10th Anniversary Lecture Series
Laboratory of Spacecraft Environment Interaction Engineering
Kyushu Institute of Technology

La SEINE

# An Overview of the Dynamic Interplay between the Space Environment & Spacecraft Materials

**JR Dennison**

*Materials Physics Group*
*Physics Department*
*Utah State University*
*Logan, Utah USA*



## Utah State University Materials Physics Group

## Support & Collaborations

*NASA SEE Program*
*JWST (GSFC/MSFC)*
*Solar Probe Mission (JHU/APL)*
*Rad. Belt Space Probe (JHU/APL)*
*Solar Sails (JPL)*
*AFRL*
*Boeing*
*Box Elder Innovations*
*Ball Aerospace*
*Orbital*
*LAM*
*USU Blood Fellowship*
*USU PDRF Fellowships*
*AFRL/NRC Fellowship*
*NASA Grad Res. Fellowships*

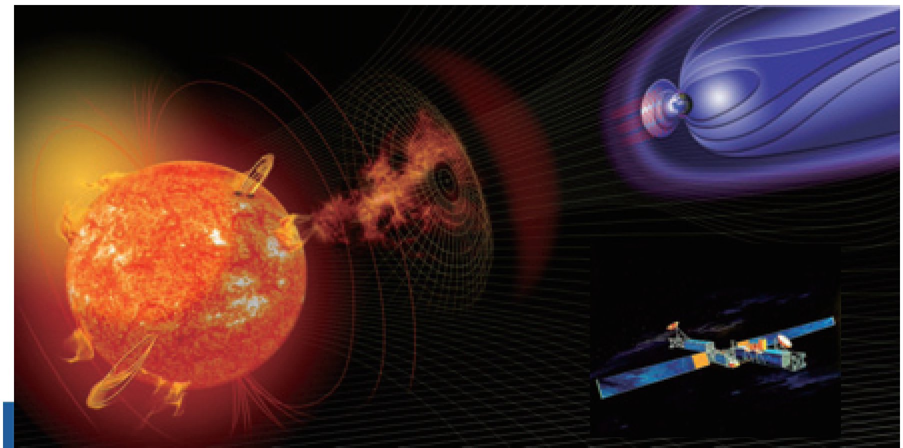
**Utah State University**

MATERIALS PHYSICS GROUP

USU MPG Webpage



# Spacecraft Charging



**The sun gives off high energy charged particles.**

**These particles interact with the Earth's atmosphere and magnetic field in interesting ways.**

**High energy particles imbed charge into spacecraft surfaces.**

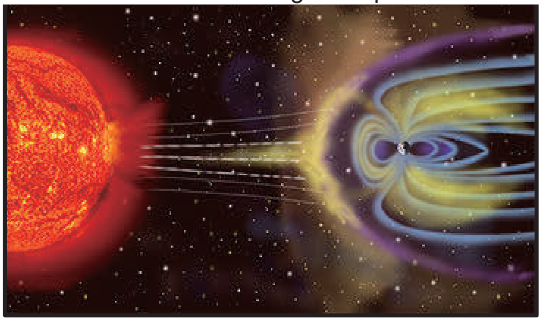
**Space environments affect spacecraft and their performance.**
**How do we quantify these effects and mitigate degradation?**

# The Space Environment

**Dynamics of the space environment and satellite motion lead to dynamic spacecraft charging (min to decades)**

- **Solar Flares, CME, Solar Cycle**
- **Orbital eclipse, Rotational eclipse**

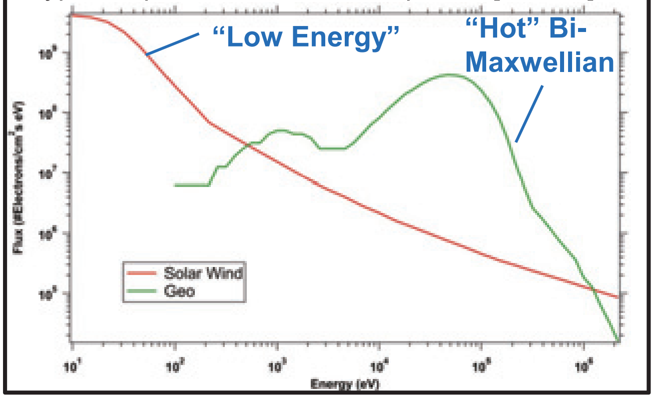
Solar wind and Earth's magneto-sphere structure.



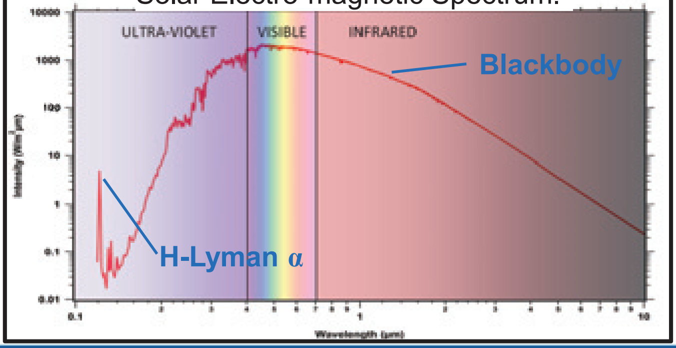
**Incident fluxes of:**

- **Electrons, $e^-$**
- **Ions, $I^+$**
- **Photons, $\gamma$**
- **Particles, m**

Typical Space Electron Flux Spectra [Larsen].




Solar Electro-magnetic Spectrum.








# USU Materials Physics Group Facilities & Capabilities

**Conductivity**
**Electroscatic Discharge**
**Induced Arcing**
**Pulsed Electroacoustics**

**Electron Induced Emission**
**Ion Induced Emission**
**Photon Induced Emission:**
**Cathodoluminescence**

**Radiation Damage**
**Environmental Simulations**
**Sample Characterization**
**& Preparation**

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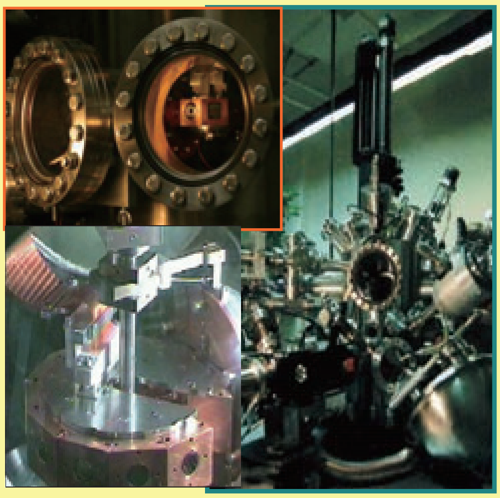
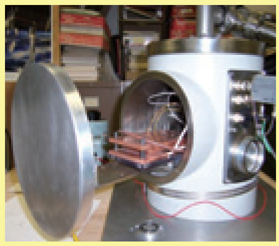
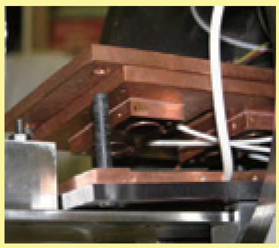






**Environment Conditions ↔ Materials Conditions ↔ Materials Properties ↔ Spacecraft Charging**

# Some Unsolicited Advice for Students
## (and an outline for the talk)

- *Define the problem*
- *Develop useful skills*
  - *Advanced knowledge*
  - *Experimental skills*
  - *Modeling skills to tie these together*
  - *Breadth to recognize important trends*
- *Keep your eyes open!*

*Let me share four examples*

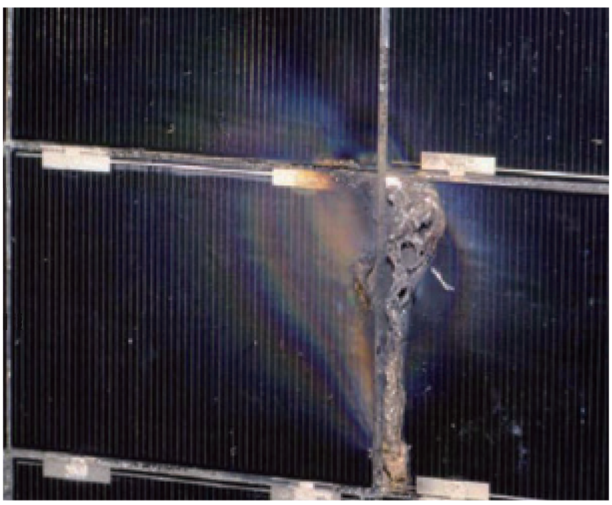


# Primary Motivation For Our Research—Spacecraft Charging

NASA's 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*
- *Arching*
- *Sputtering*
- *Enhanced contamination*
- *Shifts in spacecraft potentials*
- *Current losses*

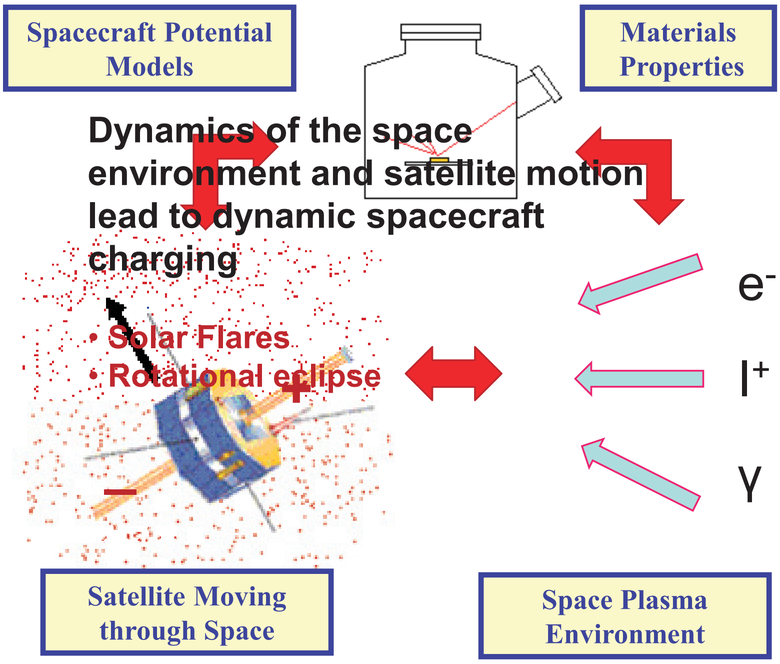


## Where Materials Testing Fits into the Solution

**Charge Accumulation**
- Electron yields
- Ion yields
- Photoyields

**Charge Transport**
- Conductivity
- RIC
- Dielectric Constant
- ESD

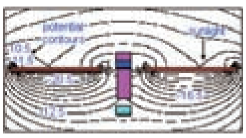
As functions of materials species, flux, and energy.

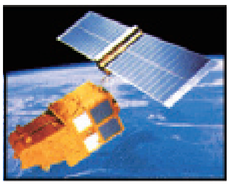



Complex dynamic interplay between space environment, satellite motion, and materials properties



## Integration with Spacecraft Charging Models





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

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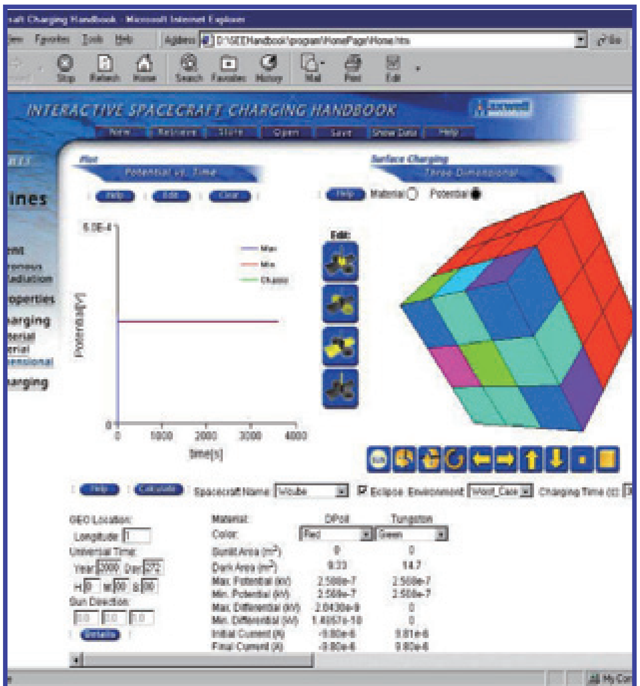
Materials Research

SAIC An Employee-Owned Company
NASCAP Upgrades

NASCAP-2K




Typical SEE Handbook Simulation

# What do you need to know about the materials properties?

**STATIC Charging codes such as NASCAP-2K SPENVIS, or MUSCAT and NUMIT2 or DICTAT require:**

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

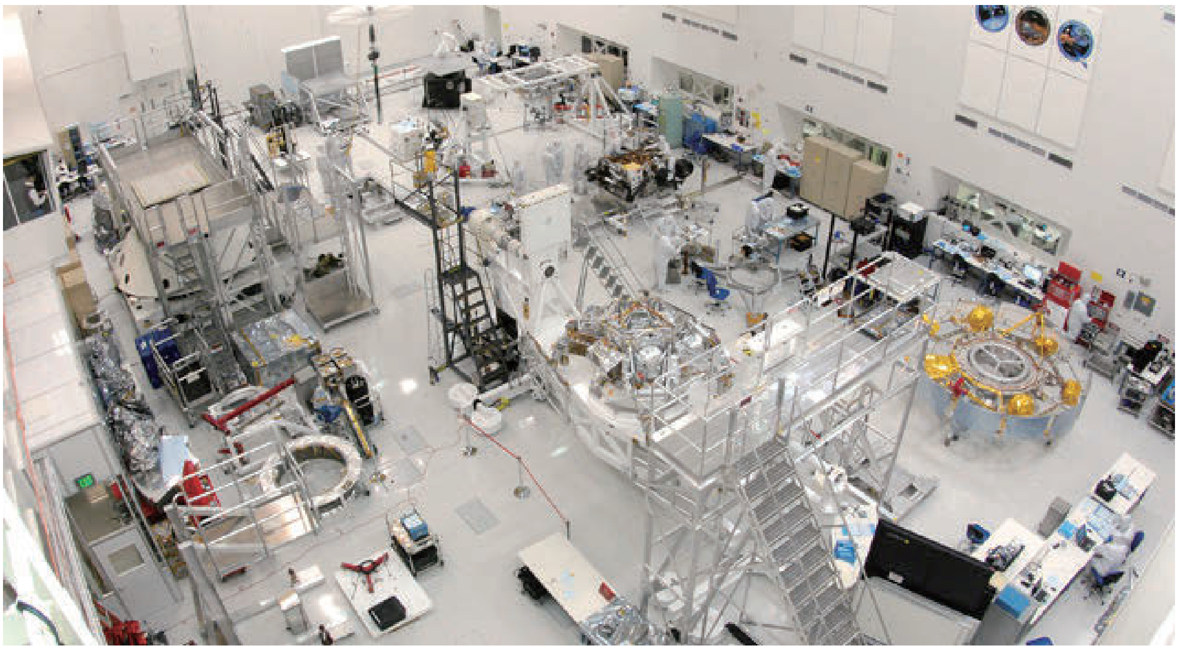
**Charge Transport**
- Conductivity
- RIC
- Permittivity
- Electrostatic breakdown
- Penetration range

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

| Parameter | Value |
|---|---|
| [1] Relative dielectric constant; $\varepsilon_r$ (Input as 1 for conductors) | 1, NA |
| [2] Dielectric film thickness; d | 0 m, NA |
| [3] Bulk conductivity; $\sigma_o$ (Input as -1 for conductors) | -1; (4.26 ± 0.04) · $10^7$ $ohm^{-1}·m^{-1}$ |
| [4] Effective mean atomic number <$Z_{eff}$> | 50.9 ± 0.5 |
| [5] Maximum SE yield for electron impact; $\delta_{max}$ | 1.47 ± 0.01 |
| [6] Primary electron energy for $\delta_{max}$; $E_{max}$ | (0.569 ± 0.07) keV |
| [7] First coefficient for bi-exponential range law, $b_1$ | 1 Å, NA |
| [8] First power for bi-exponential range law, $n_1$ | 1.39 ± 0.02 |
| [9] Second coefficient for bi-exponential range law, $b_2$ | 0 Å |
| [10] Second power for bi-exponential range law, $n_2$ | 0 |
| [11] SE yield due to proton impact $\delta^H$(1keV) | 0.3364 ± 0.0003 |
| [12] Incident proton energy for $\delta^H_{max}$; $E^H_{max}$ | (1238 ± 30) keV |
| [13] Photoelectron yield, normally incident sunlight, $j_{pho}$ | (3.64 ± 0.4) · $10^{-5}$ $A·m^{-2}$ |
| [14] Surface resistivity; $\rho_s$ (Input as -1 for non-conductors) | -1 ohms·$square^{-1}$, NA |
| [15] Maximum potential before discharge to space; $V_{max}$ | 10000 V, NA |
| [16] Maximum surface potential difference before dielectric breakdown discharge; $V_{punch}$ | 2000 V, NA |
| [17] Coefficient of radiation-induced conductivity, $\sigma_r$; k | 0 $ohms^{-1}·m^{-1}$, NA |
| [18] Power of radiation-induced conductivity, $\sigma_r$; Δ | 0, NA |



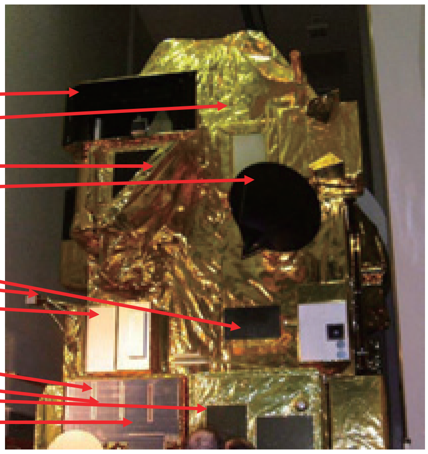
# Spacecraft Assembly Facilities



Curtesy of NASA JPL

# Spacecraft Materials and Uses

This large communication satellite incorporates materials which are contained in SUSpECS.



Graphite Composite
Au/Mylar
Kapton
Black Kapton
Aquadag
Al
White Paint
ITO
RTV
FR4
Coverglass

Curtesy of JAXA

SUSpECTS Material Samples List

| | Material | Source | |
|---|---|---|---|
| C01 | COIC A/N720 Oxide Ceramic Matrix Composite (CMC) | ATK | Provided By ATK |
| C02 | COIC S200 Nonoxide CMC | ATK | |
| C03 | Thiokol Carbon-Carbon Composite #1 | ATK | |
| C04 | Thiokol Carbon-Carbon Composite #2 | ATK | |
| C05 | Thiokol Fiber Filled Carbon-Carbon Composite | ATK | |
| C06 | Thiokol Carbon-Phenolic Composite | ATK | |
| C07 | Thiokol Graphite Epoxy Foil - No Hole | ATK | |
| C08 | Thiokol Graphite Epoxy Foil - With Hole | ATK | |
| C09 | COIC S400 Nonoxide CMC | ATK | |
| C10 | COIC S200H Nonoxide CMC | ATK | |
| C11 | COIC S300 Nonoxide CMC | ATK | |
| I01 | Kapton on Aluminum | Sheldahl | Provided By Utah State University |
| I02 | Teflon on Aluminum | Sheldahl | |
| I03 | Mylar on Aluminum | Sheldahl | |
| I04 | Nylon 6/6 | McMaster-Carr | |
| I06 | $SiO_2$ (Fused Quartz) | UQG Optics | |
| I07 | $Al_2O_3$ (Sapphire) | UQG Optics | |
| I11 | Germanium on Kapton | Sheldahl | |
| I12 | Anodized Aluminum (Chromic Acid Etch) | NASA / MSFC | |
| I13 | Anodized Aluminum (Sulferic Acid Etch) | NASA / MSFC | |
| I15 | UV Ce-doped Cover Glass | OCLI | |
| I17 | FR4 Printed Circuit Board Material | CRRES NASA | |
| I18 | CV-1147 RTV on Copper | Boeing | |
| I19 | DC93-500 RTV on Copper | Boeing | |
| I28 | Borosilicate Glass | UQG Optics | |
| T01 | Gold (99.99% Purity) | ESPI | |
| T02 | Aluminum (99.999% Purity) | ESPI | |
| T03 | 316 Stainless Steel | McMaster | |
| T04 | Gold(2um)/Nickel(2um) on 316 Stainless Steel | Gold Plating | |
| T05 | OFHC Copper (99.9% Purity) | McMaster | |
| T06 | Silver (99.7775% Purity) | United Material | |
| T07 | Inconel on Silver on Teflon on ITO | Sheldahl | |
| T10 | g-C (Graphitic Amorphous Carbon) on Copper | Arizona Carbon | |
| T11 | Aquadag on Copper | LADD Research | |
| T12 | 100XC Black Kapton | Sheldahl | |
| T13 | Thick Film Black | Sheldahl | |
| T14 | ITO on Teflon on Silver on Inconel | Sheldahl | |
| I26 | White Paint (Zinc Oxide Thermal Control Paint) | SDL | SDL |
| I27 | Composite (GIFTS Carbon Composite) | SDL | |



# 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 this talk is the change in materials properties as a function of:**

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

## Case Study One

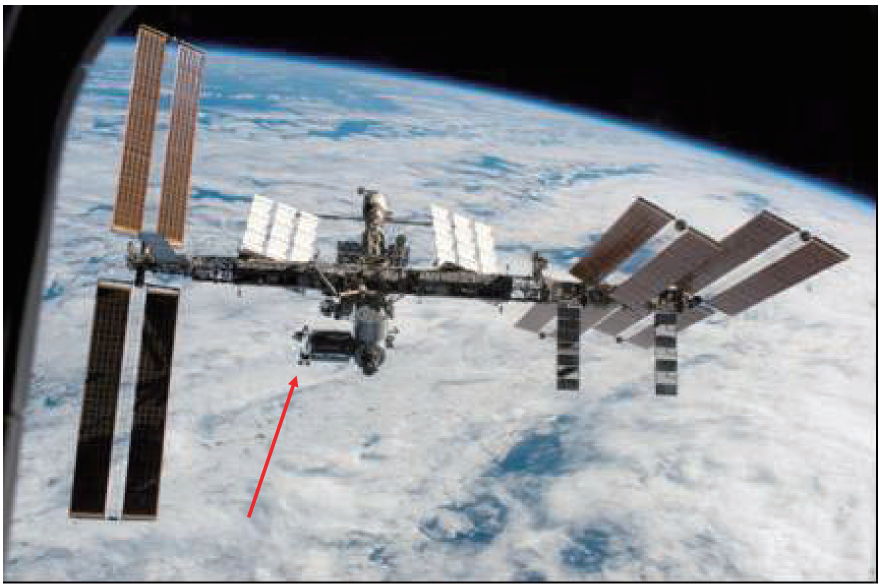
# The Poster Child for Space Environment Effects

**It is important that students bring a certain ragamuffin barefoot irreverence to their studies; they are not here to worship what is known, but to question it.**

***–Jacob Bronowski, The Ascent of Man***



# SUSpECS on MISSE 6



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

**Deployed**
**March 2008**
**STS-123**

**Retrieved**
**August 2009**
**STS-127**

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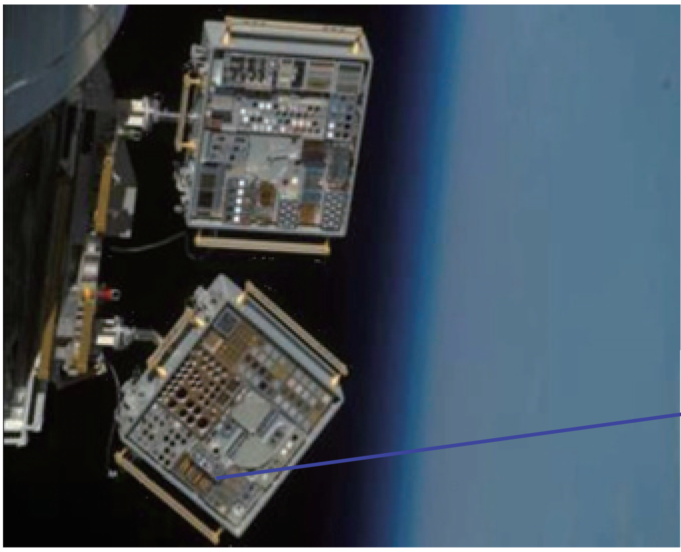
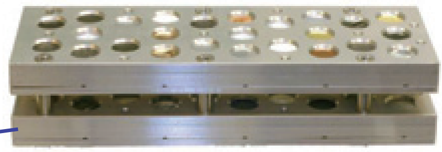
## SUSpeCS Samples on the ISS





MISSE 6 exposed to the space environment. The SUSpECS double stack can be seen in the bottom center of the lower case. The picture was taken on the fifth EVA, just after deployment.

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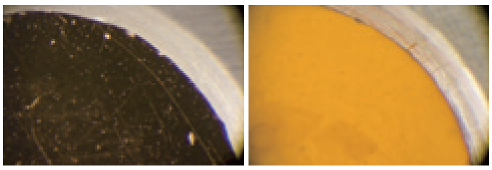
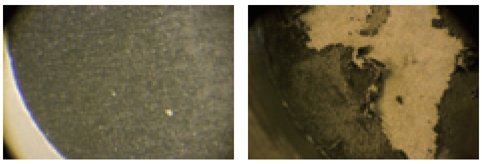
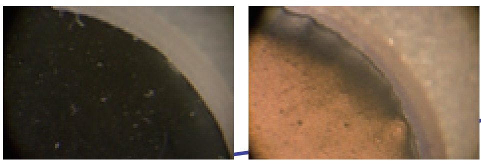
## Evolution of Contamination and Oxidation



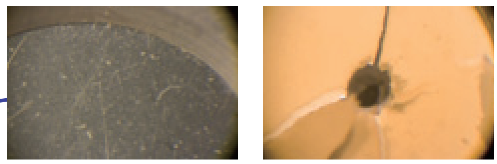
Before After
Kapton, HN



Before After
Ag



Before After
Black Kapton



Before After
Ag coated Mylar with micrometeoroid impact

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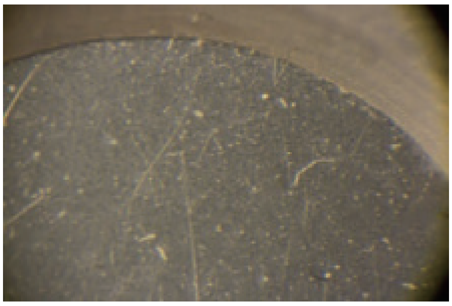
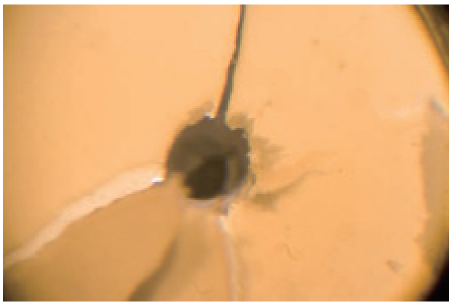
# Evolution of Materials Properties





## 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?

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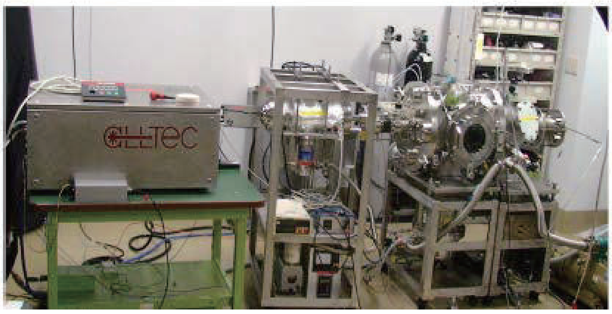
# Study of Materials Properties

UV Exposure



Atomic Oxygen Exposure

Electron Flux Exposure

Hypervelocity Impact

## Case Study Two

# A Grand Tour of Space Environments and Their Effects

### Know the physics of your problem

**"We anticipate significant thermal and charging issues."**

*J. Sample*



## A Puzzle from Solar Probe Plus: Temperature and Dose Effects

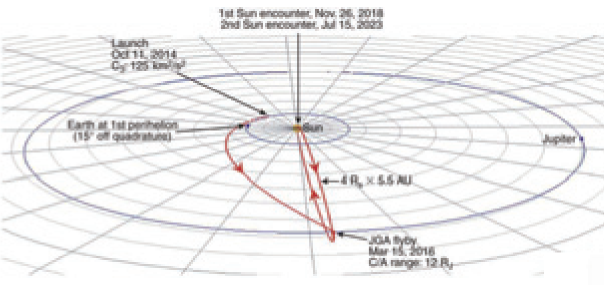



Figure 4-1. Solar Probe mission summary.

**WideTemperature Range**
**<100 K to >1800 K**

***Wide Dose Rate Range***
**Five orders of magnitude variation!**

***Wide Orbital Range***
**Earth to Jupiter Flyby**
**Solar Flyby to 4 $R_s$**

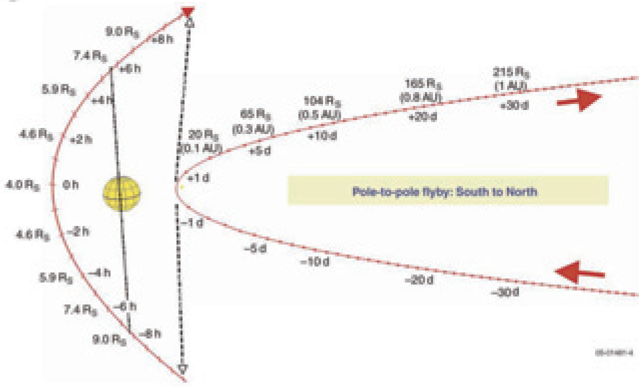
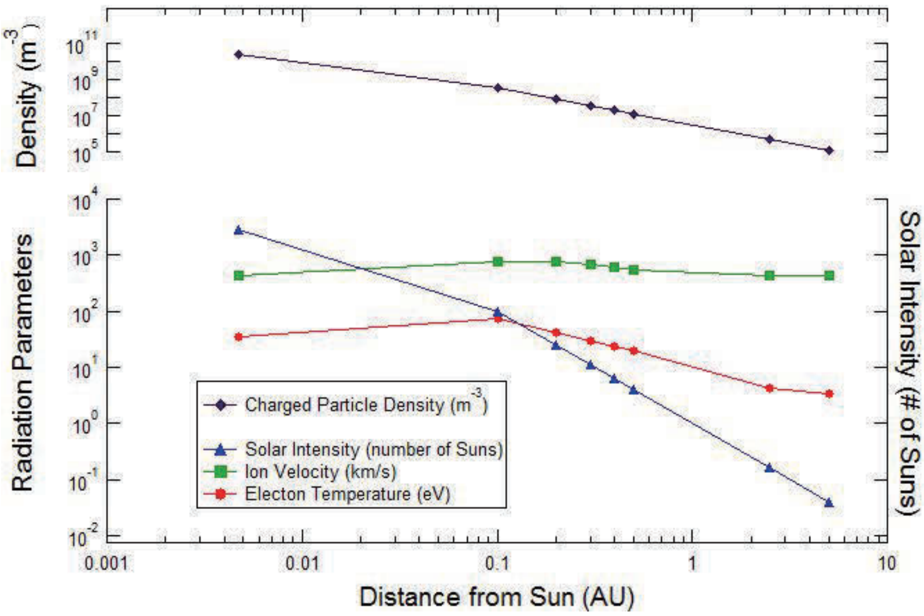



Figure 4-2. Solar encounter trajectory and timeline. Science operations begin at perihelion −5 days (65 $R_s$) and continue until perihelion +5 days.

***Charging Study by Donegan, Sample, Dennison and Hoffmann***

## A Very Wide Range of Environmental Conditions




*Wide Orbital Range*
Earth to Jupiter Flyby
Solar Flyby to 4 $R_s$

**WideTemperature Range**
<100 K to >1800 K

*Wide Dose Rate Range*
Five orders of magnitude variation!



## 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

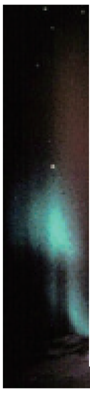
# Radiation Effects

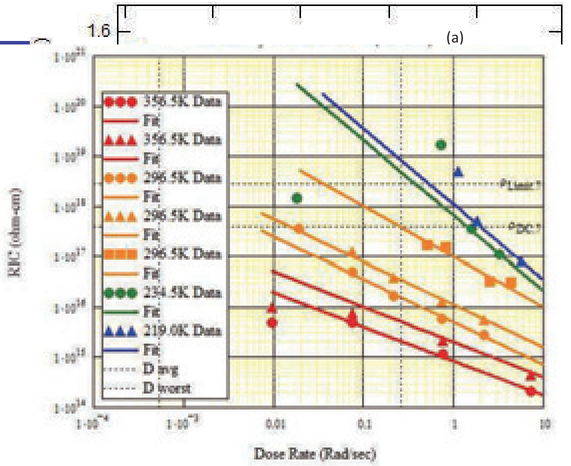
**Large Dosage (>10⁸ Rad)**

**Medium Dosage (>10⁷ Rad)**

**Low Dose Rate (>10⁰ Rad/s)**

“ Earth is for Wimps ” H. Garrett






Examples: RBSP, MMS, JUNO, JGO/JEO

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

Radiation Induced Conductivity (RIC)

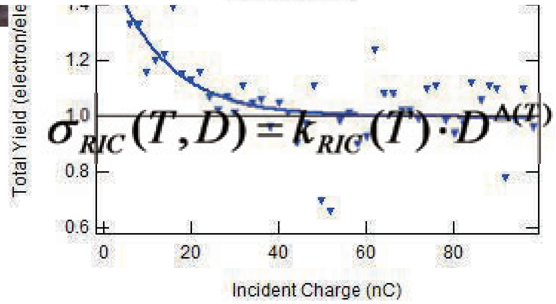
Mechanical Modification of Electron

Temperature dependent Properties

Examples: RBSP, JUNO, JGO/JEO

Caused by bondbreaking and trap creation

Mechanical and Optical Materials Damage

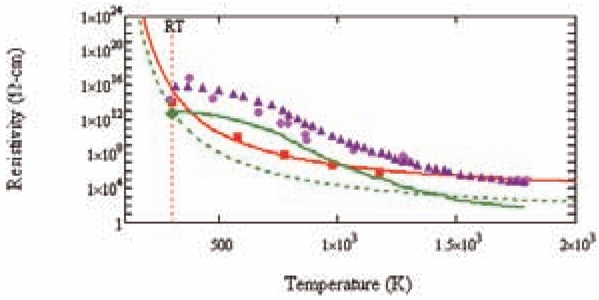



$$\sigma_{RIC}(T,D) = k_{RIC}(T)\cdot D^{\Delta(T)}$$

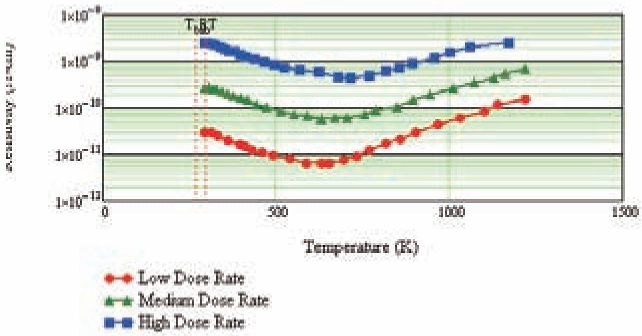


# Combined Temperature and Dose Effects

**Dark Conductivity vs T**




**RIC vs T**




**Dark Conductivity**

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

**RIC**

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

**Dielectric Constant**

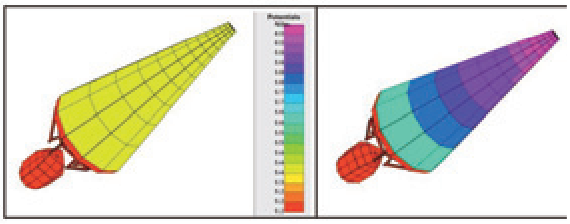
$$\varepsilon_r(T) = \varepsilon_{RT} + \Delta_\varepsilon (T - 298\,K)$$

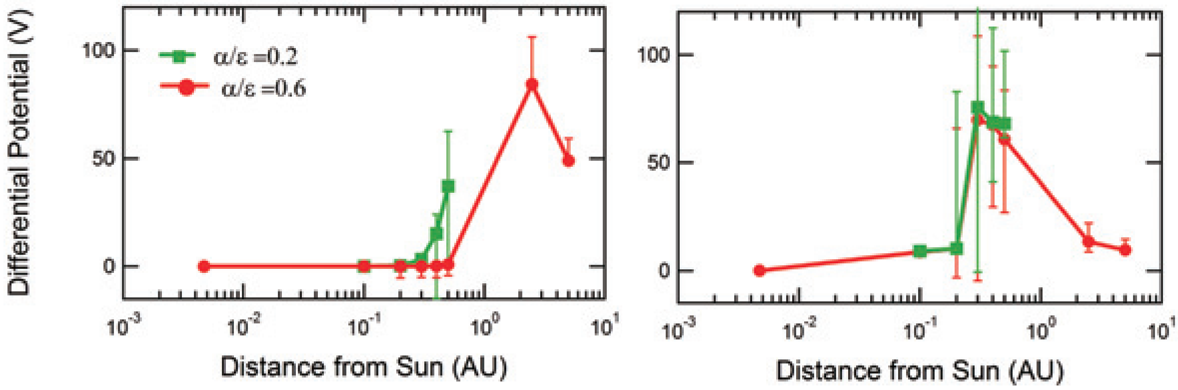
**Electrostatic Breakdown**

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

## Charging Results: Temperature and Dose Effects

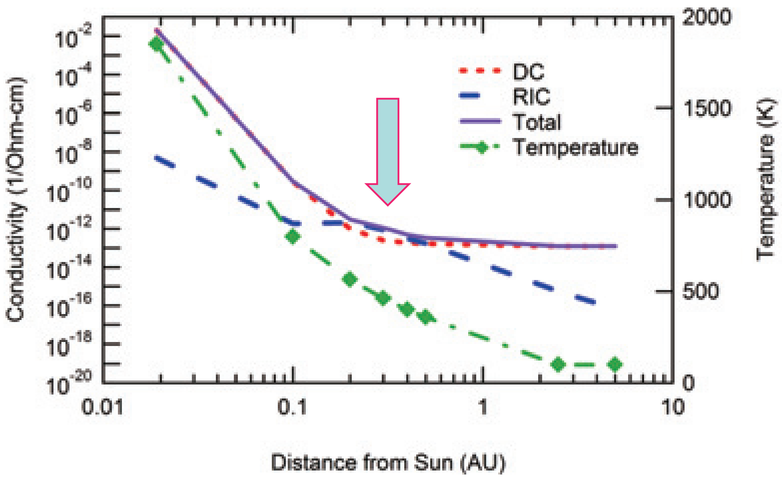
**Modeling found a peak in charging at ~0.3 to 2 AU**








## Explanation of the Temperature and Dose Effects




### General Trends

*Dose rate decreases as ~$r^{2}$*

*T decreases as ~$e^{r}$*

*$\sigma_{DC}$ decreases as ~ $e^{-1/T}$*

*$\sigma_{RIC}$ decreases as ~ $e^{-1/T}$ and decreases as ~$r^{2}$*

### A fascinating trade-off

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

## Case Study Three

# Electron Transport Measurements and Spacecraft Charging

**Unexpected consequences from unexpected sources**

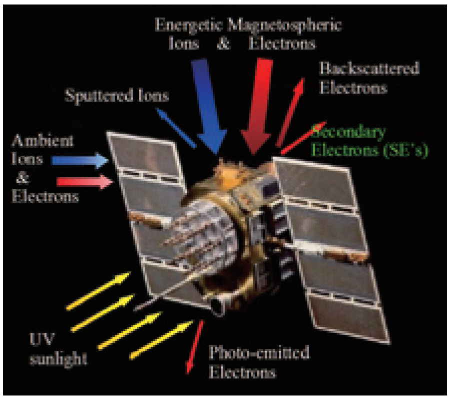


## Spacecraft Interactions with Space Plasma Environment

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

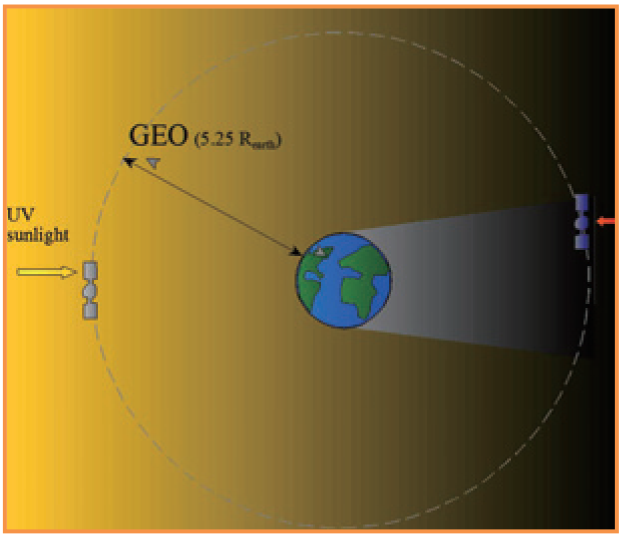
- *Incident fluxes and electron emission govern amount of charge accumulation*
- *Resistivity governs:*
  - *Where charge will accumulate*
  - *How charge will redistribute across spacecraft*
  - *Time scale for charge transport and dissipation*
- Conservation of charge implies:

$$Q_{net} = \{Q_{Incident} - Q_{Emitted}\}$$




*Incident and Emitted Currents that Result in Spacecraft Charging*

# Orbit Time and Charge Decay Time




Typical orbits from 1 to 24 hours.

Treating thin film insulator as simple capacitor, charge decay time proportional to resistivity.

$$\tau = \rho \varepsilon_r \varepsilon_0$$

1 hr → ρ•εo ~4•10$^{16}$ Ω-cm

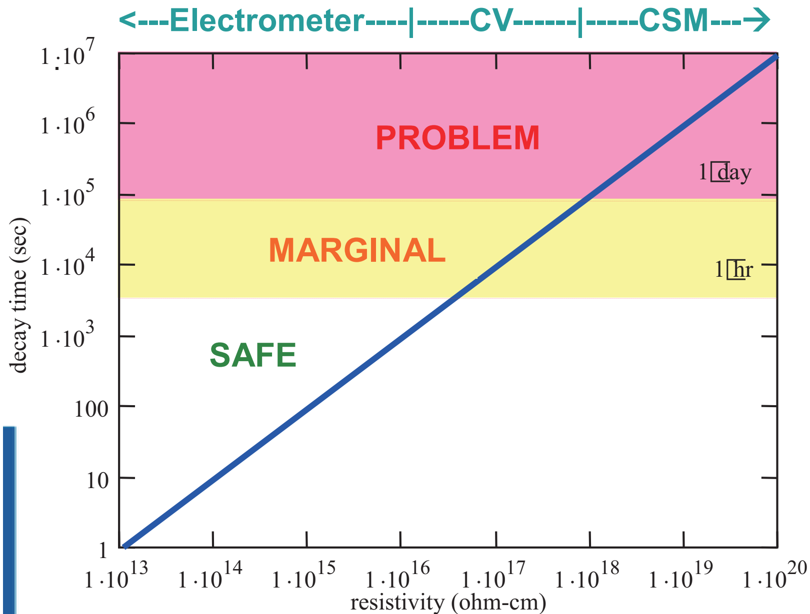
1 day → ρ•εo ~1•10$^{18}$ Ω-cm

1 yr → ρ•εo ~4•10$^{20}$ Ω-cm

10 yr → ρ•εo ~4•10$^{21}$ Ω-cm



# Critical Time Scales and Resistivites




Range of
Charge Storage Method

1 min → ρ•ε$_o$ ~1•10$^{15}$ Ω-cm

1 hr → ρ•εo ~4•1016 Ω-cm

1 day → ρ•ε$_o$ ~1•10$^{18}$ Ω-cm

1 yr → ρ•ε$_o$ ~4•10$^{20}$ Ω-cm

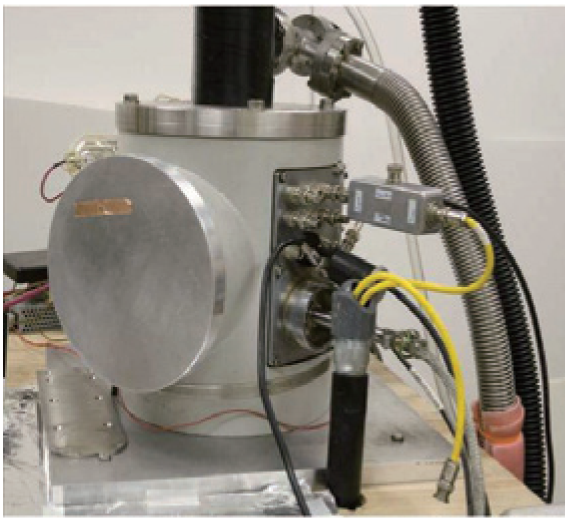
10 yr → ρ•ε$_o$ ~4•10$^{21}$ Ω-cm

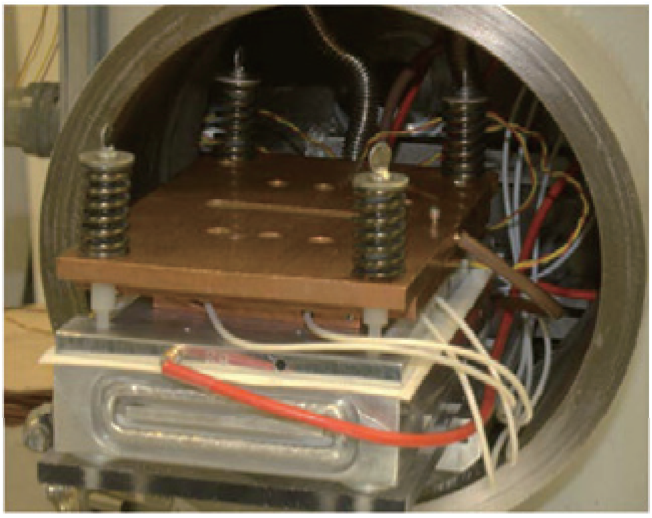
500 yr → ρ•εo ~1•10$^{23}$ Ω-cm

Decay time vs. resistivity base on simple capacitor model.

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

# Extremely Low Conductivity





**Constant Voltage Conductivity**

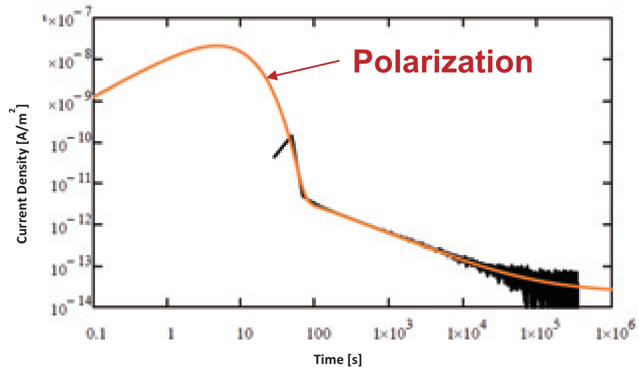
- Time evolution of conductivity
- $<10^{-1}$ s to $>10^{6}$ s
- ±200 aA resolution
- $>5 \cdot 10^{22}$ Ω-cm
- ~100 K <T< 375 K

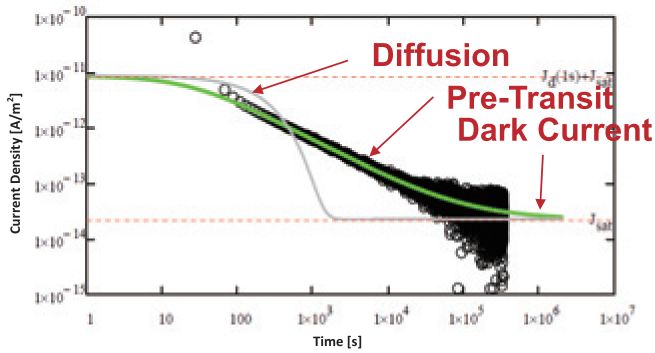
34

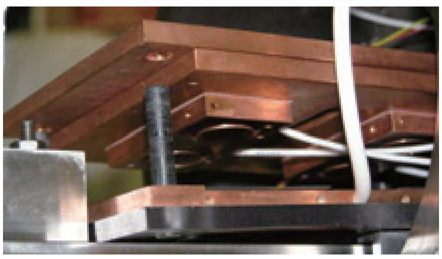


# Constant Voltage Conductivity

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



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# Conductivity vs Time

$$\sigma(t)=\sigma_{DC}\left[1+\frac{\sigma_{AC}(\nu)}{\sigma_{DC}}+\frac{\sigma^{o}_{pol}}{\sigma_{DC}}e^{\frac{-t}{\tau_{pol}}}+\frac{\sigma^{o}_{diffusion}}{\sigma_{DC}}t^{-1}+\frac{\sigma^{o}_{dispersive}}{\sigma_{DC}}t^{-(1-\alpha)}+\frac{\sigma^{o}_{transit}}{\sigma_{DC}}t^{-(1+\alpha)}+\frac{\sigma^{o}_{RIC}}{\sigma_{DC}}\left(1-e^{-\tau^{1}_{RIC}/(t-t_{on})}\right)\left(1+(t-t_{off})/\tau^{2}_{RIC}\right)^{-1}\right]$$

Dark Current, AC, Polarization, Diffusion, Pre-Transit, Post-Transit, RIC, RIC Rise, Persistent RIC

- **Dark current or drift conduction—Defect density, $N_T$, and $E_d$≈1.08 eV**
- **Diffusion-like and dispersive conductivity—Energy width of trap distribution, α**
- **Radiation induced conductivity—Shallow trap density and $\varepsilon_{ST}$**
- **Polarization—Rearrangement of bound charge, $\epsilon_r^{\infty}\epsilon_o$ and $\tau_{pol}$**
- **AC conduction—Dielectric response, $\epsilon_r(\nu)\epsilon_o$**

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# Conductivity vs Time

$$\sigma(t)=\sigma_{DC}\left[1+\frac{\sigma_{AC}(\nu)}{\sigma_{DC}}+\frac{\sigma^{o}_{pol}}{\sigma_{DC}}e^{\frac{-t}{\tau_{pol}}}+\frac{\sigma^{o}_{diffusion}}{\sigma_{DC}}t^{-1}+\frac{\sigma^{o}_{dispersive}}{\sigma_{DC}}t^{-(1-\alpha)}+\frac{\sigma^{o}_{transit}}{\sigma_{DC}}t^{-(1+\alpha)}+\frac{\sigma^{o}_{RIC}}{\sigma_{DC}}\left(1-e^{-\tau^{1}_{RIC}/(t-t_{on})}\right)\left(1+(t-t_{off})/\tau^{2}_{RIC}\right)^{-1}\right]$$

Dark Current, AC, Polarization, Diffusion, Pre-Transit, Post-Transit, RIC, RIC Rise, Persistent RIC

- $\sigma_{DC}\equiv q_e n_e \mu_e$ **dark current or drift conduction—very long time scale equilibrium conductivity.**
- $\sigma_{AC}(\nu)\equiv\sum_i\left[\left(\epsilon_r(\nu)-\epsilon_r^{o}\right)\epsilon_o\frac{1}{1+(\nu/\nu_i)^2}\right]$
  **frequency-dependant AC conduction—dielectric response to a periodic applied electric field**
- $\sigma_{pol}(t)\equiv\left[(\epsilon_r^{\infty}-\epsilon_r^{o})\epsilon_o/\tau_{pol}\right]\cdot e^{\frac{-t}{\tau_{pol}}}$ **long time exponentially decaying conduction due to polarization**
- $\sigma_{diffusion}(t)\equiv\sigma^{o}_{diffusion}\cdot t^{-1}$
  **diffusion-like conductivity from gradient of space charge spatial distribution.**
- $\sigma_{dispersive}(t)\equiv\begin{cases}\sigma^{o}_{dispersive}\cdot t^{-(1-\alpha)} & ;(\text{for } t<\tau_{transit})\\ \sigma_{transit}(t)\equiv\sigma^{o}_{transit}\cdot t^{-(1+\alpha)} & ;(\text{for } t>\tau_{transit})\end{cases}$ **broadening of spatial distribution of space charge through coupling with energy distribution of trap states.**
- $\sigma_{RIC}(t;\dot{D},\tau^{1}_{RIC},\tau^{2}_{RIC})\equiv\sigma^{o}_{RIC}(\dot{D}(t))\left(1-e^{-\tau^{1}_{RIC}/(t-t_{on})}\right)\left(1+(t-t_{off})/\tau^{2}_{RIC}\right)^{-1}$
  **radiation induced conductivity term resulting from energy deposition within the material.**

Refer to (Wintle, 1983), (Dennison *et al.*, 2009), and (Sim, 2012)

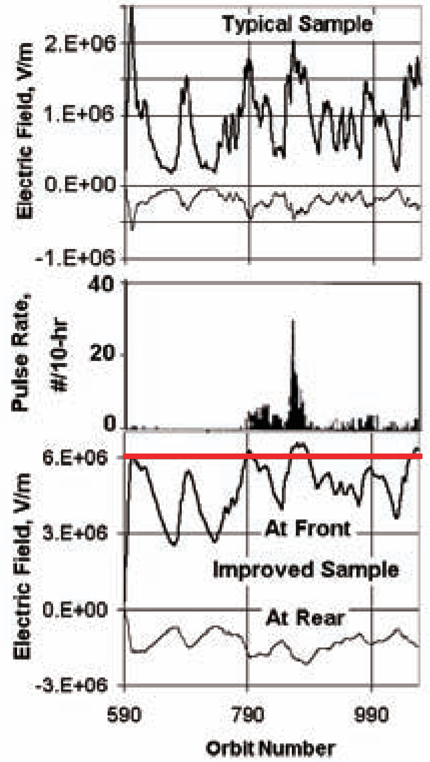
# Application to CRESS IDM Pulse Data

## *CRRES IDM Pulse and Environmental Data*

A. Robb Frederickson & Donald H. Brautigam

- Characterize electron flux data
- Model charge profile from dose rate and stopping power
- Calculate internal electric field
- Model transport with measured resistivity
- Predict pulsing rate and amplitude with only environment data, materials parameters, and Maxwell equations !!!

| Dark Conductivity | Radiation-Induced Conductivity |
|---|---|
| typical =5x10$^{-18}$ (Ω-m)$^{-1}$ | typical = 0.3x 10$^{-18}$ (Ω-m)$^{-1}$ |
| improved 5x10$^{-19}$ (Ω-m)$^{-1}$ | "improved" same as typical |
| best guess 1.7x10$^{-19}$ (Ω-m)$^{-1}$ | best guess same as typical |



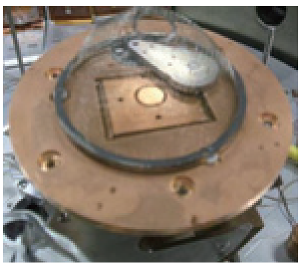


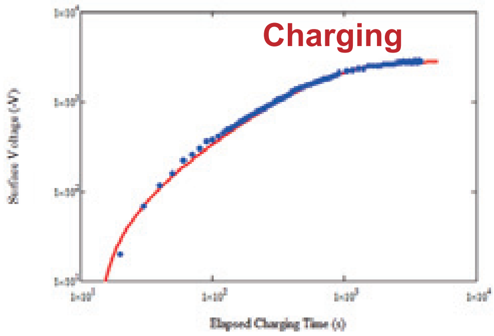

# Surface Voltage Charging and Discharging

- Uses pulsed non-penetrating electron beam injection with no bias electrode injection.
- Fits to exclude AC, polarization, transit and RIC conduction.

- **Yields $N_T$, $E_d$, $\alpha$, $\varepsilon_{ST}$**

**Instrumentation**






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

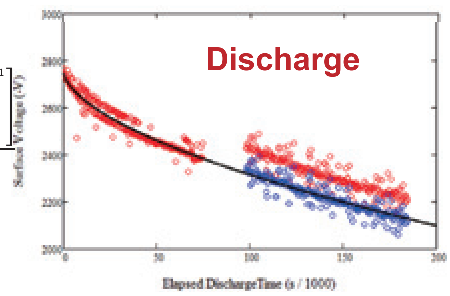
**Charging**

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

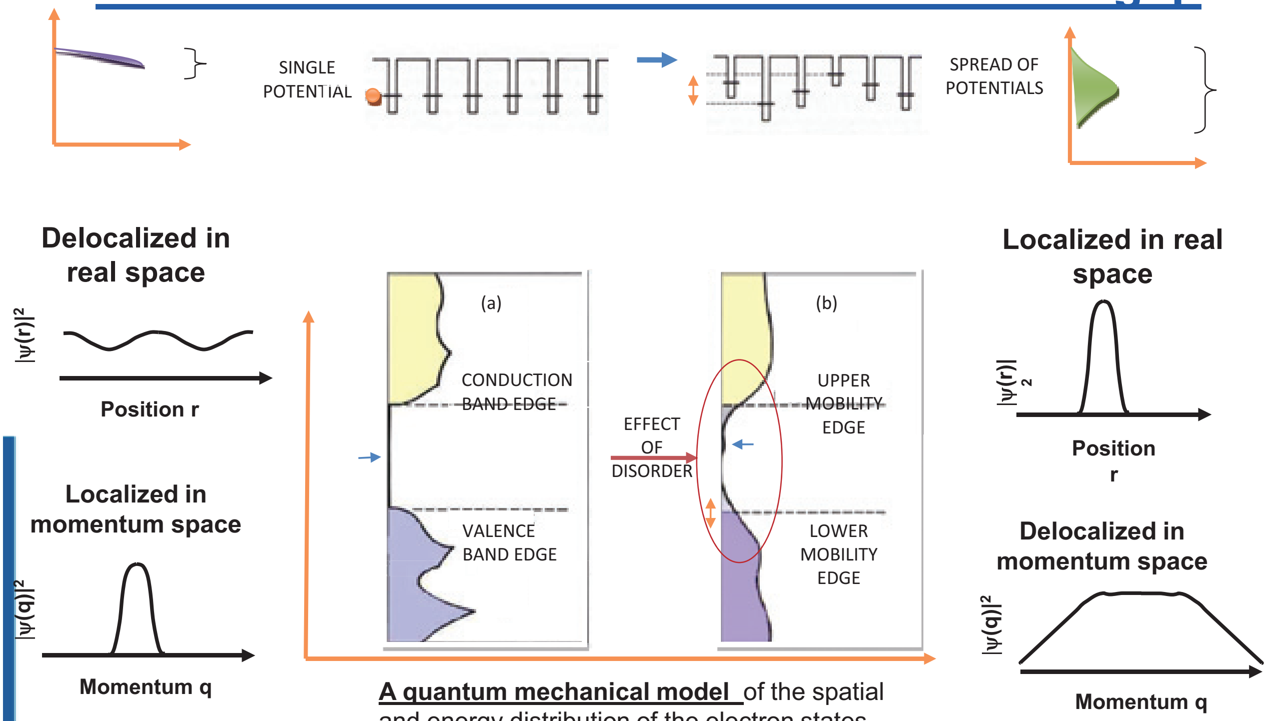
**Discharge**

$$V(t)=V_o\,e^{-t\sigma(t)/\epsilon_o\epsilon_r}$$

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



# Disorder introduces localized states in the gap




**A quantum mechanical model** of the spatial and energy distribution of the electron states



# Tunneling Between Traps—and Mott Anderson Transitions

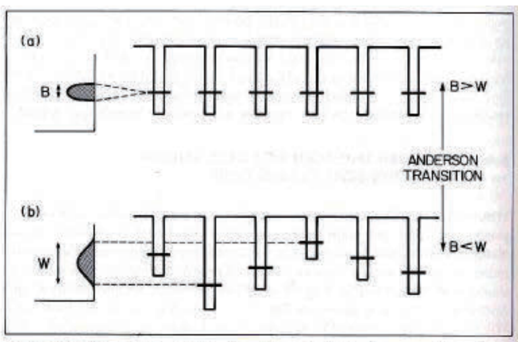



Figure 5.13 One-electron tight-binding picture for the Anderson transition. When the width *W* of the disorder exceeds the overlap bandwidth *B*, disorder-induced localization takes place.

Anderson transition between extended Bloch states and localized states caused by variations in well depth affects tunneling between states.

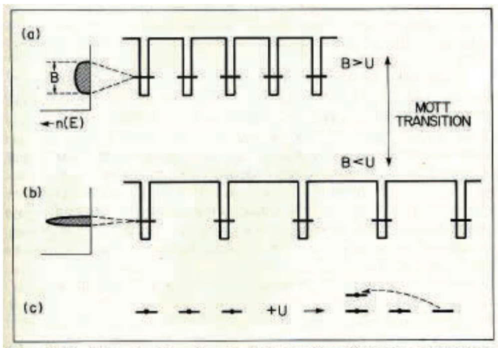


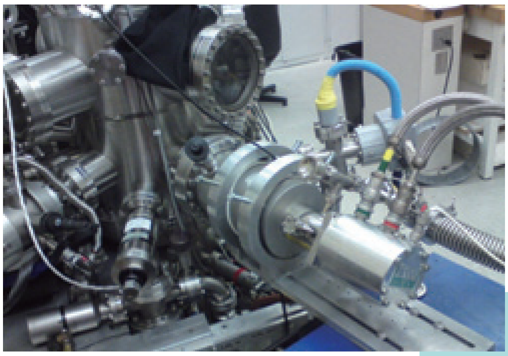

Figure 5.12 Schematic picture for the Mott transition. When the electron bandwidth *B* is decreased (by increased atom–atom separation) sufficiently to be smaller than the intrasite electron–electron energy *U*, correlation-induced localization takes place.

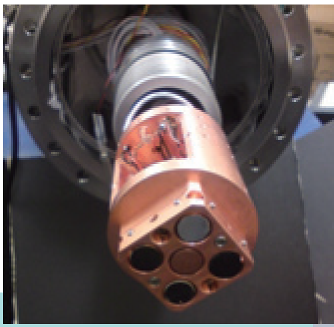
Mott transition between extended Bloch states and localized states caused by variations in well spacing which affects tunneling between states.

R. Zallen, *The Physics of Amorphous Solids*, (John Wiley and Sons, Inc. 1983).

**Nobel Prize 1977 to Sir Nevill Mott and P.W. Anderson, *Electronic Structure of Disordered Systems***

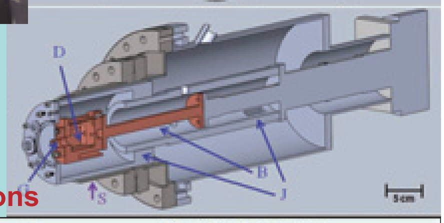
# Low Temperature Cryostat





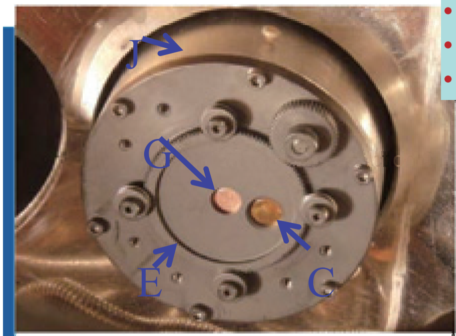
**Used with:**

- Constant Voltage Cond.
- RIC
- SEE/BSE
- Cathodoluminescence
- Arcing
- Surface Voltage Probe




**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

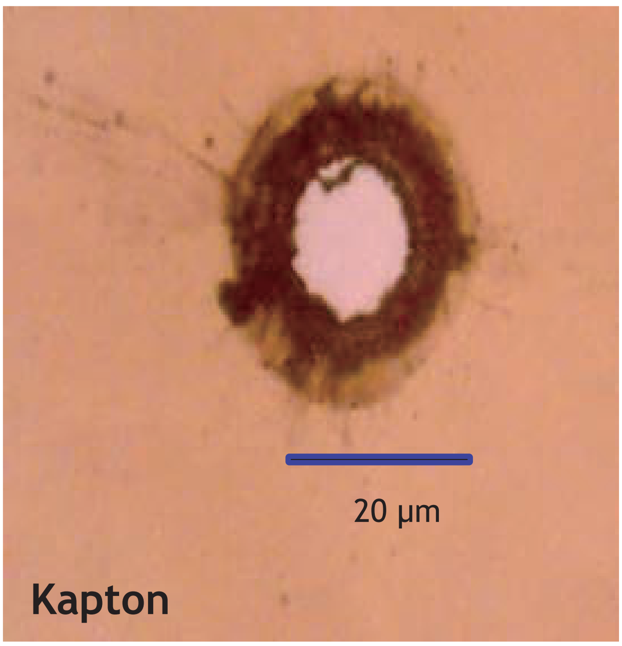
**Analysis Components**
K UV/Vis/NIR Reflectivity Spectrometers
L CCD Video Camera (400-900 nm)
M InGaAs Video Camera (800-1200 nm)
N InSb Video Camera (1000-5000 nm)
O SLR CCD Camera (300-800 nm)
P Fiber Optic Discrete Detectors
Q Collection Optics

**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



# ESD: Limit of Conductivity at High Fields

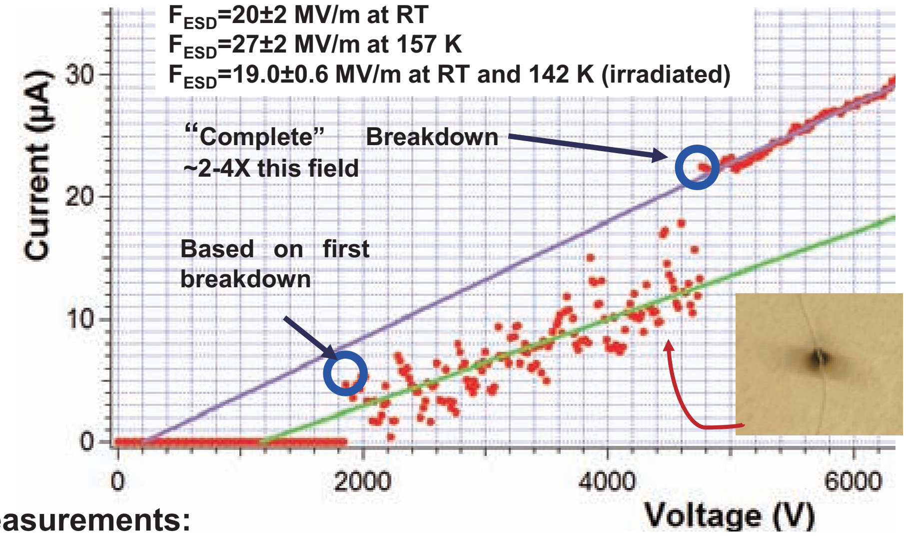
# $F_{ESD}$ Breakdown: Dual (Shallow and Deep) Defect Model

**Yields:**

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

**Separate these with T dependence**

**$\Delta G_{def}$ =0.97 eV**
**$N_T$=1·10$^{17}$ cm$^{-3}$**




**Breakdown field measurements:**

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

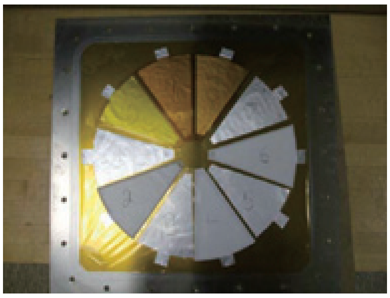
**Endurance time measurements:**

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

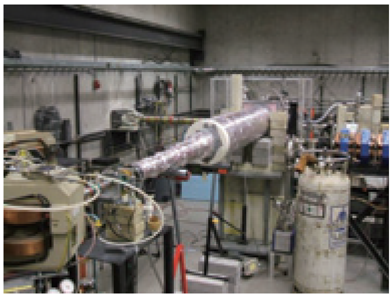


# Radiation Induced Conductivity Measurements

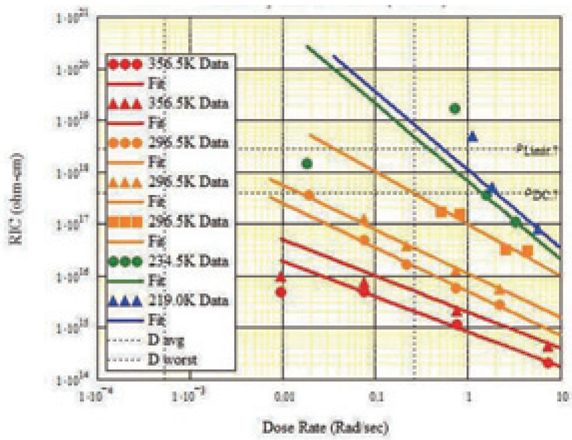
**RIC chamber uses a combination of charge injected by a biased surface electrode with simultaneous injection by a pulsed penetrating electron.**

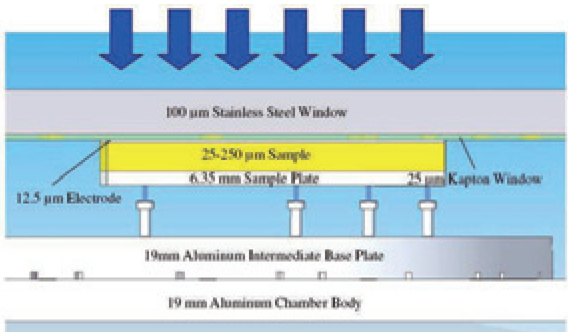


Top view of samples on window



RIC Chamber



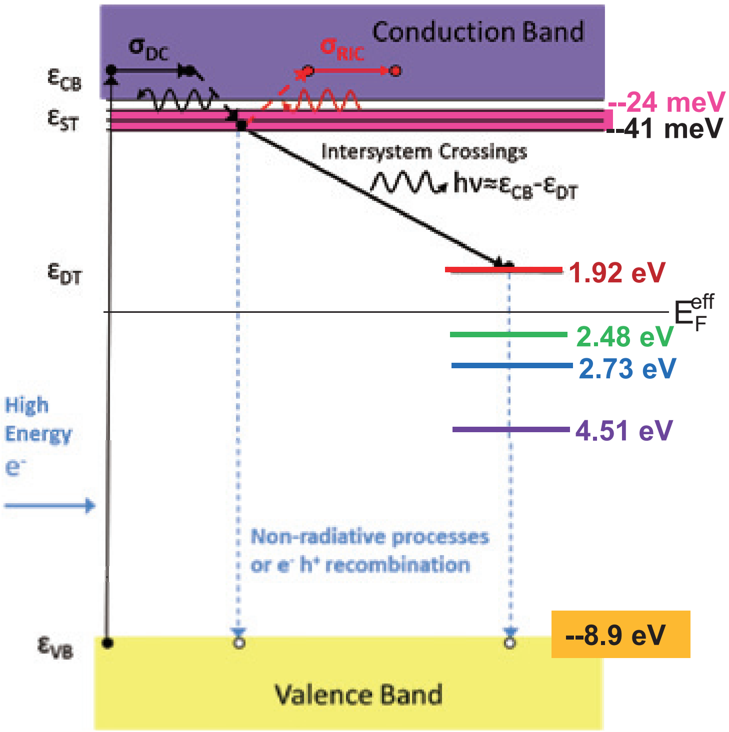

Sample stack cross section

# Complementary Responses to Radiation

## Modified Joblonski diagram

- VB electrons excited into CB by the high energy incident electron radiation.
- They relax into shallow trap (ST) states, then thermalize into lower available long-lived ST.
- Three paths are possible:

(i) relaxation to deep traps (DT), with concomitant photon emission;
(ii) radiation induced conductivity (RIC), with thermal re-excitation into the CB; or
(iii) non-radiative transitions or e⁻-h⁺ recombination into VB holes.





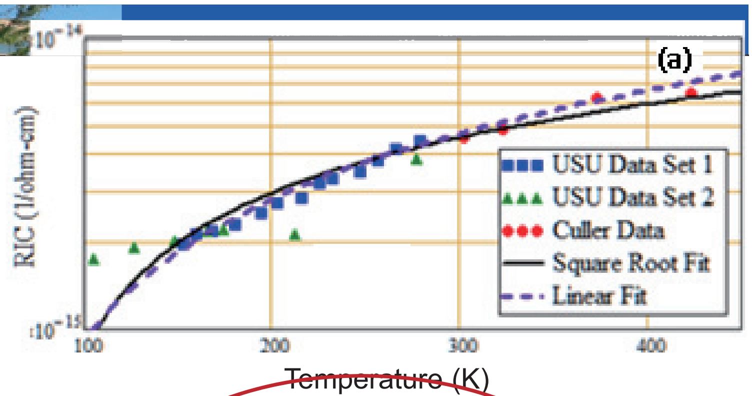


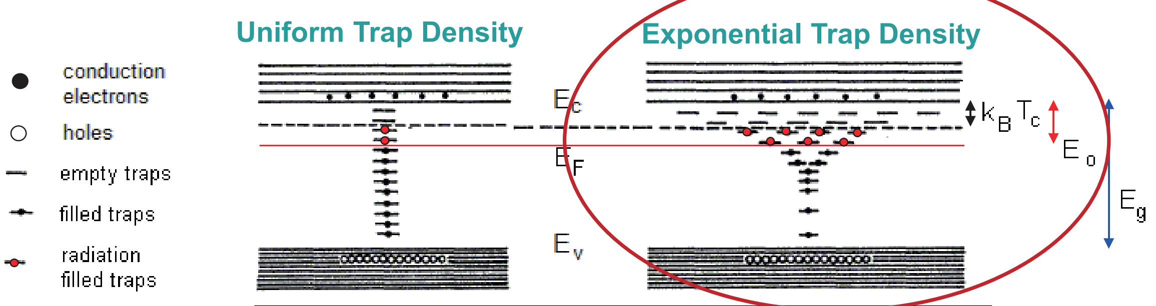

# RIC T-Dependence

**Shallow Trap DOS Profile**
**Exponential DOS Below $E_c$**

**Effective Fermi Level**

**$E_F^{eff}$ = 24 meV**




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

$$\Delta(T)\rightarrow 1 \qquad \Delta(T)\rightarrow \frac{T_c}{T+T_c}$$

$$k(T)\rightarrow k_{RICo} \qquad k(T)\rightarrow k_{RIC1}\left[2\left(\frac{m_e k_B T}{2\pi\hbar^2}\right)^{3/2}\left(\frac{m_e^* m_h^*}{m_e m_e}\right)^{3/4}\right]^{\frac{T}{T+T_c}}$$

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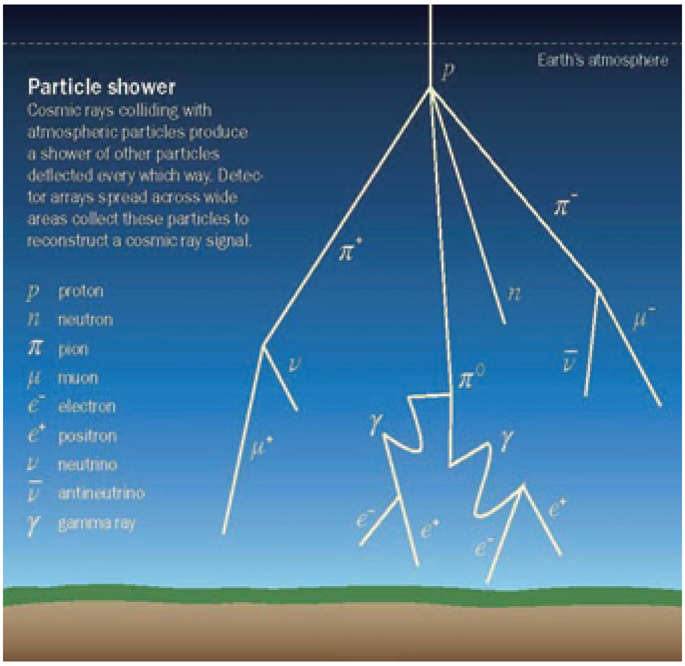
# RIC Sets a Limit for Conductivity Measurements




Decay of cosmic rays into muons [Drake 2012]

High energy cosmic rays interacting with the upper atmosphere decay into Muons that are present at the surface. Due to interactions with the atmosphere, they have a decay rate that is proportional to the altitude. With this correlation we were able to determine counts per minute on the order of ~1/hour in Logan Utah (altitude 1370 m). Fig. 2 also shows and angle dependence though the muon's decay.

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## Case Study Four

# Electron Induced Arcing and Unexpected Consequences

**"JR, could you come downstairs to the lab for a minute?"**

# Case Four: JWST—Electron-Induced Arcing

## JWST

**Very Low Temperature**
Virtually all insulators go to infinite resistance—perfect charge integrators

***Long Mission Lifetime (10-20 yr)***
No repairs
Very long integration times

***Large Sunshield***
Large areas
Constant eclipse with no photoemission

***Large Open Structure***
Large fluxes
Minimal shielding

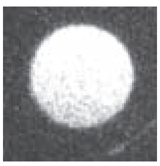
**Variation in Flux**
Large solar activity variations
In and out of magnetotail

***Complex, Sensitive Hardware***
Large sensitive optics
Complex, cold electronics

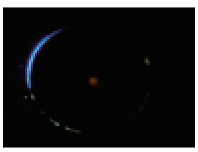


# Diversity of Emission Phenomena in Time Domain

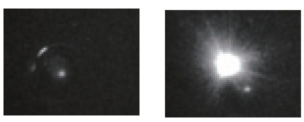
| Ball Black Kapton<br>Runs 131 and 131A | 22 keV<br>135 K | 110 or 4100 uW/cm$^2$<br>5 or 188 nA/cm$^2$ |
|---|---|---|



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

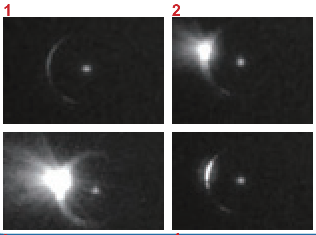


**Edge Glow**
Similar to Surface Glow, but present only at sample edge



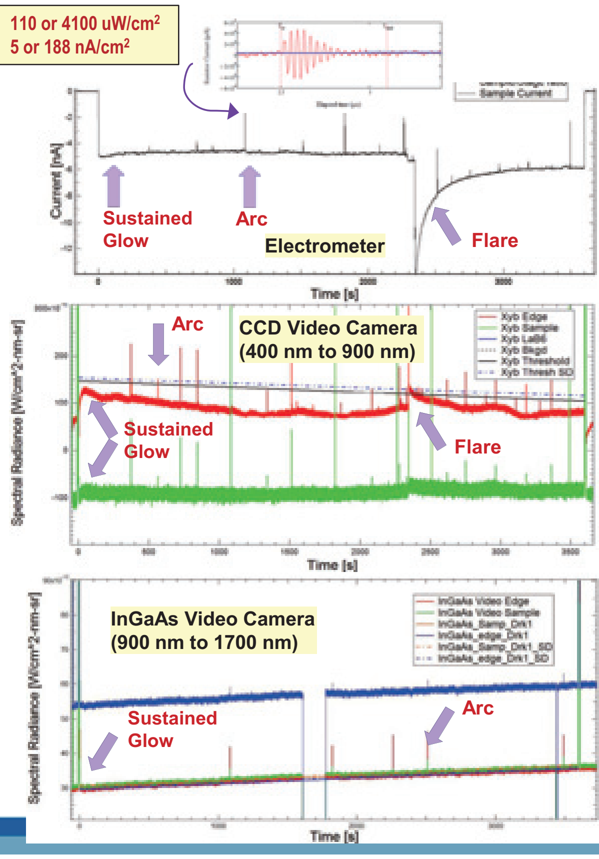
1 2

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

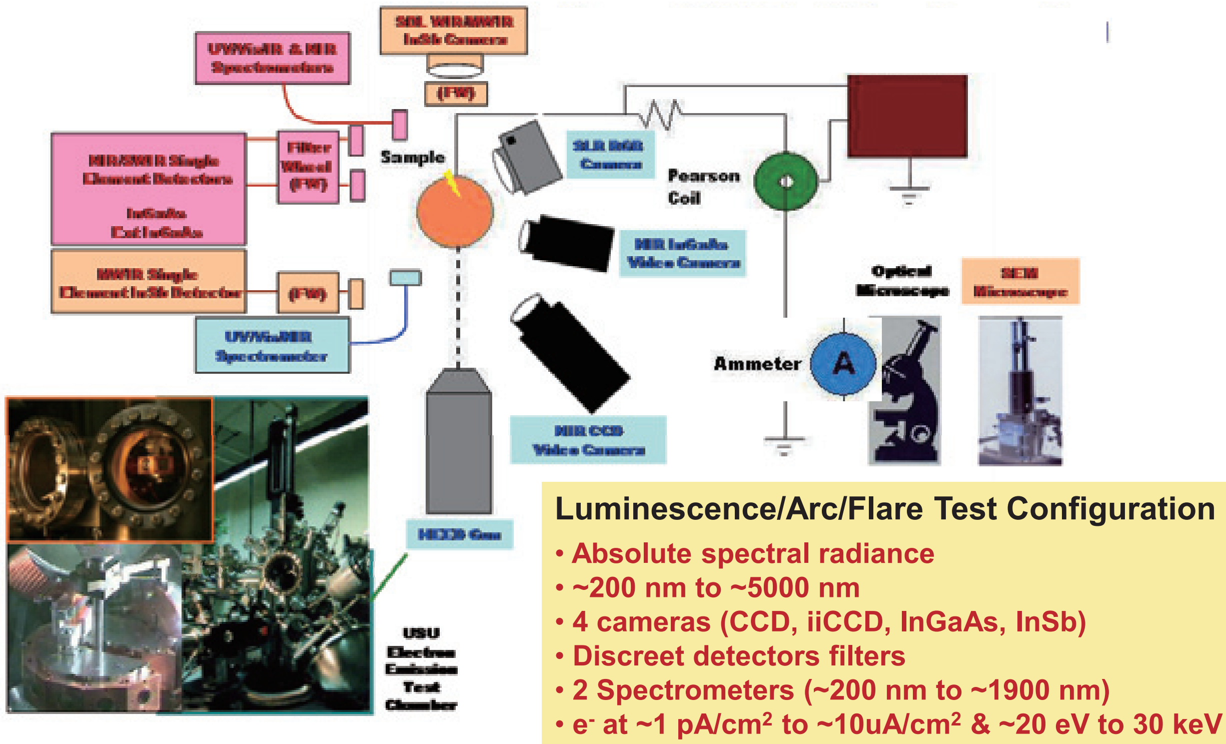


1 2 3 4

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



# Photon Emission Measurements




**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$^2$ & ~20 eV to 30 keV
- 35 K< T< 350 K
- Multiple sample configurations to ~10x10cm



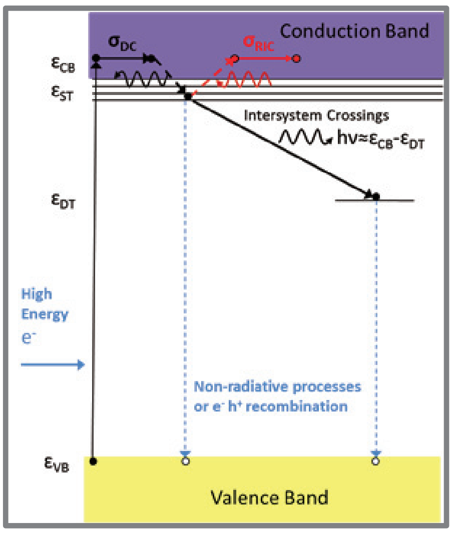
# Cathodoluminescence—Deep and Shallow Trap DOS

**Cathodoluminescence intensity (α emitted power)**

$$I_\gamma(J_b,E_b,T,\lambda) \propto \frac{\dot{D}(J_b,E_b)}{\dot{D}+\dot{D}_{sat}}\{[e^{-(\varepsilon_{ST}/k_BT)}][1-e^{-(\varepsilon_{ST}/k_BT)}]\}$$

**Dose rate (α adsorbed power)**

$$\dot{D}(J_b,E_b) = \frac{E_b J_b[1-\eta(E_b)]}{q_e\rho_m} \times \begin{cases} [1/L] & ; R(E_b) < L \\ [1/R(E_b)] & ; R(E_b) > L \end{cases}$$

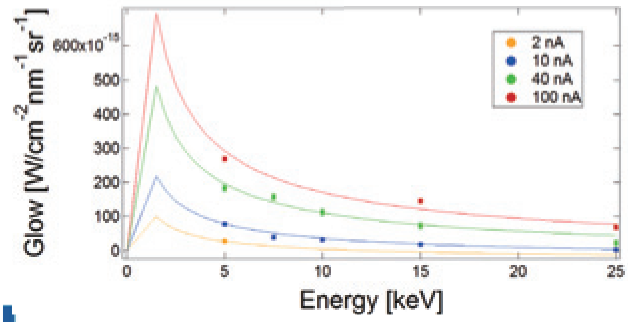



$J_b$: incident current density T: temperature
$E_b$: incident beam energy λ: photon wavelength
$q_e$: electron charge $\rho_m$: mass density
$\varepsilon_{ST}$: shallow trap energy $R(E_b)$: penetration range
$D_{sat}$: saturation dose rate L: Sample thickness

# Cathodoluminescence—$E_b$ and Range Dependence

**Incident Beam Energy**

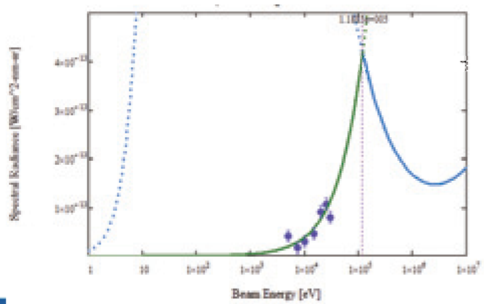
$$\dot{D}(J_b,E_b) = \frac{E_b\, J_b[1-\eta(E_b)]}{q_e \rho_m} \times \begin{cases} [1/L] & ;\ R(E_b) < L \\ [1/R(E_b)] & ;\ R(E_b) > L \end{cases}$$



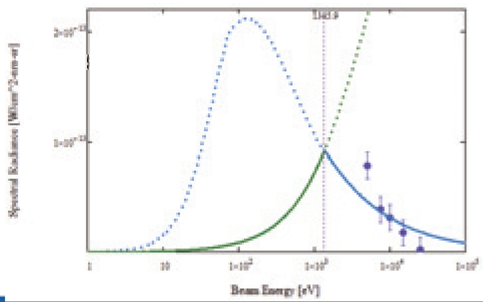

**Nonpenetrating Radiation** {R($E_b$) < L}: all incident power absorbed in coating and intensity and dose rate are linear with incident power density

**Penetrating Radiation** {R($E_b$) > L}: absorbed power reduced by factor of L/R($E_b$).

**Nonpenetrating: Low $E_b$, Thick**




**Penetrating: High $E_b$, Thin**




**Can map R($E_b$) with inflection points**



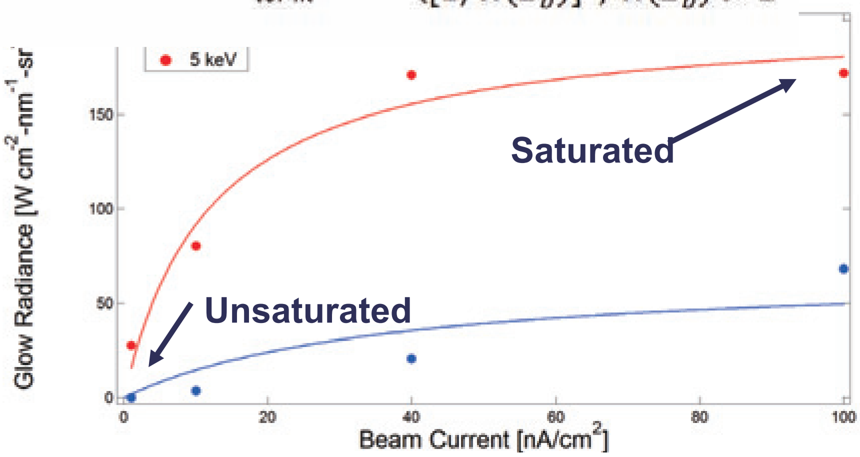
# Cathodoluminescence—$J_b$ and Dose Dependence

**Cathodoluminescence intensity (α emitted power)**

$$I_\gamma(J_b,E_b,T,\lambda) \propto \frac{\dot{D}(J_b,E_b)}{\dot{D}+\dot{D}_{sat}} \{[e^{-(\varepsilon_{ST}/k_B T)}][1-e^{-(\varepsilon_{ST}/k_B T)}]\}$$

**Dose rate (α adsorbed power)**

$$\dot{D}(J_b,E_b) = \frac{E_b\, J_b[1-\eta(E_b)]}{q_e \rho_m} \times \begin{cases} [1/L] & ;\ R(E_b) < L \\ [1/R(E_b)] & ;\ R(E_b) > L \end{cases}$$



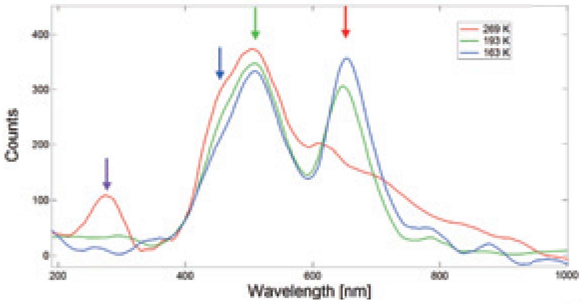

$\dot{D}_{sat}$

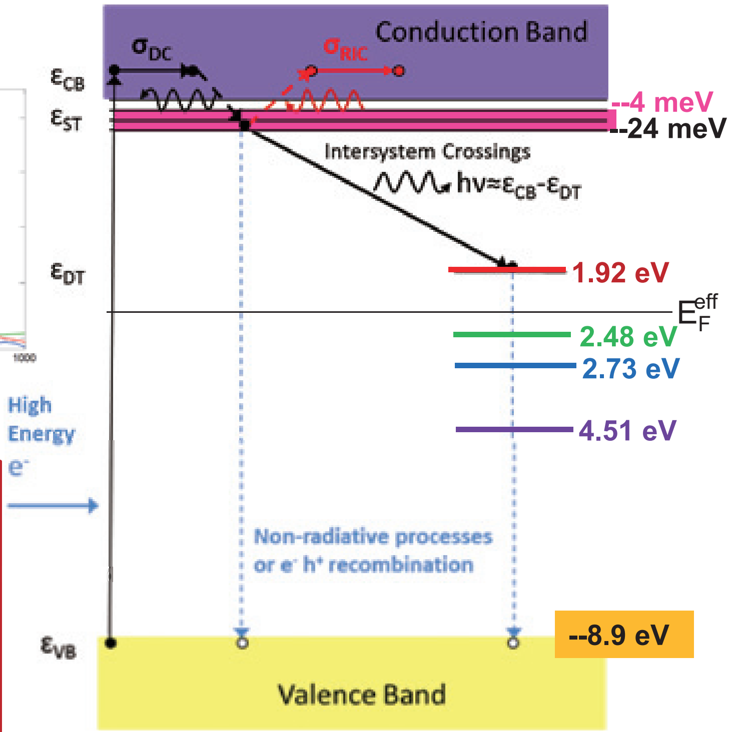
**Measure of charge required to fill traps.**

**~10 Gy/s for $SiO_2$ coatings.**

# Cathodoluminescence Emission Spectra

**Photon Emission Spectra**
**Peak Wavelength**




**Multiple peaks in spectra correspond to multiple DOS distributions**

Peak positions ⇐⇒ Center of DOS
Peak amplitude ⇐⇒ $N_T$
Peak width ⇐⇒ DOS width

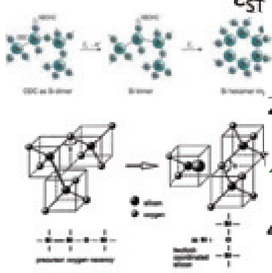


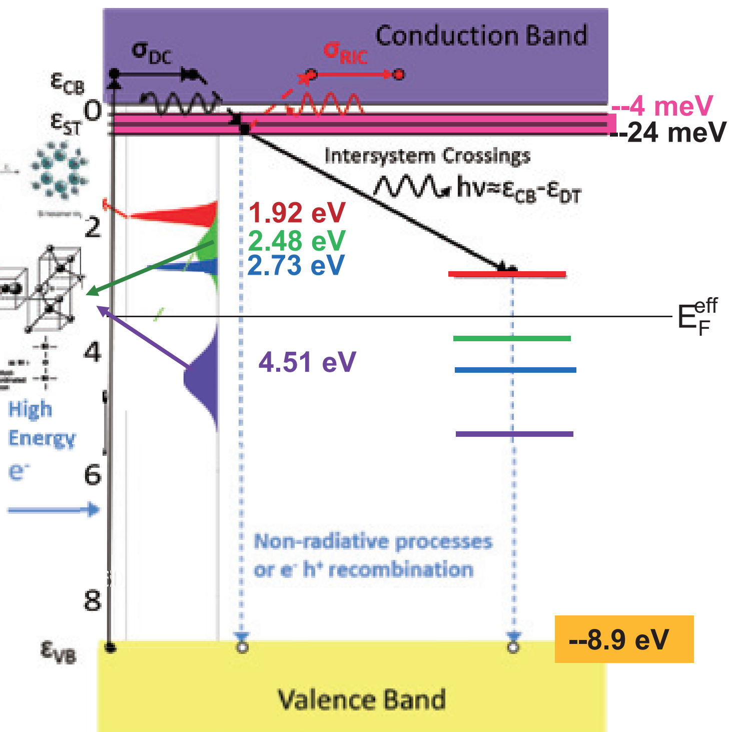
# A Path Forward for Dynamic Materials Issues

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.





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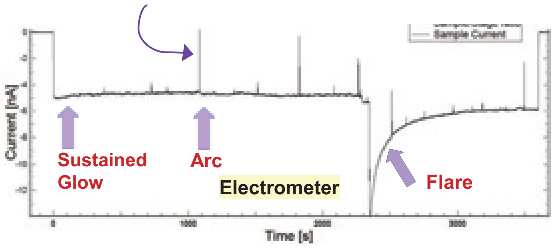
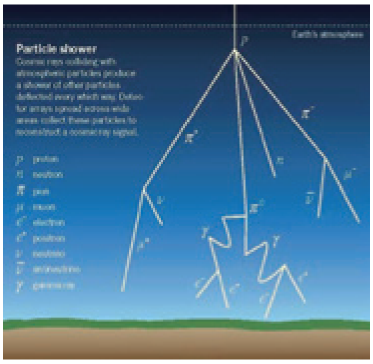
# Does Cosmic Background Radiation Explain "Flares"

**"Flare"**

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

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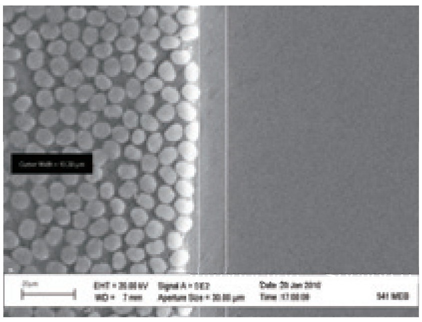
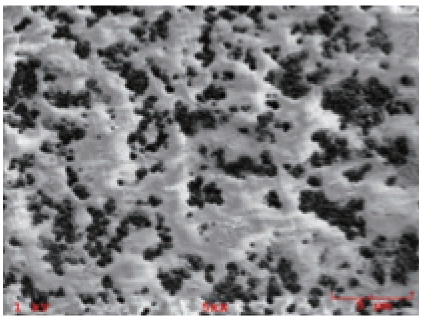
# The Next Case: Multilayer/Nanocomposite Effects???

**Length Scale**
- Nanoscale structure of materials
- Electron penetration depth
- SE escape depth

***Time Scales***
- Deposition times
- Dissipation times
- Mission duration

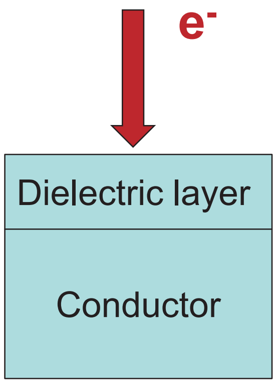


C-fiber composite with thin ~1-10 μm resin surface layer



10 μm

Black Kapton™ (C-loaded PI)




Thin ~100 nm disordered SiO2 dielectric coating on metallic reflector

# Conclusions

- Complex satellites require:
  - Complex materials configurations
  - More power
  - Smaller, more sensitive devices
  - More demanding environments
  - More sophisticated modeling with dynamic materials properties
- There are numerous clear examples where accurate dynamic charging models require accurate dynamic materials properties
- It is not sufficient to use static (BOL or EOL) materials properties
- Enivronment/Materials Modification feedback mechanisms can cause many new and unexpected problems
- Understanding of the microscale structure and transport mechanisms are required to model dynamic materials properties for dynamic spacecraft charging models



# A Truly Daunting Task .

**To address:**

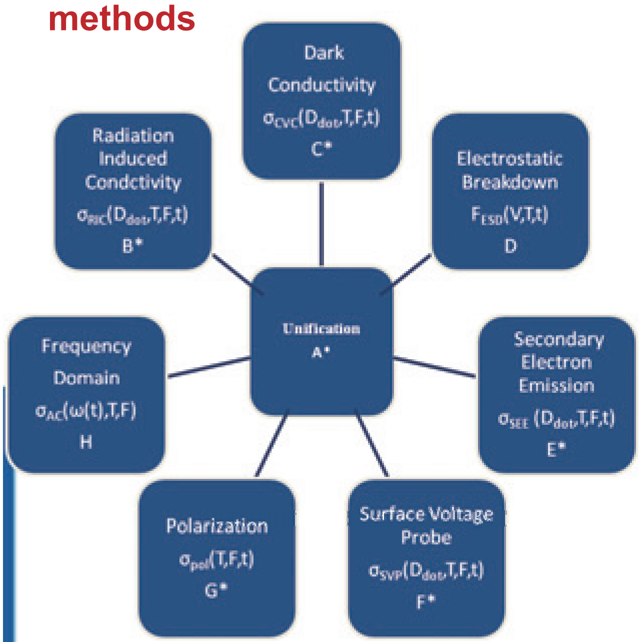
- Myriad spacecraft materials
- New, evolving materials
- Many materials properties
- Wide range of environmental conditions
- Evolving materials properties
- Feedback, with changes in materials properties affecting changes of environment

**Requires:**

- Conscious awareness of dynamic nature of materials properties can be used with available modeling tools to foresee and mitigate many potential spacecraft charging problems
- For dynamic materials issues in spacecraft charging, as with most materials physics problems, synthesis of results from different studies and techniques, and 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.
- Solid State models based on defect DOS provide synergism between methods for more extensive and accurate materials properties.

# A Materials Physics Approach to the Problem

**Measurements with many methods**




**Interrelated through a**

**Complete set of dynamic transport equations**

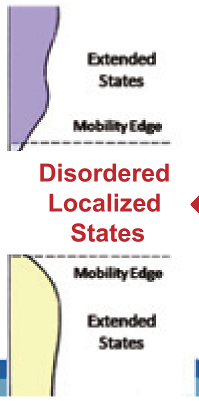
$$J = q_e n_e(z,t)\mu_e F(z,t) + q_e D \frac{dn_{tot}(z,t)}{dz}$$

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

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

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

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




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



# Some Unsolicited Advice for Students
## (and a summary of the talk)

- *Define the problem*
- *Develop useful skills*
  - *Advanced knowledge*
  - *Experimental skills*
  - *Modeling skills to tie these together*
  - *Breadth to recognize important trends*
- *Keep your eyes open!*

*Good luck (and have fun!)*