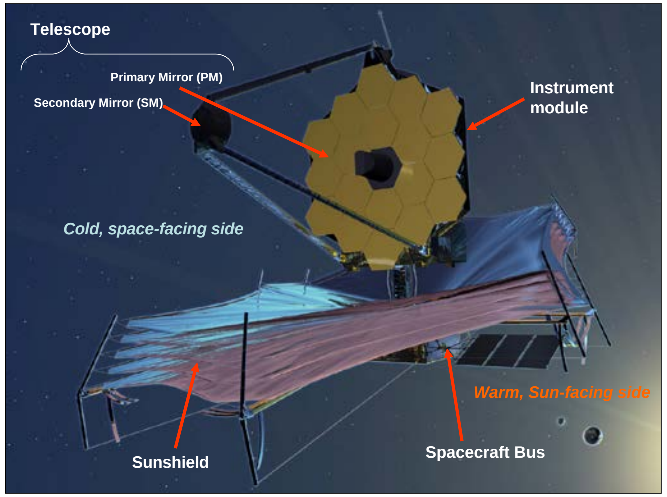




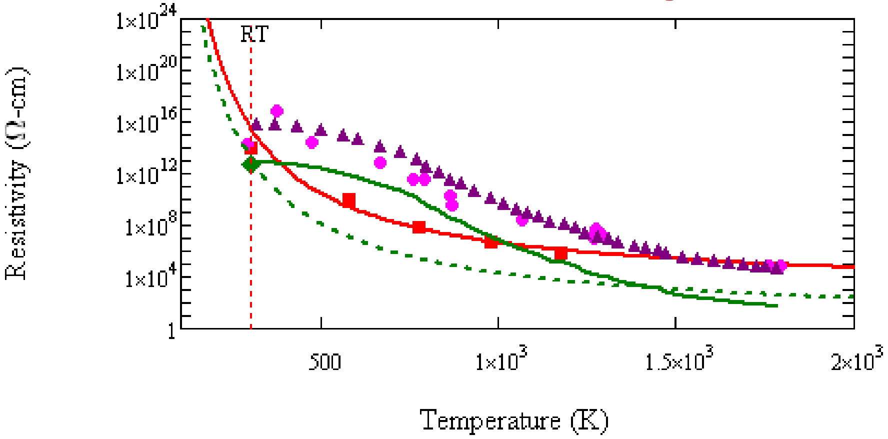
$$\sigma_{RIC}(T,D) = k_{RIC}(T)\cdot D^{\Delta(T)}$$

Combined Temperature and Dose Effects

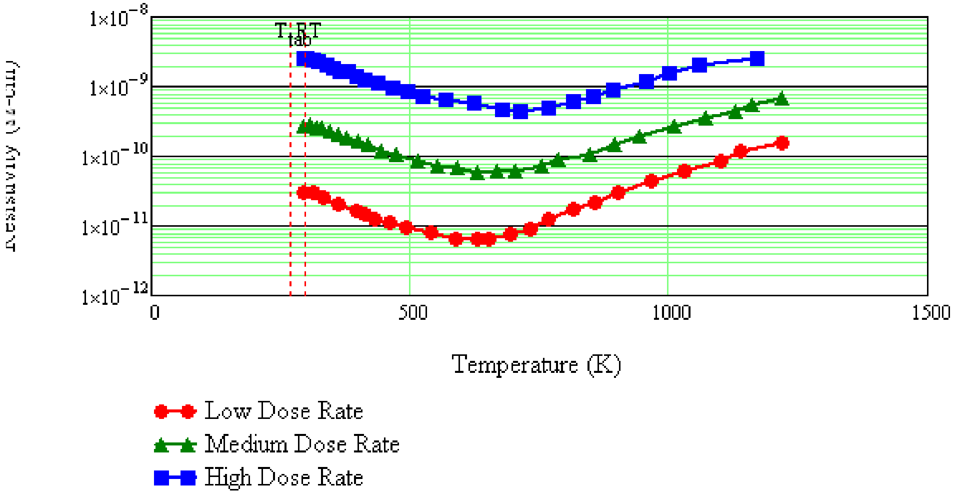
LDPE Study for JWST



Dark Conductivity vs T



RIC vs T



Dark Conductivity

$$\sigma_{DC}(T) = \sigma_o^{DC}\, e^{-E_o / k_B T}$$

RIC

$$\sigma_{\mathrm{RIC}}(\mathrm{T}) = \mathrm{k}_{\mathrm{RIC}}(T)\, \dot{D}^{\Delta(T)}$$

Dielectric Constant

$$\varepsilon_r(T) = \varepsilon_{RT} + \Delta_\varepsilon (T - 298\,K)$$

Electrostatic Breakdown

$$E_{ESD}(T) = E_{ESD}^{RT}\, e^{-\alpha_{ESD}(T - 298\,K)}$$

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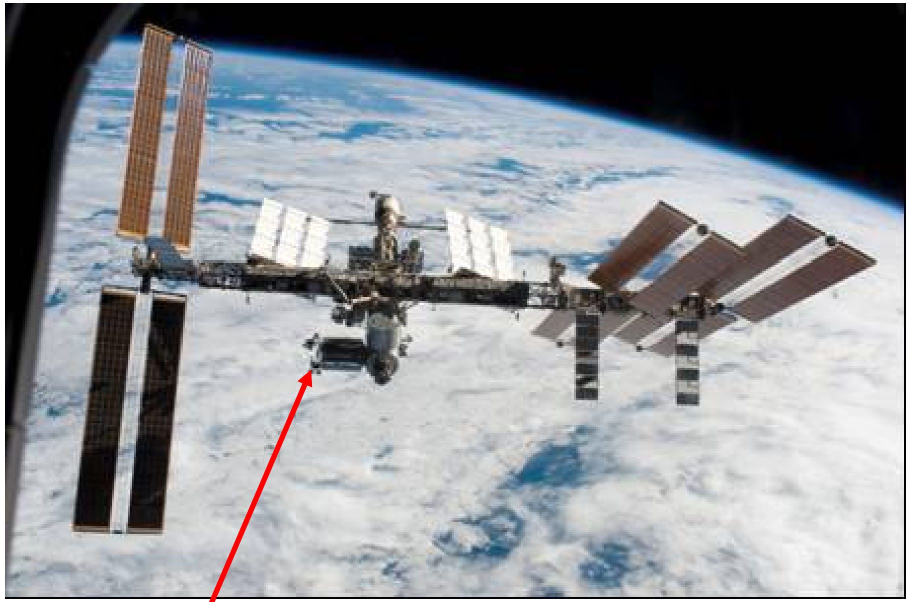
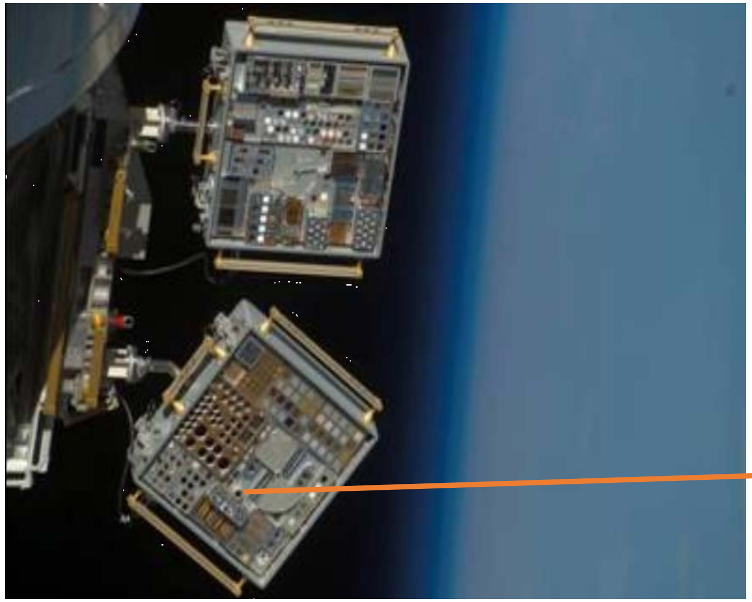
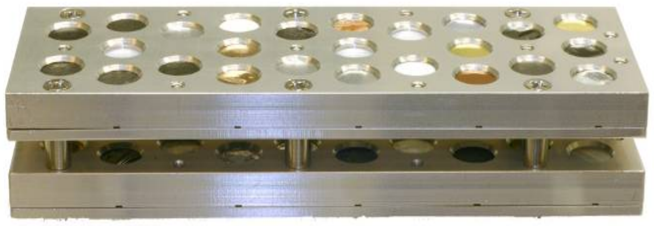
SUSpECS on MISSE 6



The International Space Station with SUSpECS just left of center on the Columbus module.



MISSE 6 exposed to the space environment. The picture was taken on the fifth EVA, just after deployment.

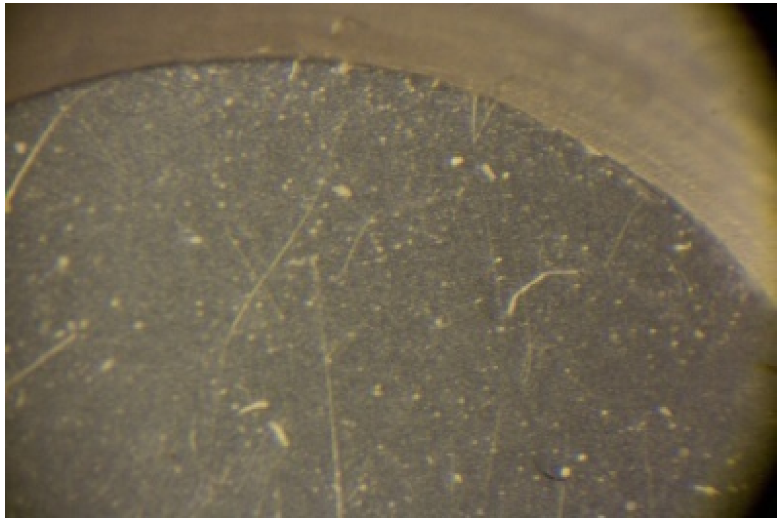


The SUSpECS double stack can be seen in the bottom center of the lower case.

Deployed
March 2008
STS-123

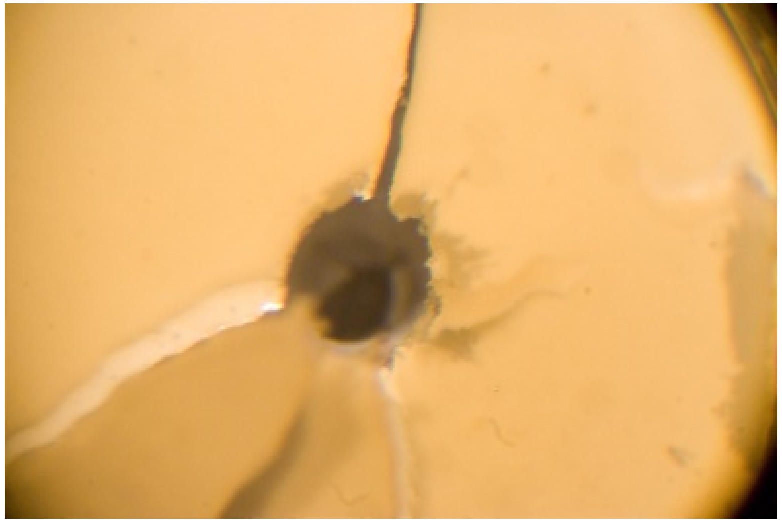
Retrieved
August 2009
STS-127

The Poster Child for Space Environment Effects



Ag coated Mylar

- Atomic Oxygen removes Ag
- UV Yellows clear PET
- Micrometeoroid impact
- Continued aging

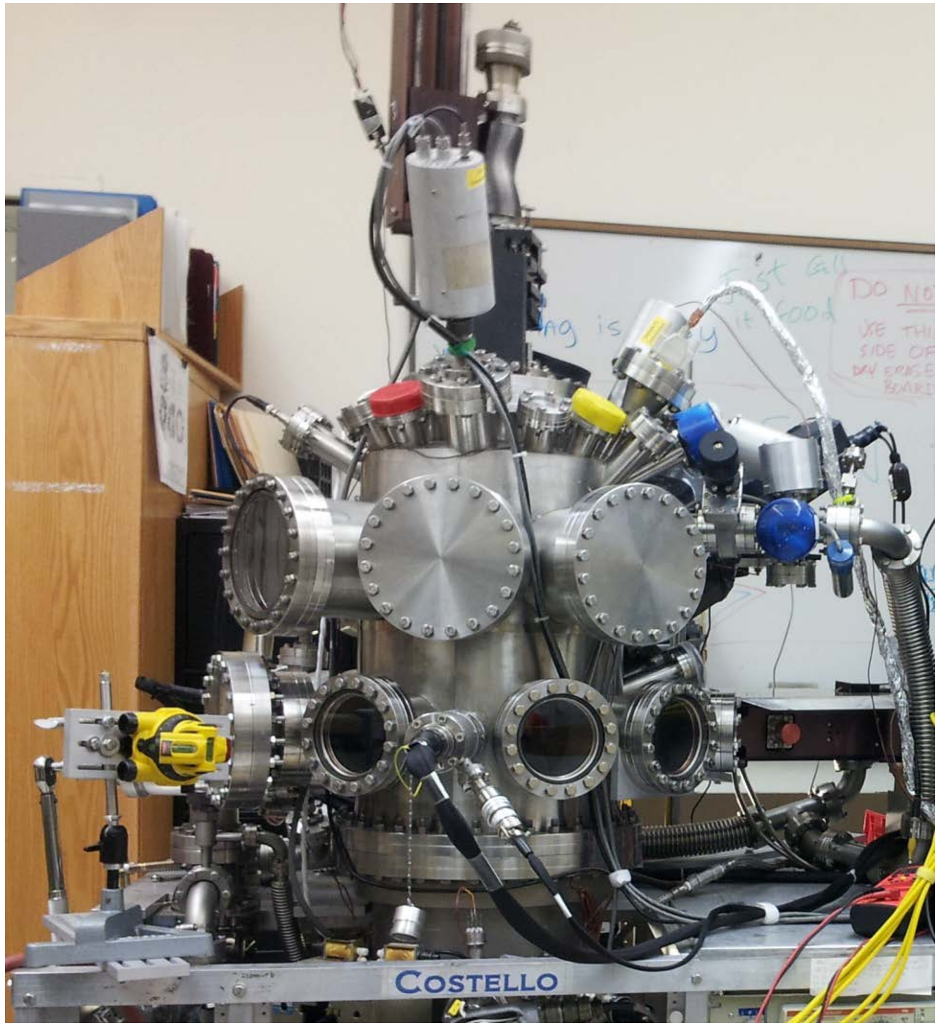


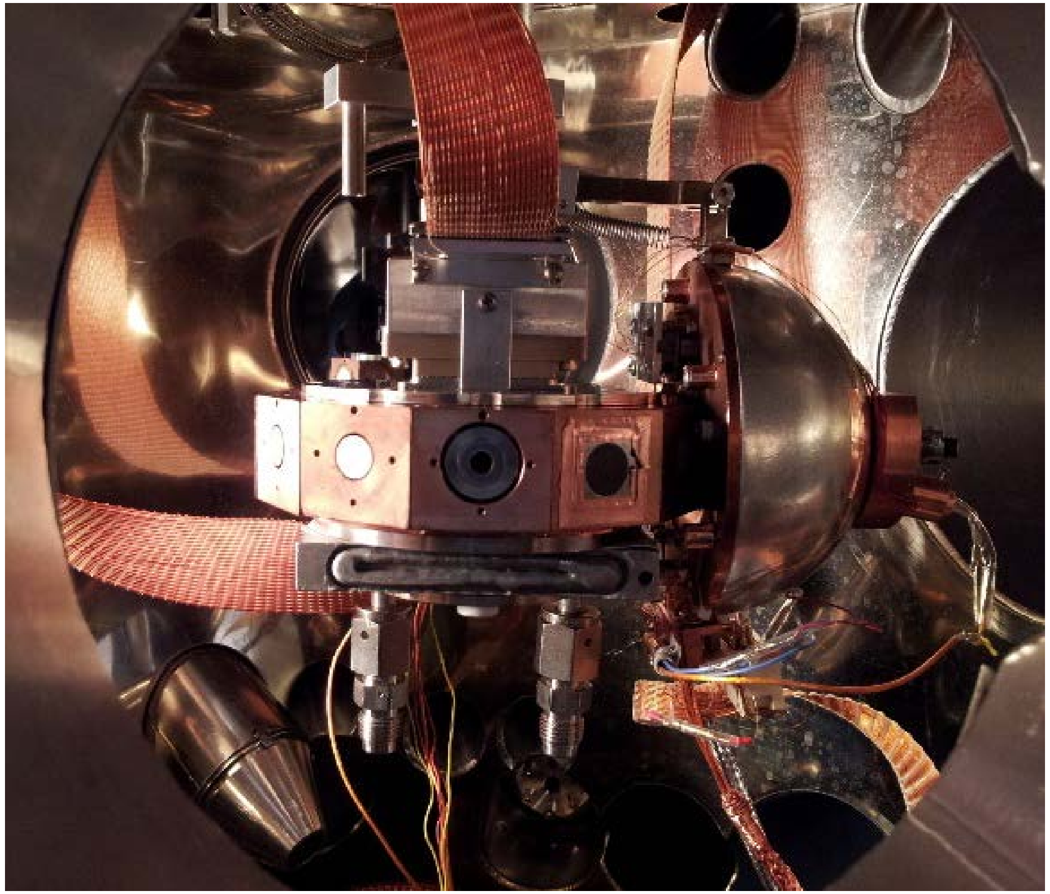
Dynamic changes in materials properties are clearly evident.

How will changes affect performance?

How will changes affect other materials properties?

Simulating Space in the Electron Emission Test Chamber





Space Survivability Test Chamber

Fig. 4. Cutaway View with Source Beams.

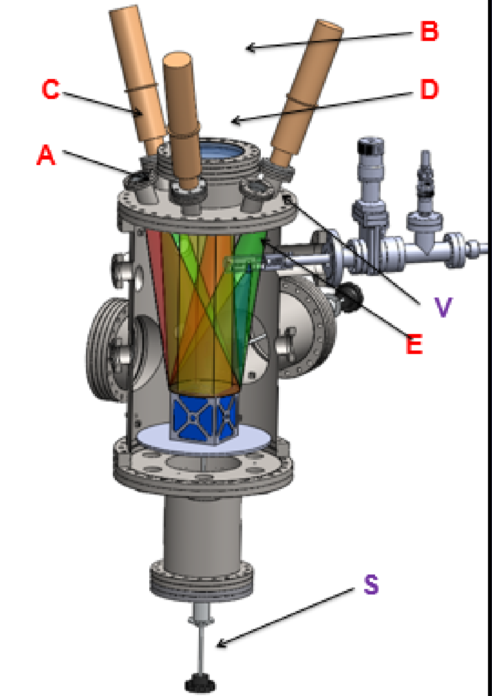
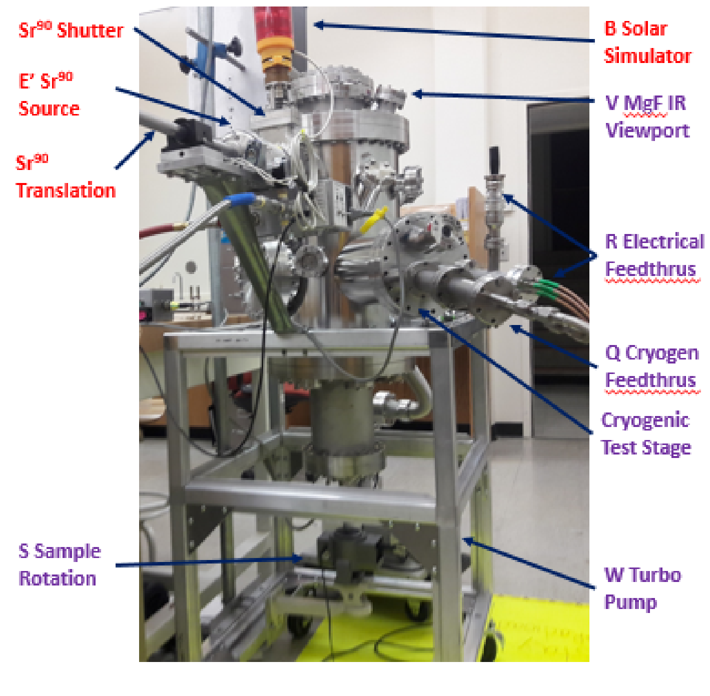


Fig. 5 SST Chamber. Configured for electrostatic discharge testing.



Sample Stages

(Above) 21 cm diameter sample stage (M) connected to 360° rotary feedthrough (S) to enhance flux uniformity by periodic rotation. The standard breadboard allows versatile sample configurations. (Left) 1U CubeSat mounted on sample stage. (Right) Stage with thermal control and linear translation stage with *in situ* characterization probes.

Radiation Sources
- A High Energy Electron Gun
- A' Low Energy Electron Gun
- B UV/NIS/NIR Solar Simulator
- C FUV Kapton Discharge Lamps
- D Air Mass Zero Filter Set
- E Flux Mask
- E' Sr^{90} Radiation Source

Analysis Components
- F UV/VIS/NIR Reflectivity Spectrometers
- G IR Emissivity Probe
- H Integrating Sphere
- I Photodiode UV/VIS/NIR Flux Monitor
- J Faraday Cup Electron Flux Monitor
- K Platinum Resistance Temperature Probe

Sample Carousel
- L Samples
- M Rotating Sample Carousel
- N Reflectivity/Emissivity Calib. Standards
- O Resistance Heaters
- P Cryogen Reservoir

Chamber Components
- Q Cryogen Vacuum Feedthrough
- R Electrical Vacuum Feedthrough
- S Sample Rotational Vacuum Feedthrough
- T Probe Translational Vacuum Feedthrough
- U Sapphire UV/VIS Viewport
- V MgF UV Viewport
- W Turbomolecular/Mech. Vacuum Pump
- X Ion Vacuum Pump
- Y Ion/Convectron Pressure Gauges
- Z Residual Gas Analyzer

Chamber Components
- α CubeSat
- β CubeSat Test Fixture
- Γ Radiation Shielding
- Δ COTS Electronics
- ε Rad Hard Breadboard
- η COTS Text Fixture
- θ Electron Gun

Instrumentation (Not Shown)
- Data Acquisition System
- Temperature Controller
- Electron Gun Controller
- UV/VIS/NIR Solar Simulator Controller
- FUV Kr Resonance Lamp Controller
- Spectrometers and Reflectivity Source

Electron Flux

A high energy electron flood gun (A) (20 keV – 100 keV) provides ≤5 X 10^6 electrons/cm^2 (~1pA/cm^2 to 1 μA/cm^2) flux needed to simulate the solar wind and plasma sheet at more than the 100X cumulative electron flux. A low energy electron gun (A') (10 eV-10 keV) simulates higher flux conditions. Both have interchangeable electron filaments.

Ionizing Radiation

A 100 mCi encapsulated Sr^{90} radiation source (E') mimics high energy (~500 keV to 2.5 MeV) geostationary electron flux.

Infrared/Visible/Ultraviolet Flux

A commercial Class AAA solar simulator (B) provides NIR/VIS/UVA/UVB electromagnetic radiation (from 200 nm to 1700 nm) at up to 4 times sun equivalent intensity. Source uses a Xe discharge tube bulbs with >1 month lifetimes for long duration studies.

Far Ultraviolet Flux

Kr resonance lamps (C) provide FUV radiation flux (ranging from 10 to 200 nm) at 4 times sun equivalent intensity. Kr bulbs have ~3 month lifetimes for long duration studies.

Temperature

Temperature range from 60 K [4] to 450 K is maintained to ±2 K.

Vacuum

Ultrahigh vacuum chamber allows for pressures <10^{-7} Pa to simulate LEO

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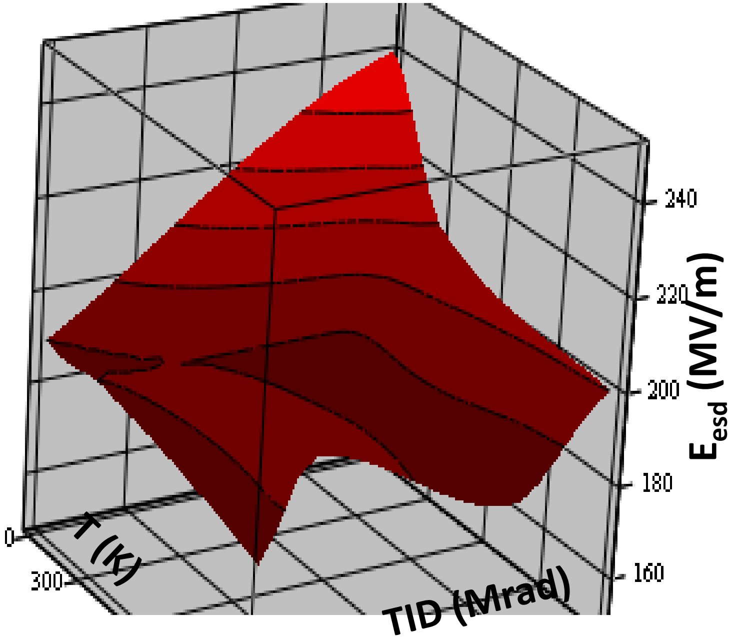
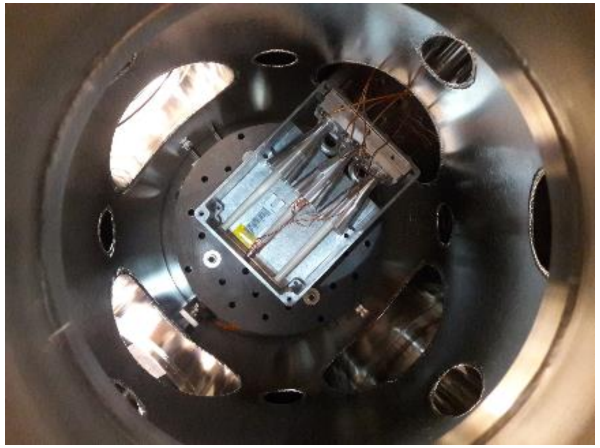
Simulating Space in the Space Survivability Test Chamber

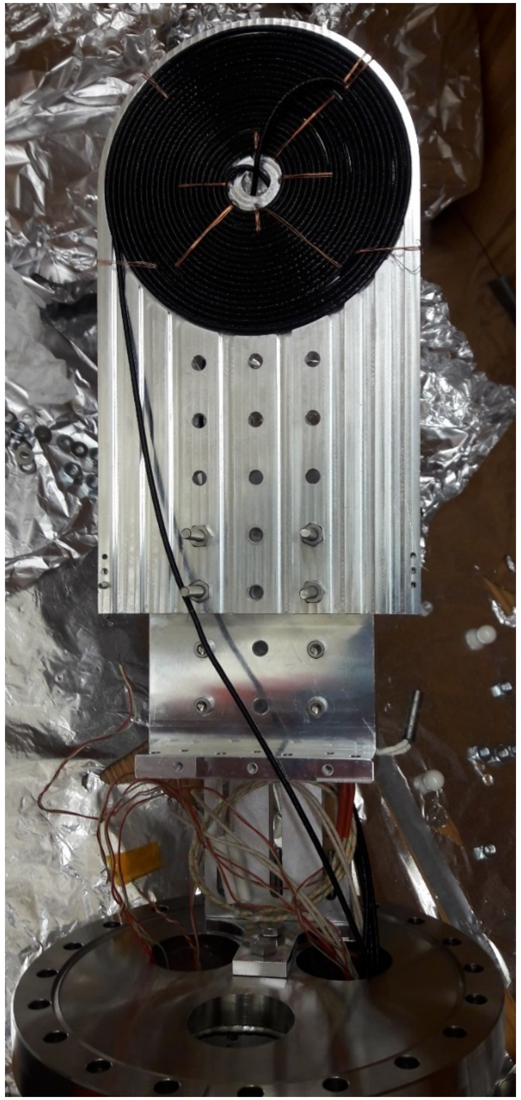
Space Components
- **Radiation induced arcing and material damage in Microwave antennas**
- **Radiation induced arcing in RF Cables**
- **Radiation damage of COTS Parts**
- **VUV Degradation of thermal control paints**
- **SDL Electronics Boards**

Biological Tests
- ***Radiation damage of seeds***
- ***Radiation damage of muscle cells***



Dependence of ESD Breakdown Field Strength on TID and T

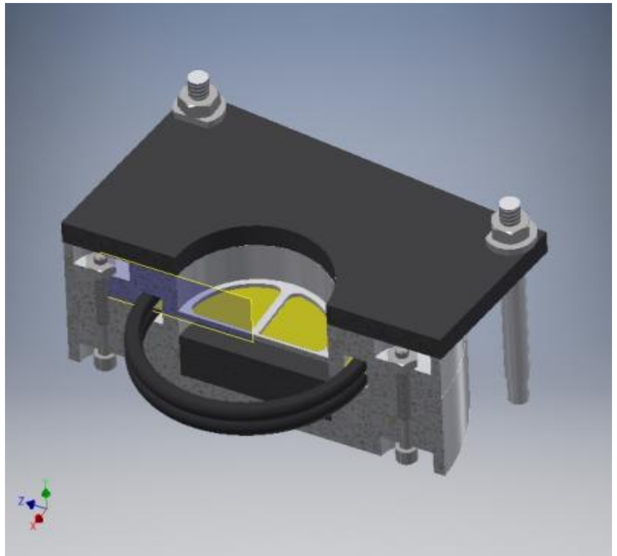




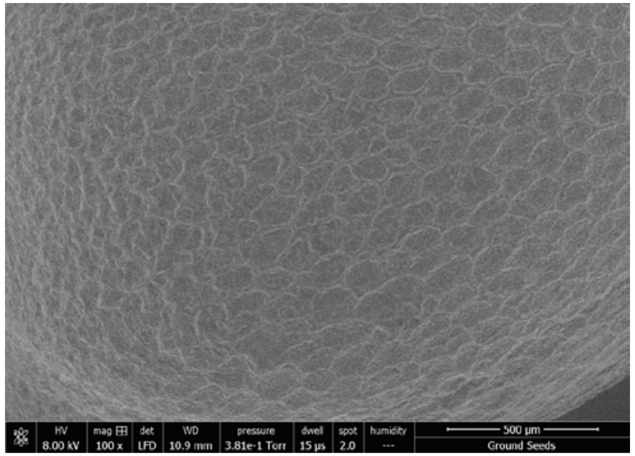
Simulating Space in the Space Survivability Test Chamber

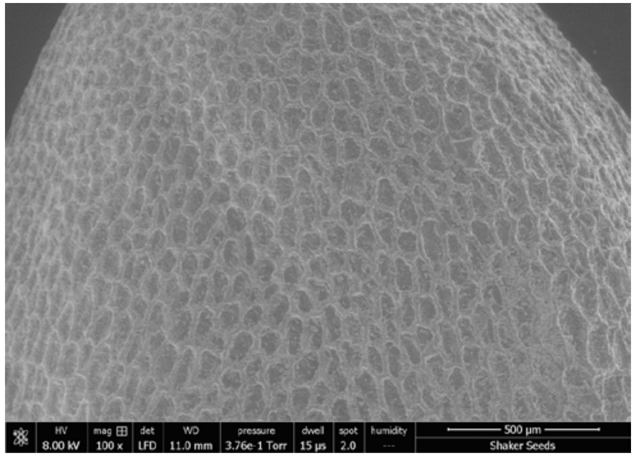
Inverted Vacuum Chamber for Biological Tests

Simulating Radiation and Vibration of Radish Seeds exposed on Russian flight



Both radiation and vibrations enhance germination rate, as was seen in flight seeds





Absolute Electron Emission Calibration: Round Robin Tests of Au and Graphite

JR Dennison, Justin Christensen, Justin Dekany, Clint Thomson, Neal Nickles, Robert E. Davies,
Mohamed Belhaj,
Kazuhiro Toyoda, Kazutaka Kawasaki,
Isabel Montero, Leandro Olano, María. E. Dávila, and Luis Galán

Materials Physics Group, Utah State University
Onera - The French Aerospace Lab
LaSEINE, Kyushu Institute of Technology
CSIC, *Instituto de Ciencia de Materiales de Madrid*

Introduction

Accurate determination of the absolute electron yields of conducting and insulating materials is essential for models of spacecraft charging and related processes involving charge accumulation and emission due to electron beam and plasma interactions. Measurements of absolute properties require careful attention to calibration, experimental methods, and uncertainties.

This study presents a round robin comparison of these absolute yields measurements performed in four international laboratories. The primary objectives were to determine the consistency and uncertainties of such tests, and to investigate the effects of the similarities and differences of the diverse facilities. Apparatus using various low-fluence pulsed electron beam sources and methods to minimize charge accumulation have been developed and employed at these facilities.

Measurements were made for identical samples with reproducible sample preparation of three standard materials:

- the elemental conductor Au (25 μm thick 6N high purity Au foils)
- the elemental semimetal HOPG (bulk DOW highly oriented pyrolytic graphite)
- the polymeric insulator polyimide (25 μm thick Kapton HN™).

Total electron yields (TEY) of Au and HOPG are reported here.

Absolute electron yield measurements for various materials are necessary to determine absolute charging levels and hence to predict possible electrostatic breakdown and injection of charges into plasmas. They have direct application to spacecraft charging, high voltage direct current (HVDC) power and transmission lines, ion thrusters, plasma deposition, multipactors, semiconductor metal-oxide interfaces, and nanodielectrics.

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[3] G. Torregrosa-Peñalva, A. Coves, B. Gimeno, I. Montero, C. Vicente and V. E. Boria, "Multipactor Susceptibility Charts of a parallel-plate dielectric-load waveguide," *IEEE Trans. on Electron Devices*, **57**(5), 2010, 1160-1166.
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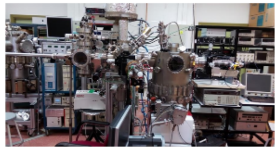
Descriptions of Facilities and Methods

CSIC SEY Facility

The CSIC SEY Facility of the Surface Nanostructuring for Space and Terrestrial Communications Group of ICMM-CSIC.

This CSIC group does research on dielectric, magnetic and metallic materials for space applications. A main goal of these research activities is the surface characterization by UHV spectroscopic techniques and low-secondary emission surfaces to avoid multipaction effects in RF high-power devices for satellite communications systems.



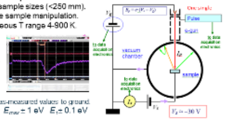
Equipped with:

- **Four interconnected UHV chambers** (10^{-7} Pa).
- **Four electron guns** (pulsed/continuous).
- **Ion gun** (Ar, O, CHx, …).
- **VUV source** (pulsed/continuous)
- **X-ray source** (Mg/Al anodes)
- **Hemispherical electron analyzer**
- **Quadrupole residual gas analyzer**
- **Flexible sample size** (12 - 250 mm).
- **Sample Manipulation**
  - **Sample rotation:** -90° to +90°
  - **UHV Helium cryostat-micrometric manipulator** XYZθ (4 K - 900 K)
  - **UHV Micrometric manipulator** XYZθ (<900K).
  - **UHV X(Zθ) nanometric manipulator.**
  - **UHV XZθ manipulator** (1.8 m length).
- **Temperature** range: 4 K – 900 K.

Measurements capabilities include:

- **SEY (true secondaries and backscattered):**
  - Continuous method: total primary current <5nA/cm2.
  - Pulsed (single pulse) method: pulse time <180 ns.
- **Energy Distribution Curves (EDC).** Primary energy: 0-5 keV and relative emission angle-dependence.
- **X-Ray Photoemission spectroscopy (XPS):** Depth Profiles.
- **Auger Spectroscopy (AES), RHEELS**
- **Intensity-Voltage and Capacitance-Voltage** characteristics.
- **VUV Photoemission** quantum yield.
- **Thermal desorption** processes.
- **Versatile sample conditions:**
  - Flexible sample sizes (<250 mm).
  - Extensive sample manipulation.
  - Simultaneous T range 4-900 K.

$$\sigma = 1 - \frac{I_S}{I_P}$$

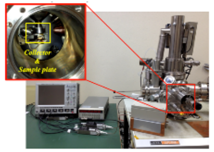


I_s and I_p are as-measured values to ground.
$\sigma \pm 0.005$ $E_{max} \pm 1$ eV $E_1 \pm 0.1$ eV

LaSEINE TEEY Facility

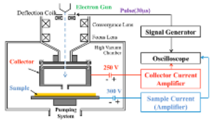
The Laboratory of Spacecraft Engineering INteraction Engineering (LaSEINE) at Kyushu Institute of Technology has studied spacecraft charging and discharging.

We have developed the Total Electron Emission Yield (TEEY) measurement facility for data base of the charging analysis tool MUSCAT. We have measured the TEEY of space conductive materials, as well as insulating material. We also measured TEEY after irradiation with ionizing radiation, atomic oxygen, and ultraviolet ray.



Measurements capabilities include:

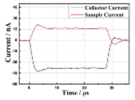
- **Vacuum** analysis chamber: below 10^{-5} Pa.
- **Electron Gun**: 300 eV-10 keV.
- **Electron Irradiation:** continuous or pulsed.
- **Sample Stage** movable in X-Y directions.
- **Temperature** sample holder control 240-370 K



Total electron emission yield measurement method:

- Sample holder and collector are biased at -300V and -250V, respectively. (For example, the electron incident energy on the sample surface becomes 50eV with using 350eV electron beam.)
- Sample current and collector current are measured for calculating TEEY.
- For insulating materials, pulse scanning method is used. The sample is shifted after one shot of pulsed electron beam in order to prevent charging effect on the sample surface.

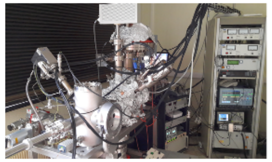
$$\sigma = 1 - \frac{I_S}{I_C + I_S}$$



ONERA DEESSE Facility

The DEESSE (Dispositif d'Etude de l'Emission Secondaire Sous Electrons) facility at ONERA is a UHV chamber equipped with:

The Space Environment Department of Onera (DESP) works on many projects closely related to space applications dealing with electron emission, such as charging effects of spacecraft and Hall Effect Thruster technology (HET).



Measurements capabilities include:

- **Vacuum** Analysis chamber: 10^{-7} to 10^{-8} Pa; Transfer chamber: 10^{-6} Pa.
- **Electron Guns** Kimball Physics: 1 eV-2 keV; Kimball Physics: 50 eV-5 keV; Staib 1 keV-22 keV.
- **Electron Irradiation** continuous or pulsed.
- **Incident Current** measured by Faraday cup.
- **Energy distribution** measured by hemispherical electron analyzer.
- **Sample Rotation** -90° to +90° to study incidence angle effects.
- **Surface Analysis** Auger Electron Spectroscopy (AES) and XPS.
- **Electron Energy Loss Spectroscopy** (EELS).
- **Ion source** (Ar, Xe, H) from 25 eV -5 keV.
- **VUV and X-ray sources** (Mg/Al sources).
- **Kelvin surface potential probe.**
- Residual gas analyzer
- **Temperature Control** of sample holder from ambient to 500°C

Electron emission yield was measured using the sample current method:

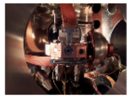
- Incident current measured as function of incident energy using the Faraday cup (polarized to +24 V).
- Thereafter, sample current was measured as function of incident energy.
- Sample holder biased to -18 V in order to avoid the collection of the low energy tertiary electrons by the sample surface.
- After that, incident current stability was confirmed for select energies. With Kimball Physics electron gun, the observed variation is <2%.
- To limit conditioning effect, electron beam was pulsed (5 μs pulse for conducting materials).

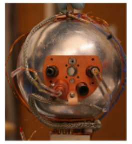
$$\sigma = 1 - \frac{I_S}{I_B}$$

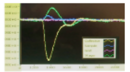
USU SEEM Facility

The Utah State University Materials Physics Group (MPG) Space Environment Effects Materials (SEEM) test facility performs state-of-the-art ground-based testing of electrical charging and electron transport properties of both conducting and insulating materials, emphasizing studies of electron emission, conductivity, luminescence, and electrostatic discharge.

We have studied how variations in temperature, accumulated charge, exposure time, contamination, surface modification, radiation dose rate and cumulative dose affect these electrical properties—or related changes in structural, mechanical, thermal and optical properties—of materials and systems.



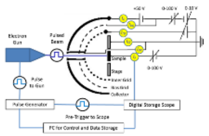




Measurements capabilities include:

- **Total / Secondary / Backscattered Electron Emission** using <20 eV to 50 keV mono-energetic continuous and pulsed beams with <5% absolute uncertainty.
- **Electron Emission Spectra** versus energy (0-5 keV with ~0.1 eV resolution) and emission angle-dependence.
- **Ion-Induced Electron Emission** spectra and yields for various <300 eV to 5 keV mono-energetic inert and reactive ions.
- **Photon-Induced Electron Emission** spectra and yields for <0.6 eV to >6.5 eV (165-2000 nm) monochromated photons.
- **Surface Voltage** simultaneous measurements of 0-10 kV with <0.2 eV resolution.
- **Induced Electrostatic Breakdown** simultaneous current and NIR/VIS/UV optical measurements.
- **Temperature capabilities** from <60 K to >450 K .
- **Vacuum** $<10^{-7}$ Pa.

$$\sigma = 1 - \frac{\int_{pulse}[I_S + I_{St} + I_{IG} + I_{BG} + I_{DT}]dt}{\int_{pulse}[I_C + I_S + I_{St} + I_{IG} + I_{BG} + I_{DT}]dt}$$

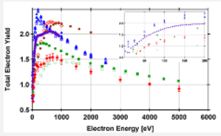


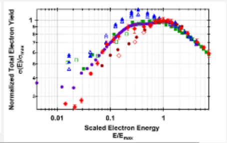
Electron yields are calculated from integrated current traces from six detector elements (A) of a fully enclosed hemispherical grid retarding field analyzer used for emission electron energy discrimination.

Round Robin Tests Results

Measurements were made of the absolute total electron yields at normal incidence over the full range of incident energies accessible with each group's instrumentation (a full range of ~5 eV to ~5 keV). Figures show linear plots with low energy detail insets (left) and log-log plots of scaled yields $\sigma(E)/\sigma_{max}$ versus scaled energy E/E_{max}.

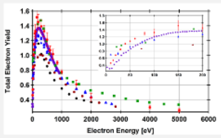
Gold

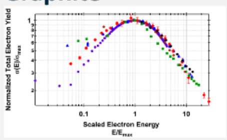




Symbol	Facility	Refs.	Measured Values			
			σ_{max}	E_{max} (eV)	E_1 (eV)	E_2 (eV)
●	CSIC SEY Facility (contin.)	1-3	2.06±0.02	600±20	24±1	NA
■	Onera—DEESSE Facility	4-5	1.81±0.03	360±20	28±1	~6000
□	Onera—DEESSE (Etched)	4-5	1.46±0.03	1250±50	NA	~6000
▲	LaSeine—TEY Facility (March 2)	6-7	2.48±0.03	200±20	NA	NA
△	LaSeine—TEY Facility (March 6)	6-7	2.3±0.1	240±30	12±2	NA
♦	USU—SEEM Facility (pulsed)	8-9	1.54±0.08	700±30	55±3	4000±200
◊	USU—SEEM Facility (contin.)	8,15	2.24±0.02	650±50	NA	NA
	Round Robin Average Values		2.0±0.4	600±460	24±9	5000±1000
●	Standard: Thomas & Pattinson	11	2.21±0.02	900±30	50±10	NA

HOPG Graphite





Symbol	Facility	Refs.	Measured Values			
			σ_{max}	E_{max} (eV)	E_1 (eV)	E_2 (eV)
●	CSIC SEY Facility	1-3	1.38±0.02	215±5	68±1	629±10
■	LaSeine—TEY Facility	4-5	1.48±0.05	270±20	60±2	610±40
▲	Onera—DEESSE Facility	6-7	1.28±0.05	190±10	69±1	552±20
♦	USU—SEEM Facility (clean)	8,9,15	1.4±0.1	200±30	40±2	895±20
	Round Robin Average Values		1.39±0.08	220±36	59±13	670±150
●	Standard 1: Whetten	12	1.01±0.01	300±20	250±30	350±20
●	Standard 2: Wintucky	13	NA	NA	NA	330±20

Summary

Summary of results:

- Shape of normalized curves are very consistent
- **Highly sensitive to surface contamination** [14],
- Very good agreement of absolute yield for $E>E_{max}$, but less agreement for $E<E_1$
- **HOPG agreement between facilities is the best: ~5% for σ_{max} and ~20% for energies**
- HOPG has the advantage that clean smooth surfaces are easy to prepare with tape cleaving
- Au samples exhibit differing degrees of contamination--as evidenced by surface analysis tests--exhibiting two TEY peaks near 700 eV (clean Au) and 200 eV (C contamination) [14].

Topics of future Round Robin analysis:

- Charge sensitive measurements of dielectrics: Polyimide (Kapton HN™) results,
- Energy discriminated measurements: Secondary/Backscattered results and emission spectra,
- Surface sensitivity: surface cleanliness tests, effects of contamination and Ar sputtering,
- Discussions of the relative strengths and weaknesses of our various methods.

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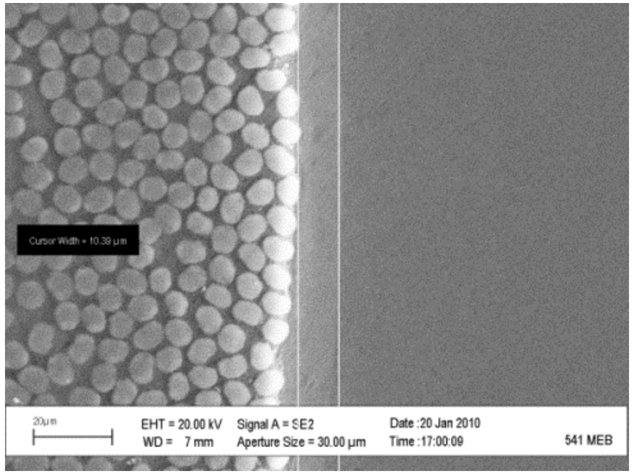
A Multitude of Materials: Multilayer/Nanocomposite Effects

Length Scale

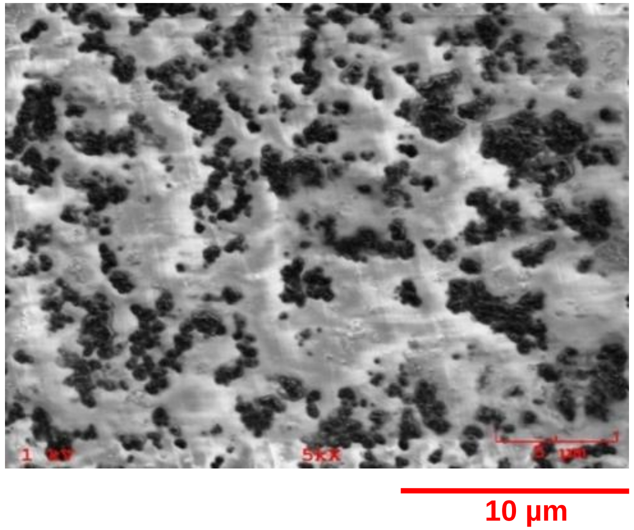
- Nanoscale structure of materials
- Electron penetration depth
- SE escape depth

Time Scales

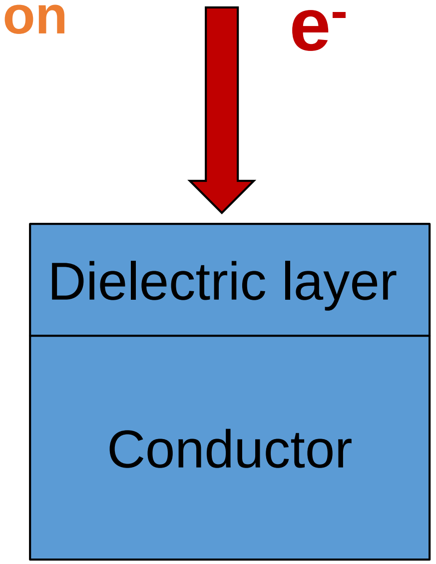
- Deposition times
- Dissipation times
- Mission duration



C-fiber composite with thin ~1-10 µm resin surface layer



Black Kapton™ (C-loaded PI)



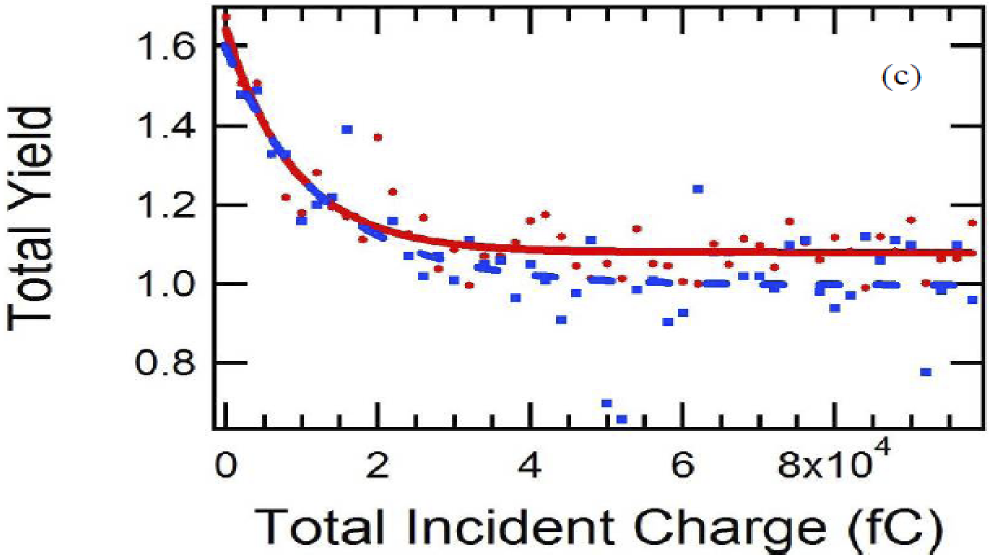
Thin ~100 nm disordered SiO_2 dielectric coating on metallic reflector

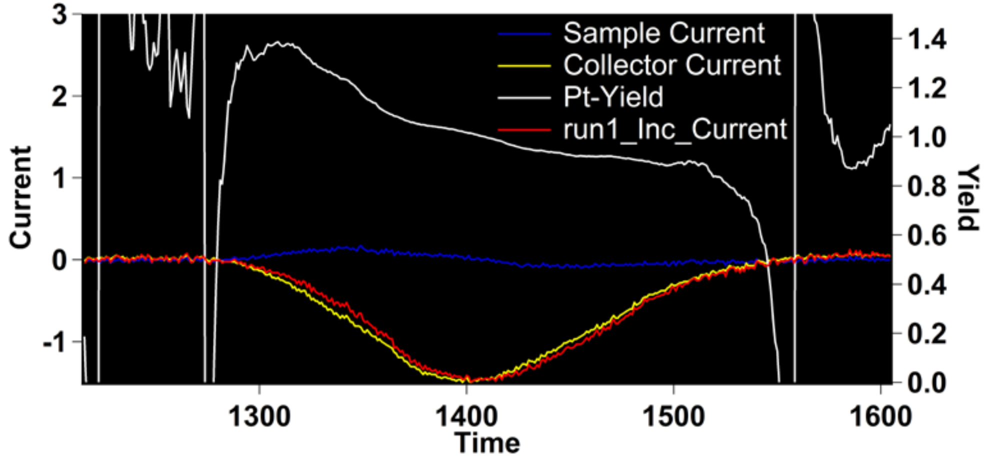
Point-wise Electron Yield Tests of Highly Insulating Materials

•Current analysis program could show how yield changes over the course of a pulse. (~1% of total pulse charge)

•Gold data should show no charging effects.

•Zero charge plateau.





Support & Collaborations

Current Funding

NASA GRC
NASA MSFC
AFRL
NSF
Box Elder Innovations
Solar Probe Plus (Berkley Space Lab)
ViaSat
Lockheed Martin
Times Microwave
NASA Grad Res. Fellowships
USU PDRF Fellowships
Utah NASA Space Grant Consortium

Past Funding

USU Space Dyanamics Lab
NASA SEE Program
JWST (GSFC/MSFC)
Solar Probe Mission (JHU/APL)
Rad. Belt Space Probe (JHU/APL)
Solar Sails (JPL)
AFRL
Boeing
Ball Aerospace
Orbital
LAM
AFRL/NRC Fellowship
Sienna Technologies

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Backup Charts

MPG Space Environment Effects Materials Test Facility Test

The Space Environment Effects Materials (SEEM) test facility operated by the Utah State University Materials Physics Group (MPG) is a leading research center for the study of space environment effects on aerospace materials. The MPG performs state-of-the-art ground-based testing of electrical charging and electron transport properties of both conducting and insulating materials, emphasizing studies of electron emission, conductivity, luminescence, and electrostatic discharge. Our efforts in this field over more than two decades—in cooperation with NASA, AFOSR, and numerous aerospace companies—have been primarily motivated by the space community's concern for charging of crafts caused by plasma environment fluxes and for radiation modification and damage of materials and components. We have studied how variations in temperature, accumulated charge, exposure time, contamination, surface modification, radiation dose rate and cumulative dose affect these electrical properties—or related changes in structural, mechanical, thermal and optical properties—of materials and systems. Our research also has direct application to high voltage direct current (HVDC) power and transmission lines, plasma deposition, semiconductor metal-oxide interfaces, and nanodielectrics.

Research Projects & Collaborations

The MPG has been actively involved in more than 40 projects with external funding over the last two decades related to space environment effects. Our interdisciplinary research projects have involved collaborations with numerous space agencies, aerospace corporations and academic institutions, including:

- NASA Centers (GRC, GSFC, JPL, JSC, LaRC, MSFC),
- NASA Space Environments Effects Program,
- AFRL Spacecraft Charging & Instrument Calibration Lab,
- AFRL Space Weather Center of Excellence,
- Arnold AFB Engineer Development Center,
- European and Japanese Space Agency (ESA, ESTEC, CNES, ONERA, LAPLACE, JAXA)
- DOE Idaho National Laboratory Center for Space Nuclear Research,
- Johns Hopkins Applied Physics Laboratory,
- USU Space Dynamics Laboratory,
- Aerospace Corporation, ATK, Ball, Boeing, DPL Science, Northrop Grumman, Orbital, SAIC, Vanguard Space Technologies,
- SBIR projects (Ashwin, Advanced Scientific, Box Elder Innovations, Sienna Technologies).

These ventures have studied both basic science and specific effects and mitigation strategies in a wide variety of extreme environments, each of which present their own unique sets of issues and materials. These environments have included:

- Low Earth Orbit (Satellites, CubeSats, ISS, *MISSE*),
- Geosynchronous Earth Orbit (Communication Satellites, CRRES/IDM, GOES, Landsat LCDM),
- Polar Orbit (Radiation Belt Space Probes, CubeSats),
- L1 and L2 (James Webb Space Telescope, DSCOVR),
- Near-solar (Solar Probe Mission, Solar Probe Plus)
- Lunar and Martian (Dust Mitigation),
- Jovian (Prometheus, JUNO, Solar Probe Mission, SIRSE, Europa)
- Interplanetary (Solar Sails, Solar Probe Mission)

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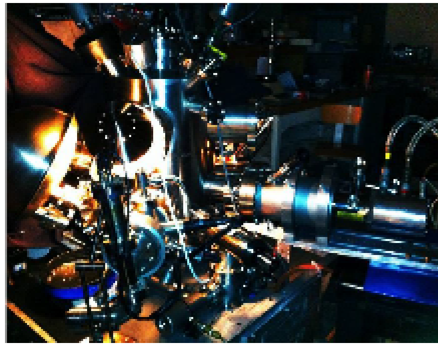
Space Environment Effects Materials Test Facility



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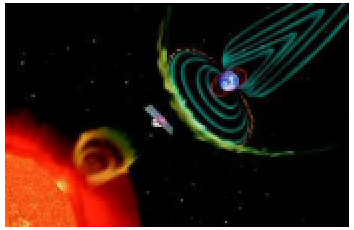
USA



Recent Publications

1. A Andersen, JR Dennison, AM Sim, C Sim, "Electrostatic Discharge and Endurance Time Measurements of Spacecraft Materials: A Defect-Driven Dynamic Model," *IEEE Tran. Plasma Science*, 2015, 11 pp, in press.
2. RE Davies and JR Dennison, "Evolution of Secondary Electron Emission Characteristics of Spacecraft Surfaces," *J. Spacecraft and Rockets*, 34, 571-574 (1997).
3. J Dekany, RH Johnson, G Wilson, AE Jensen, JR Dennison, "Ultrahigh Vacuum Cryostat System for Extended Low Temperature Space Environment Testing," *IEEE Trans. Plasma Sci.*, 42(1), 2014, 266-271.
4. J Dekany, AM Sim, J Brunson, JR Dennison, "Electron Transport Models and Precision Measurements with the Constant Voltage Conductivity Method," *IEEE Trans. Plasma Sci.*, 41(12), 2013, 3565-3576.
5. JR Dennison, "The Dynamic Interplay Between Spacecraft Charging, Space Environment Interactions and Evolving Materials," *IEEE Tran. Plasma Science*, 2015, 8 pp. in press.
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9. JR Dennison, RC Hoffmann, J Abbott, "Triggering Threshold Spacecraft Charging with Changes in Electron Emission from Materials," AIAA-2007-1098, *Proc. 45th AIAA Meeting on Aerospace Sciences*, 16 pp., Reno, NV, 2007.
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11. JL Hodges, AM Sim, J Dekany, G Wilson, A Evans, JR Dennison "*In Situ* Surface Voltage Measurements of Layered Dielectrics," *IEEE Trans. Plasma Sci.*, 42(1), 2014, 255-265.
12. RC Hoffmann and JR Dennison, "Methods to Determine Total Electron-Induced Electron Yields Over Broad Range of Conductive & Nonconductive Materials," *IEEE Trans. Plasma Sci.*, 40, 2012, 298.
13. AE Jensen and JR Dennison, "Defects Density of States Model of Cathodoluminescent Intensity and Spectra of Disordered SiO_2," *IEEE Tran. Plasma Science*, 2015, 7 pp., in press.
14. AE Jensen, G Wilson, J Dekany, AM Sim, JR Dennison "Low Temperature Cathodoluminescence of Space Observatory Materials," *IEEE Trans. Plasma Sci.*, 42(1), 2014, 305-310.
15. RH Johnson, LD Montierth, JR Dennison, JS Dyer, E Lindstrom, "Small Scale Simulation Chamber for Space Environment Survivability Testing," *IEEE Trans. Plasma Sci.*, 41(2013, 3453-3458.
16. AM Sim and JR Dennison, "Comprehensive Theoretical Framework for Modeling Diverse Electron Transport Experiments in Parallel Plate Geometries," AIAA-2013-2827, 5th *AIAA Atmosph. & Space Environ. Conf.*, San Diego, CA, 2013, 31 pp.
17. G Wilson, JR Dennison, AE Jensen, J Dekany, "Electron Energy-Dependent Charging Effects of Multilayered Dielectric Materials," *IEEE Trans. Plasma Sci.*, 41(12), 2013, 3536-3544.
18. G Wilson and JR Dennison, "Approximation of Range in Materials as a Function of Incident Electron Energy," *IEEE Trans. Plasma Sci.*, 40(2), 2012, 305-310.

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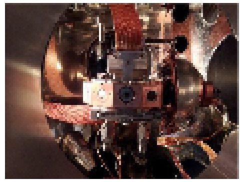
MATERIALS PHYSICS GROUP

MPG Space Environment Effects Materials Test Facility

Utah State University Space Environments Effects Materials (SEEM) Test Facilities

Electron Emission

Electron emission studies for incident electrons, ions and photons, with precision absolute yields of conductors, semiconductors, insulators & extreme insulators[12].

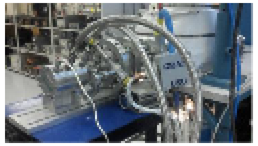


Measurements include:

- **Total / Secondary / Backscattered Electron Emission** using <20 eV to 50 keV mono-energetic pulsed beams with <5% absolute uncertainty [2,12,17].
- **Electron Emission Spectra** versus energy (0-5 keV with ~0.1 eV resolution) and angle.[12]
- **Ion-Induced Electron Emission** spectra and yields for various <300 eV to 5 keV mono-energetic inert and reactive ions.
- **Photon-Induced Electron Emission** spectra and yields for <0.6 eV to >6.5 eV (165-2000 nm) monochromated photons. (10 eV near-H Lyman-α source under development.)
- **Surface Voltage** simultaneous measurements of 0-10 kV with <0.2 eV resolution [11,17].
- **Induced Electrostatic Breakdown** simultaneous current &NIR/VIS/UV optical measurements [18]
- **Temperature capabilities** from <60 K to >450 K [3]. (Higher temperatures under development.)

Conductivity & Charge Transport

Conductivity and charge transport studies for conductors, semiconductors, & extreme insulators. Measurements include:



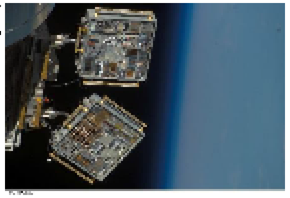
- **Bulk and surface conductivity** using constant voltage and charge storage methods for conductivities as low as 10^{-23} (Ω-cm)$^{-1}$ [4,8,10].
- **Radiation Induced Conductivity (RIC),** with temperature and temporal dependence [5,8].
- **Phototyield IV curves.**
- **Surface Voltage** spatial and temporal measurements over 0-10 kV with <0.2 eV resolution [11,17]
- **Temperature capabilities** from <60 K to >450 K [3]. (Higher temperatures under development.)

Space Simulation

The **Space Survivability Test (SST) chamber** [15] has unique capabilities for simulating and testing potential environmental-induced modifications of small satellites, components, and materials of up to 350 cm^2 area. It is particularly well suited for cost-effective tests of multiple small scale materials samples over prolonged exposure to simulate critical environmental components including:

- **Neutral gas atmosphere/Vacuum** <10^{-7} Pa.
- **Temperatures** from 60 K [3] to 450 K with < ±2 K.
- **Electron fluxes** with simultaneous low and high energy electron guns from <20 eV to ~100 keV with ~1 pA/cm^2 to >1 μA/cm^2) fluxes to simulate the solar wind and plasma sheet at more than the 100X cumulative electron flux [9,11,12].
- **Ionizing Radiation** with a 100 mCi Sr^{90} broadband (~500 keV to 2.5 MeV) β radiation source [15].
- **NIR/VIS/UVA/UVB radiation** (200 nm to 1700 nm) at up to 4X sun equivalent intensity flux.
- **Far UV** simulation of H Lyman-α with Kr resonance lamps at up to 4X sun intensity.

Studies underway will determine how well space degradation of materials can be simulated in the SST. Materials exposed in the SST are compared to 165 samples exposed to the ISS space environment for 18 months in the USU *SUSpECS* project on the MISSE-6 mission [6].



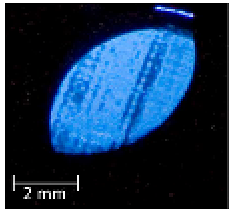
Characterization & Preparation

Extensive capabilities for sample preparation and characterization. These include:

- **Bulk Composition** Inductively Coupled Plasma-Atomic Emission Spectroscopy (ICP-AES), FTIR and Raman spectroscopy.
- **Surface Composition** Auger Electron Spectroscopy and AES mapping, Energy Dispersive X-ray (EDX) spectroscopy.
- **Surface Morphology** Scanning Electron Microscopy (FE-SEM), Electron Backscatter Diffraction (EBSD), Atomic Force (AFM) and Scanning Tunneling (STM) Microscopies.
- **Vacuum Thermal Ovens** Various ovens down to <10^{-4} Pa and temperatures up to >1500 K.
- **Optical Characterization** Specular and Diffuse Reflectivity/Transmission, Thin-Film Interferometry, T-dependent Emissivity.
- **Luminescence** Optically Stimulated Luminescence (OSL), Thermal Stimulated Luminescence (TSL).

Cathodoluminescence

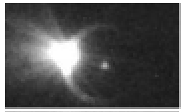
Absolute intensity and low level electron-induced luminescence spectra.

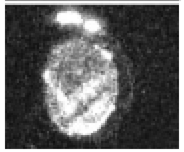


- **Spectra** (0.6-6.0 eV or 200-1700 nm with <0.1 nm resolution) [13,14].
- **Temperature capabilities** from <60 K to >450 K [3,14]
- **Charging and Saturation studies** [13,14]

Electrostatic Discharge & Arcing

- **Electrostatic Breakdown Field Strength** (<25 kV or <10^{8} V/m at 25 μm) [1,18].
- **Temperature and Vacuum capabilities** from <120 K to >350 K at <10^{-3} Pa [1].
- **Electron-Induced Arcing** with current and spatially and temporally resolved optical measurements from <6 K to >350 K at <10^{-7} Pa [18]





Collaborative Facilities

The MPG collaborates with nearby facilities that extend our capabilities. These include:

- **USU Space Dynamics Laboratory** for satellite and sensor development, fabrication & missions.
- **SDL Nano-Satellite Operation Verification and Assessment (NOVA)** test facility for characterization and verification of subsystem and system performance of small satellites.
- **Idaho Accelerator Center** for high energy electron, proton and positron beams and radiation sources.
- **USU Nanoscale Device Lab** for device and sample fabrication and characterization.
- **USU Core Microscopy Facility** for high resolution electron and optical microscopy.
- **USU Luminescence Lab** for optical and thermal stimulated luminescence testing.

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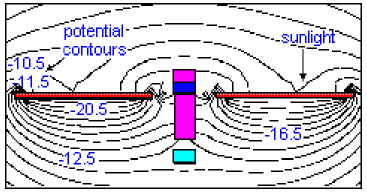
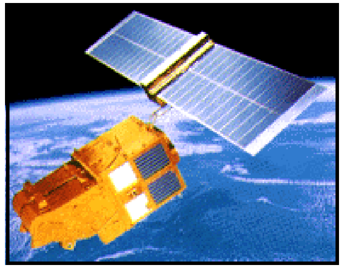
Integration with Spacecraft Charging Models





SEE Handbook or NASCAP predicts on-orbit spacecraft charging in GEO and LEO environments

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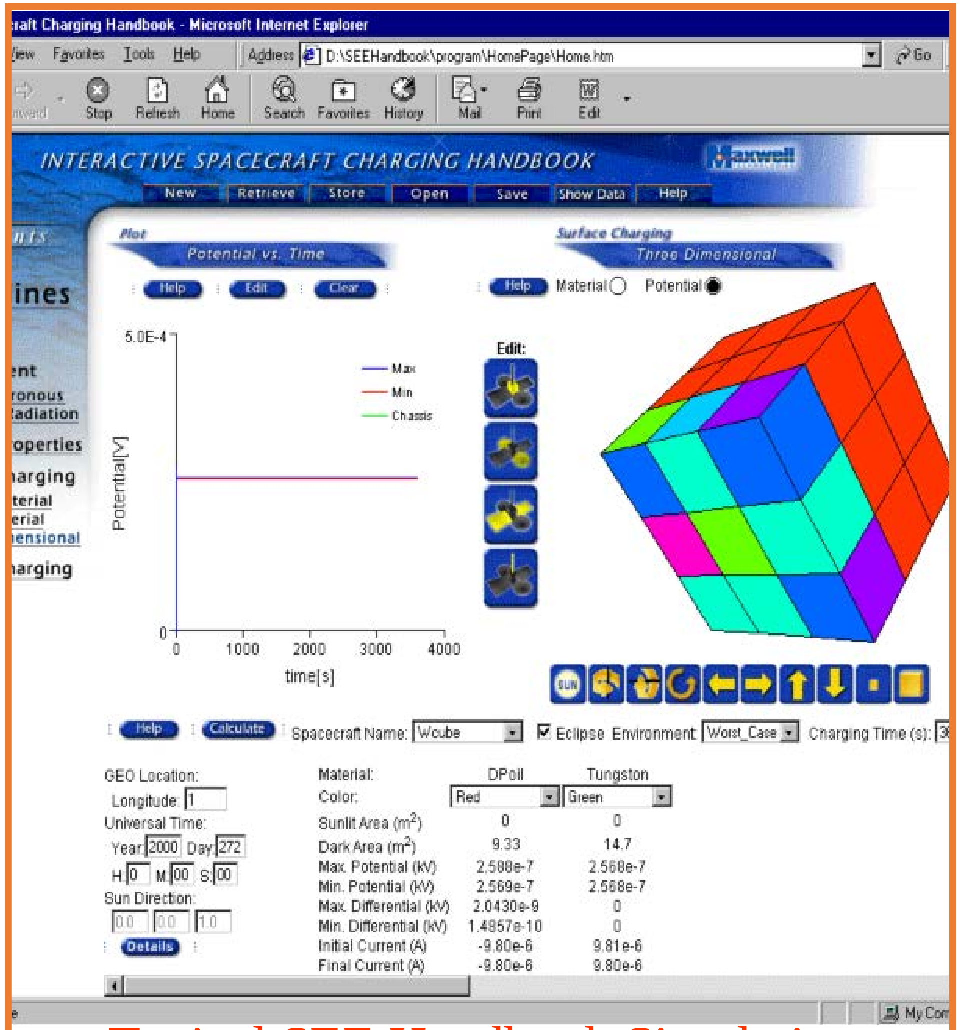
Materials Research

SAIC
An Employee-Owned Company

NASCAP Upgrades

NASCAP-2K



Typical SEE Handbook Simulation

Understanding the Physics