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

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Utah State Univesity

10th Anniversary Lecture Series

Laboratory of Spacecraft Environment Interaction Engineering

Kyushu Institute of Technology

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

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Physics Department
Utah State University
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Utah State University Materials Physics Group

Logan, Utah

Yellowstone, NP

Tetons, NP

~~Arcs~~ Arches, NP

Grand Canyon, NP

Support & Collaborations

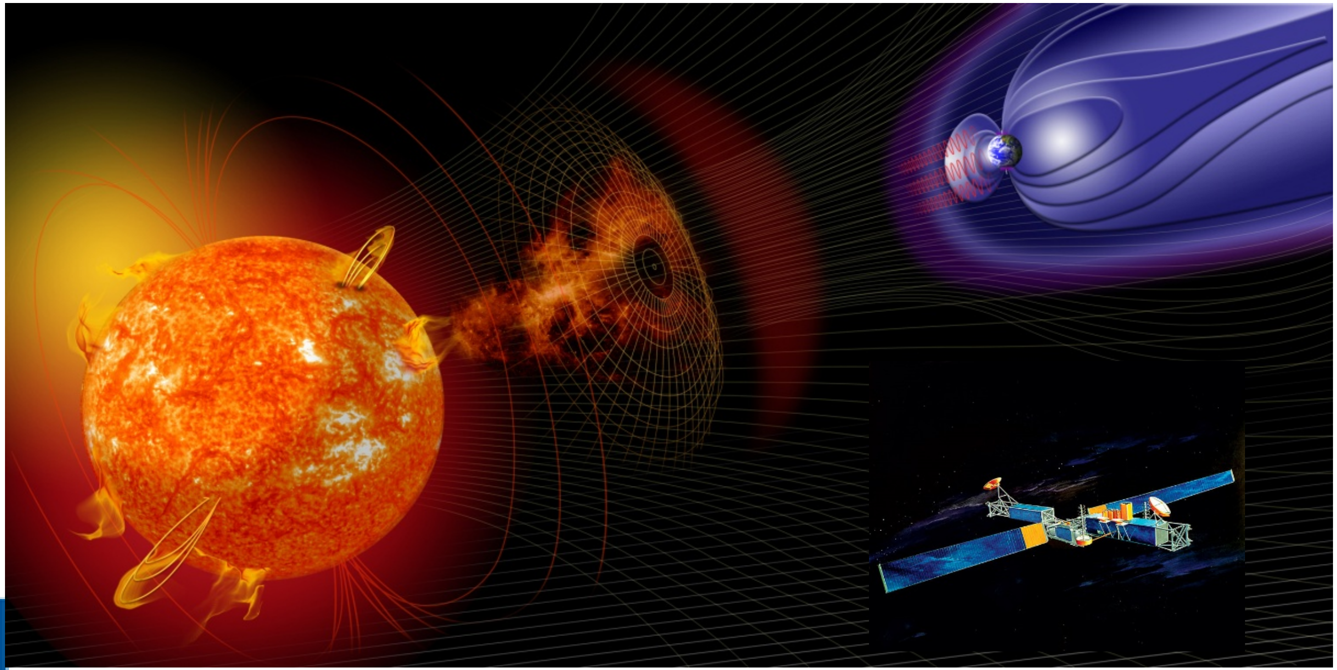
NASA SEE Program
JWST (GSFC/MSFC)
Solar Probe Mission (JHU/APL)
Rad. Belt Space Probe (JHU/APL)
Solar Sails (JPL)
AFRL
Boeing
Box Elder Innovations
Ball Aerospace
Orbital
LAM
USU Blood Fellowship
USU PDRF Fellowships
AFRL/NRC Fellowship
NASA Grad Res. Fellowships

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.

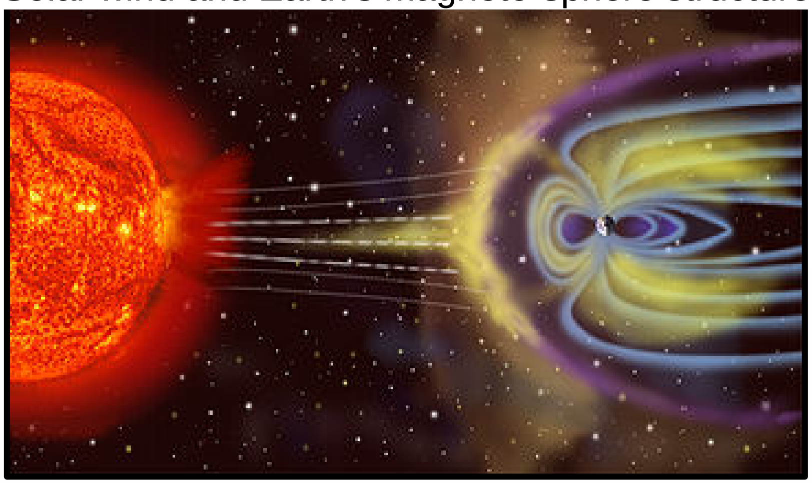
Space environments affect spacecraft and their performance.
How do we quantify these effects and mitigate degradation?

The Space Environment

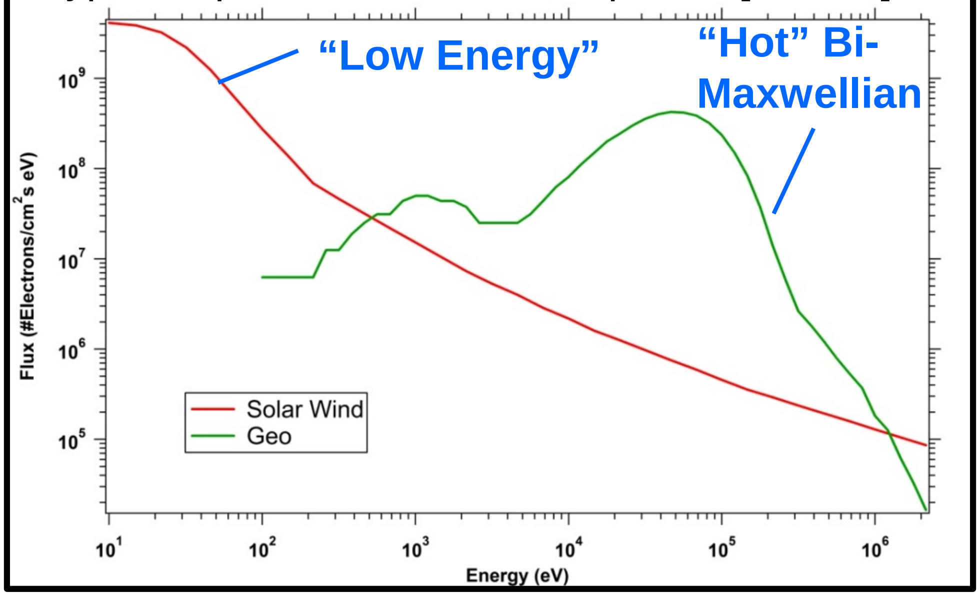
Dynamics of the space environment and satellite motion lead to dynamic spacecraft charging (min to decades)

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

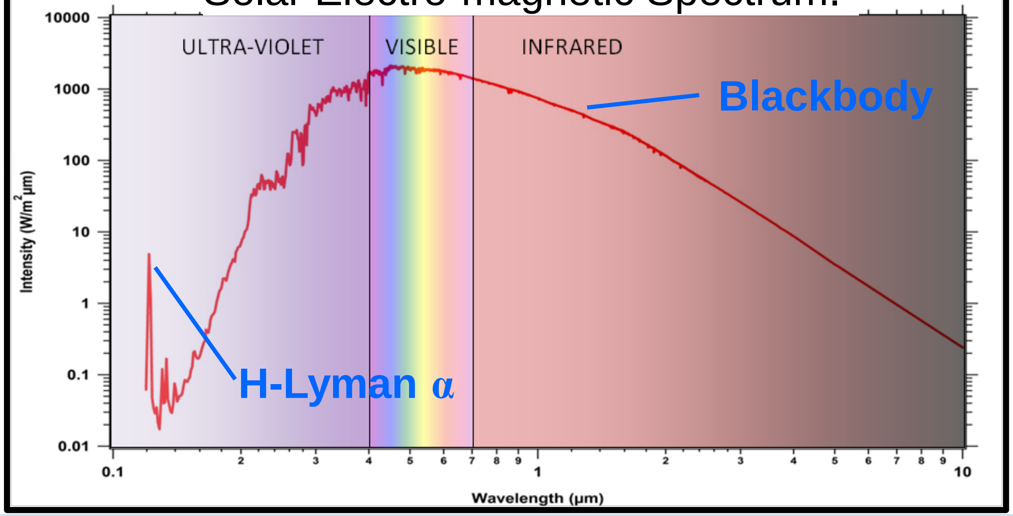
Solar wind and Earth's magneto-sphere structure.



Typical Space Electron Flux Spectra [Larsen].



Solar Electro-magnetic Spectrum.



Incident fluxes of:

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

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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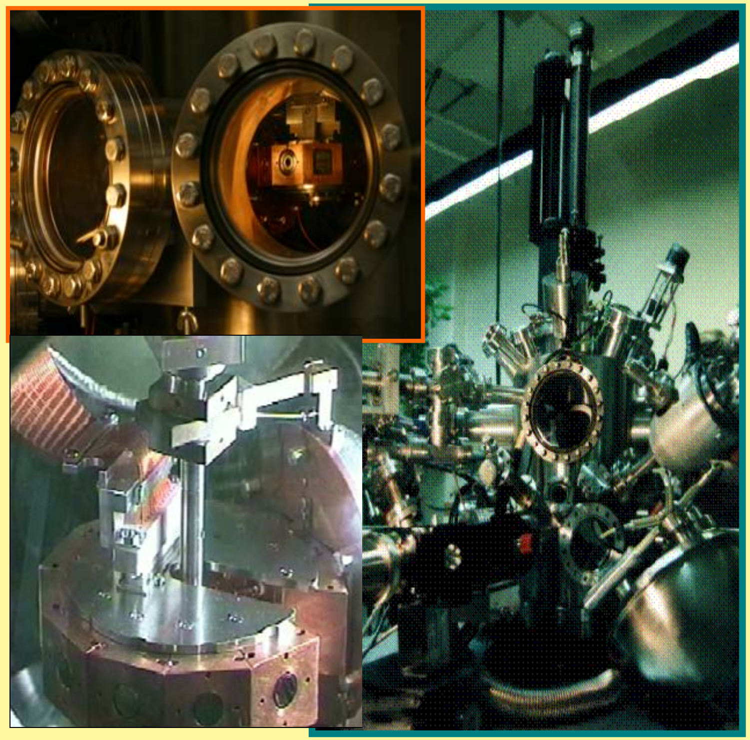
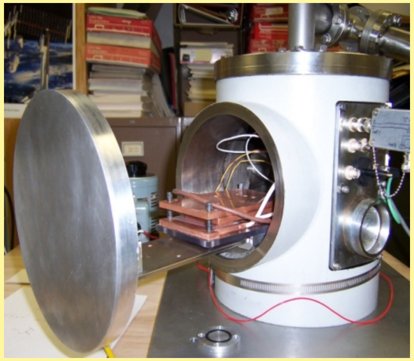
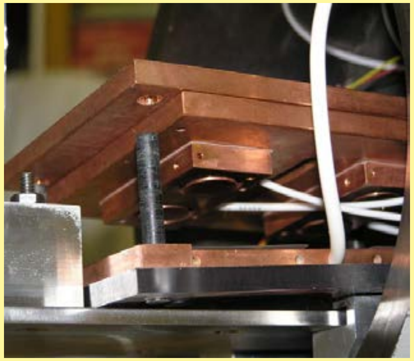






Environment Conditions ↔ Materials Conditions ↔ Materials Properties ↔ Spacecraft Charging

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!*

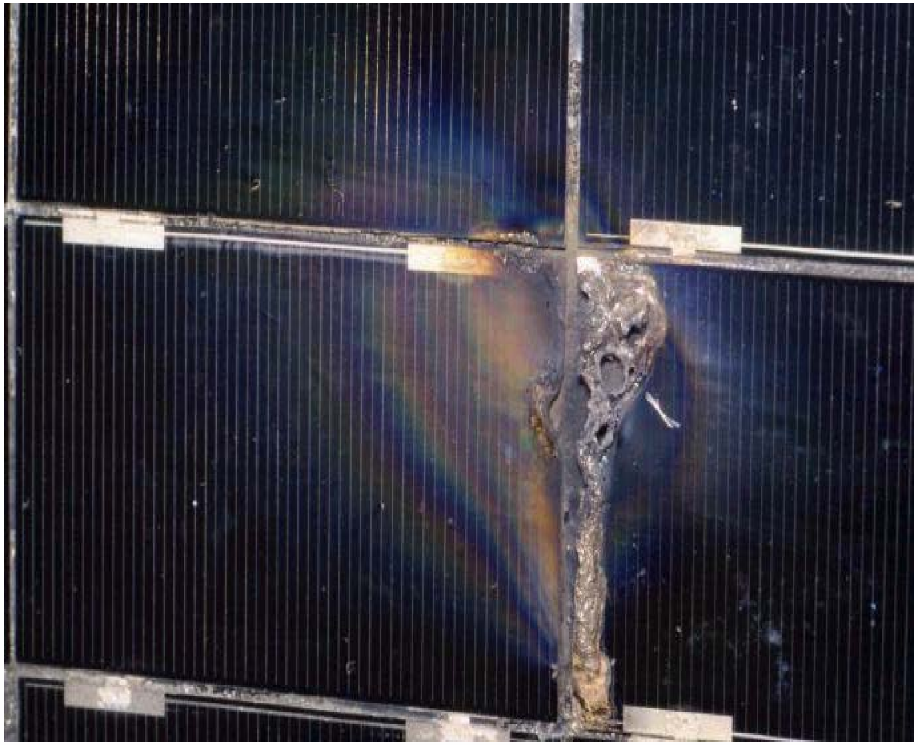
Let me share four examples

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

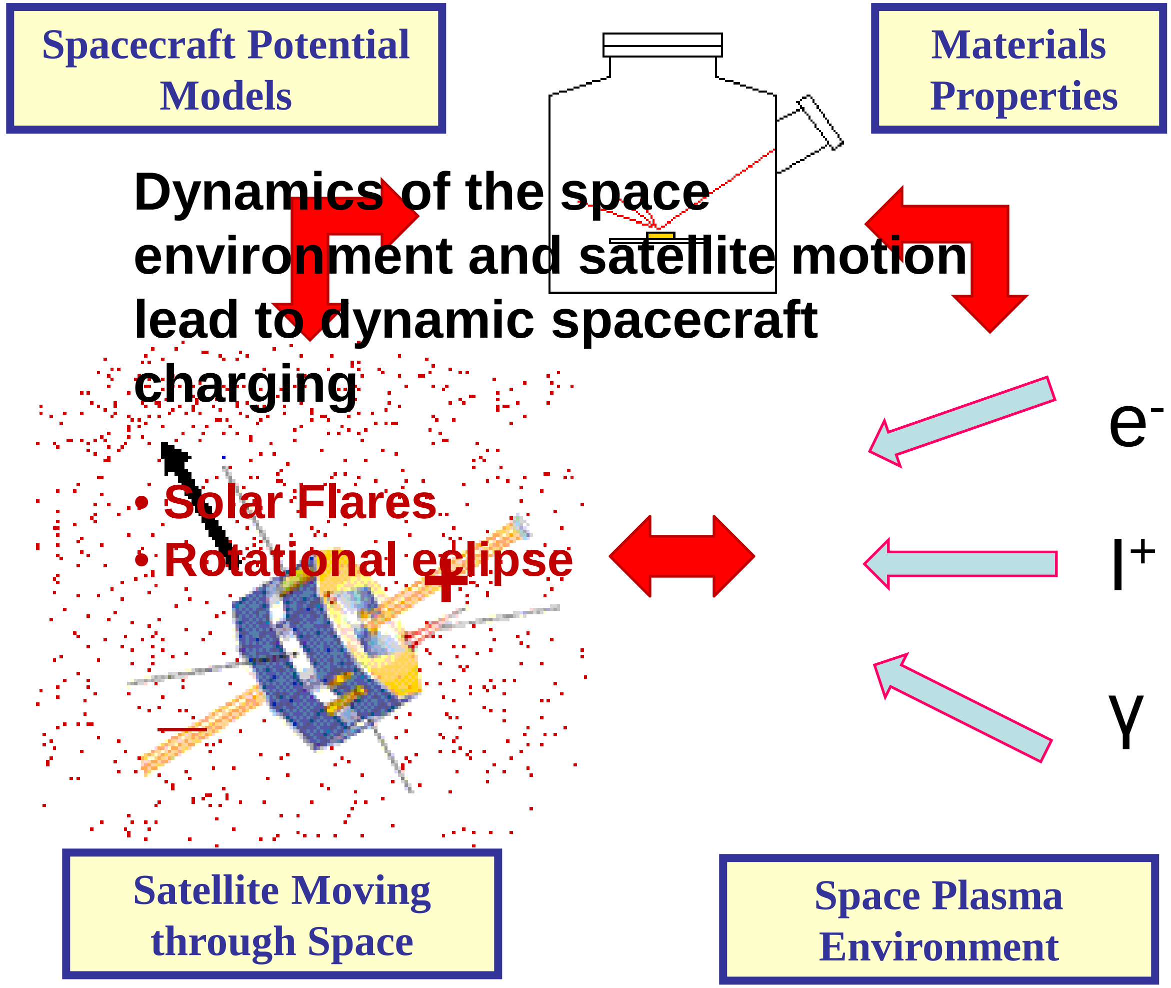
Charge Accumulation

- Electron yields
- Ion yields
- Photoyields

Charge Transport

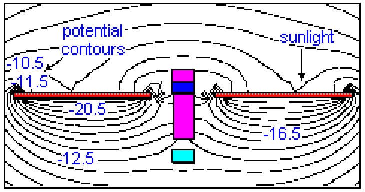
- Conductivity
- RIC
- Dielectric Constant
- ESD

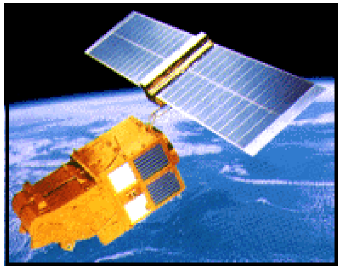
As functions of materials species, flux, and energy.



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

Integration with Spacecraft Charging Models





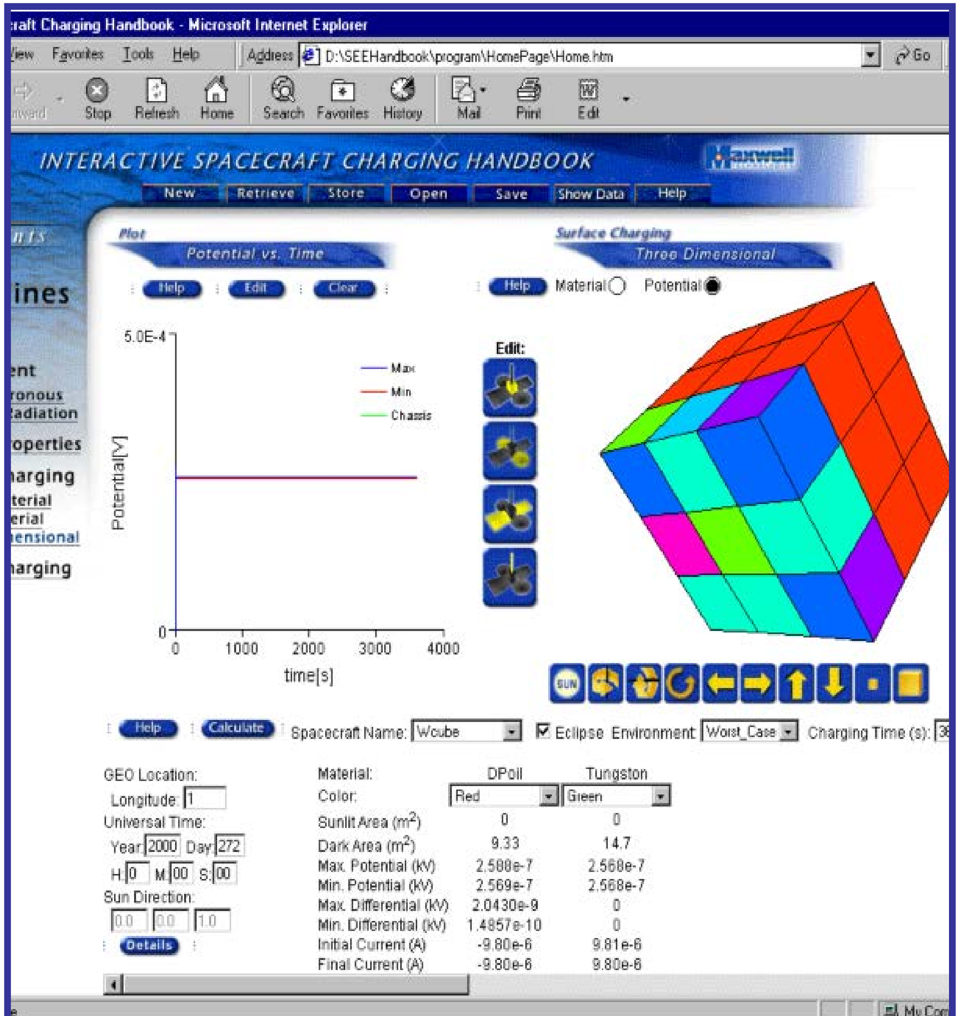
SEE Handbook or NASCAP predicts on-orbit spacecraft charging in GEO and LEO environments

Materials Research

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

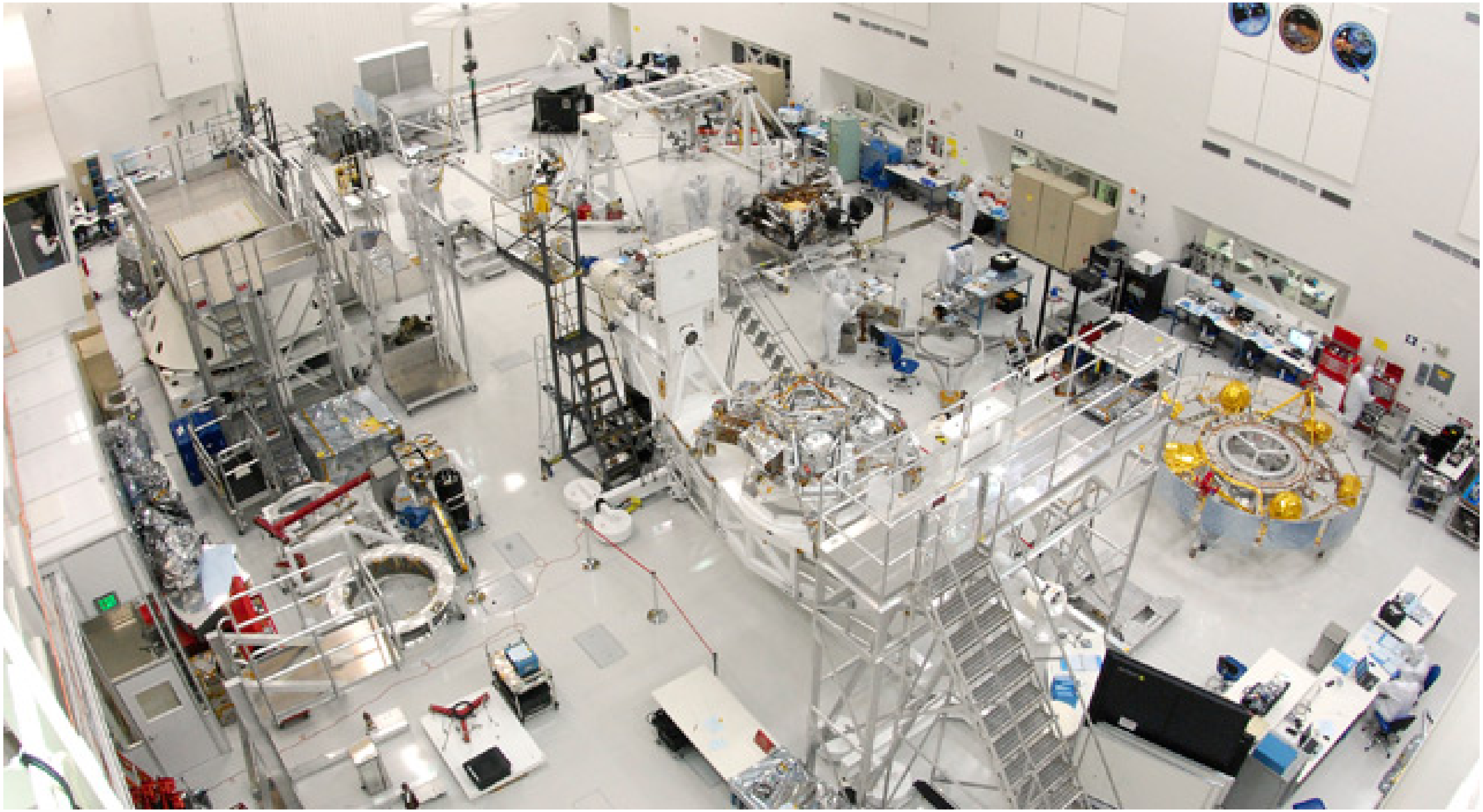
Charge Transport

- Conductivity
- RIC
- Permittivity
- Electrostatic breakdown
- Penetration range

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

Parameter	Value
[1] Relative dielectric constant; ε_r (Input as 1 for conductors)	1, NA
[2] Dielectric film thickness; d	0 m, NA
[3] Bulk conductivity; σ_o (Input as -1 for conductors)	-1; $(4.26 \pm 0.04) \cdot 10^{7}$ ohm$^{-1}\cdot$m^{-1}
[4] Effective mean atomic number <Z_{eff}>	50.9 ± 0.5
[5] Maximum SE yield for electron impact; δ_{max}	1.47 ± 0.01
[6] Primary electron energy for δ_{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 δ^H(1keV)	0.3364 ± 0.0003
[12] Incident proton energy for δ^H_{max}; E^H_{max}	(1238 ± 30) keV
[13] Photoelectron yield, normally incident sunlight, j_{pho}	$(3.64 \pm 0.4) \cdot 10^{-5}$ A$\cdot$m^{-2}
[14] Surface resistivity; ρ_s (Input as -1 for non-conductors)	-1 ohms$\cdot$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, σ_r; k	0 ohms$^{-1}\cdot$m^{-1}, NA
[18] Power of radiation-induced conductivity, σ_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

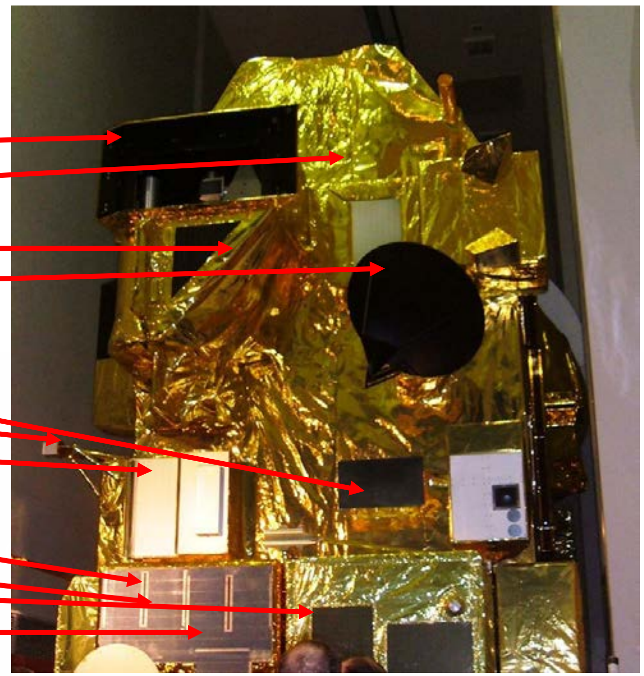
White Paint

ITO

RTV

FR4

Coverglass



Curtesy of JAXA

SUSpECTS Material Samples List

	Material	Source	
C01	COIC AS/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.???% Purity)	United Material	
T07	Inconnel 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), Ŏ**
- **Conductivity Profiles, σ(z)**

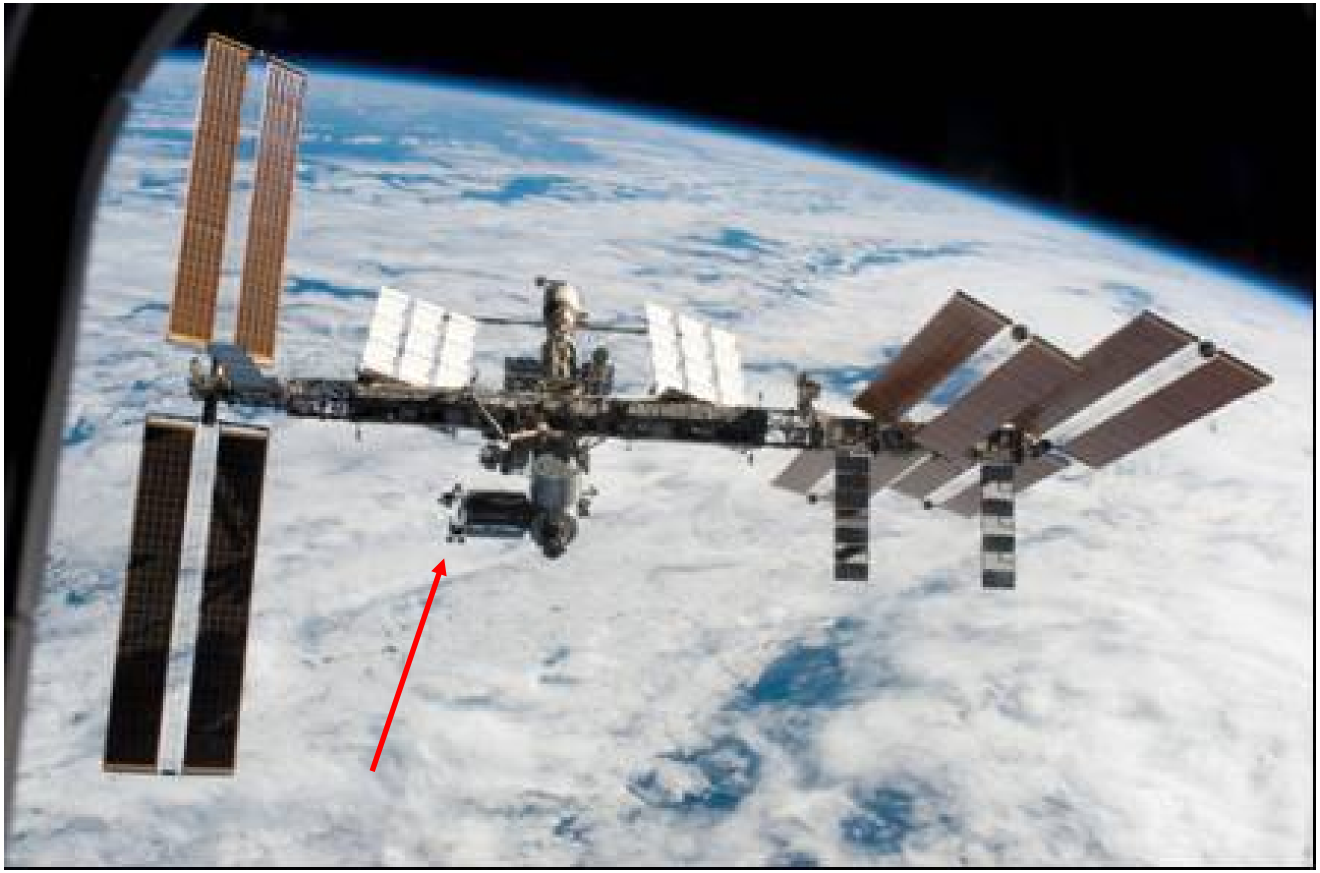
Case Study One

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

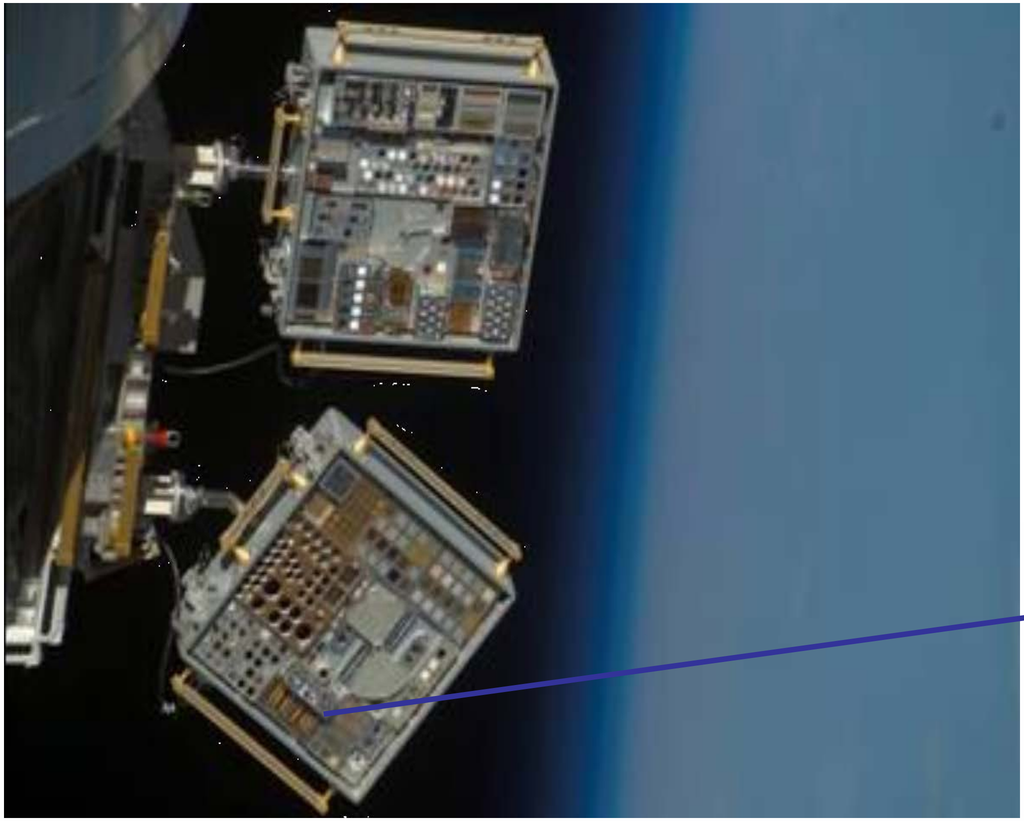


The International Space Station with SUSpECS just left of center on the Columbus module.

Deployed March 2008 STS-123

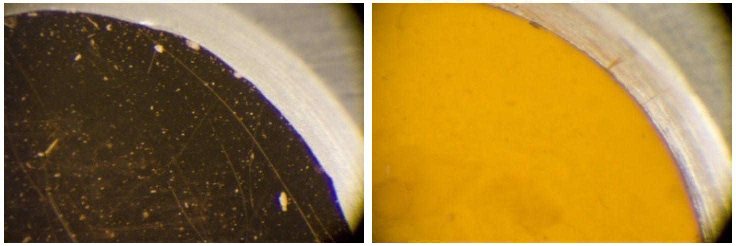
Retrieved August 2009 STS-127

SUSpeCS Samples on the ISS



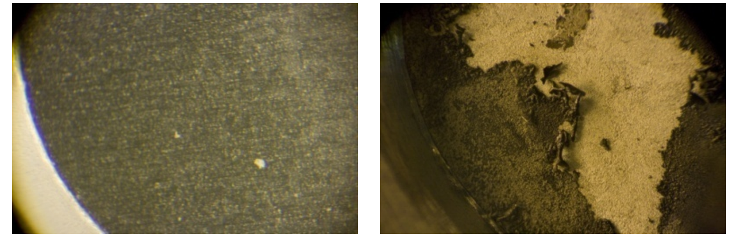
MISSE 6 exposed to the space environment. The SUSpECS double stack can be seen in the bottom center of the lower case. The picture was taken on the fifth EVA, just after deployment.

Evolution of Contamination and Oxidation



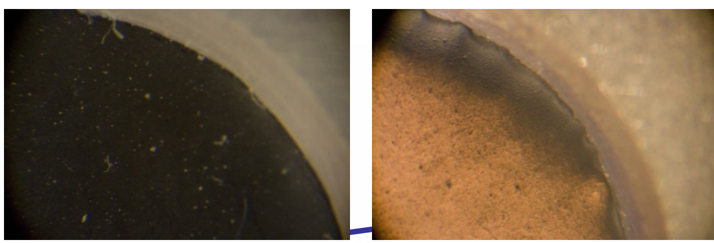
Before After

Kapton, HN



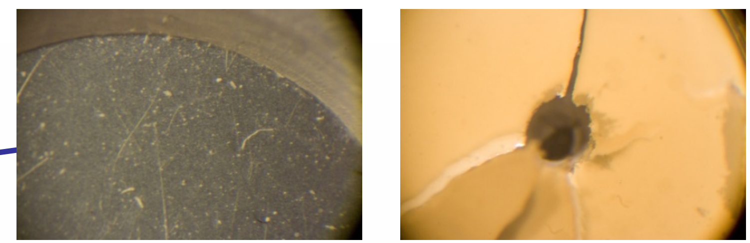
Before After

Ag



Before After

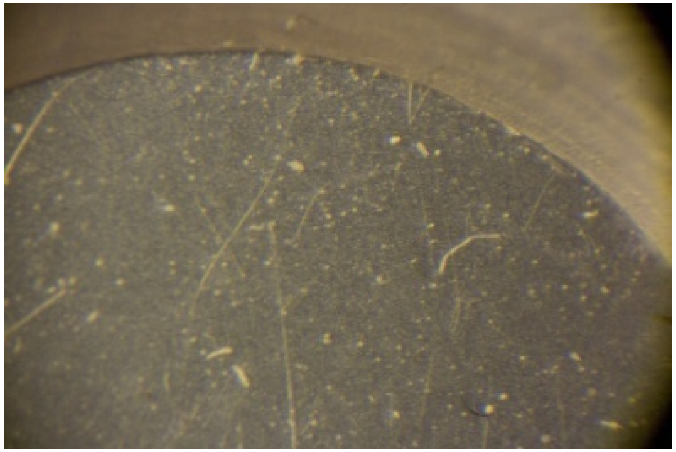
Black Kapton



Before After

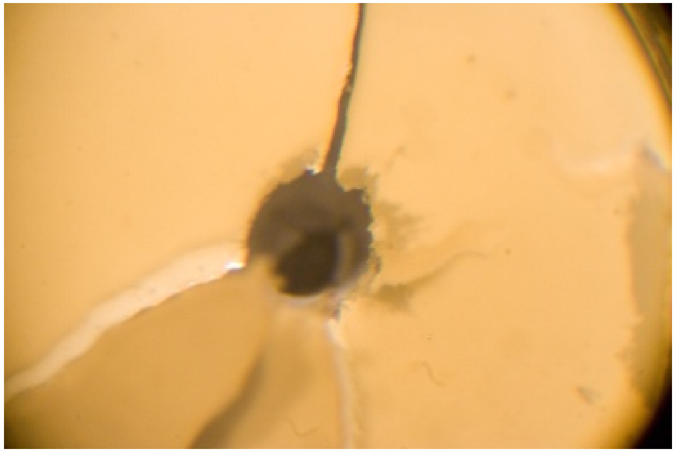
Ag coated Mylar with micrometeoroid impact

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?

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

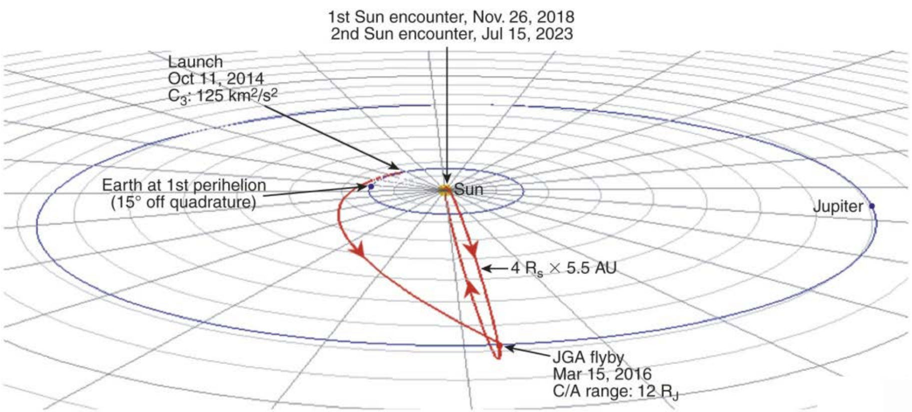


Figure 4-1. Solar Probe mission summary.

WideTemperature Range
<100 K to >1800 K

Wide Dose Rate Range
Five orders of magnitude variation!

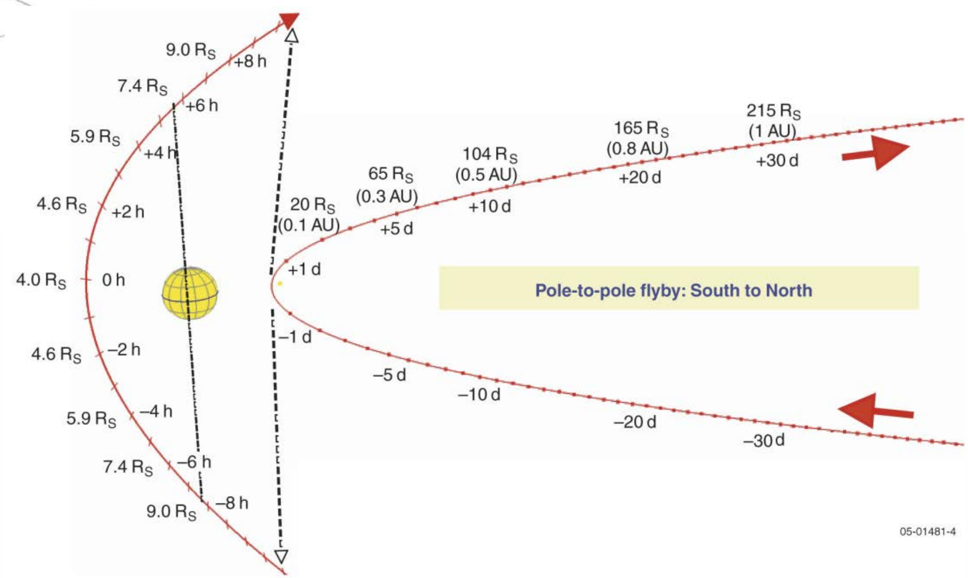
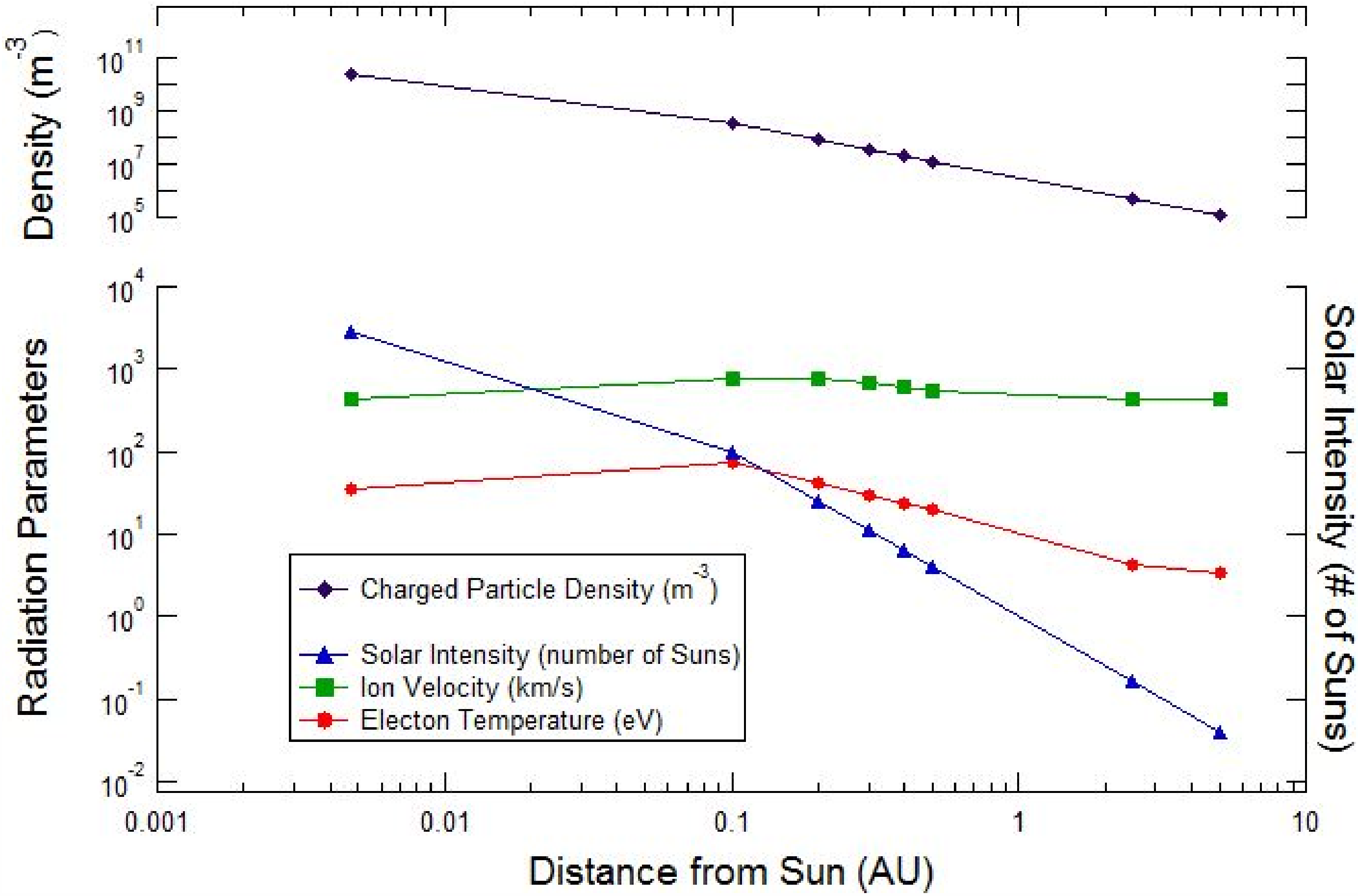


Figure 4-2. Solar encounter trajectory and timeline. Science operations begin at perihelion —-5 days ($65 R_s$) and continue until perihelion +5 days.

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

Charging Study by Donegan, Sample, Dennison and Hoffmann

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,

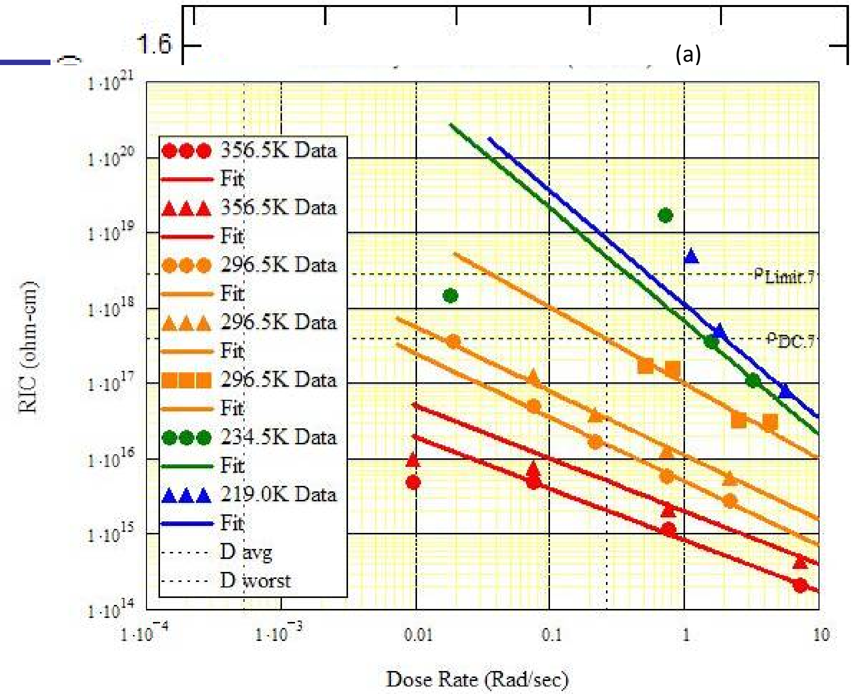
Inner Planetary Mission
SPM, Ulysses, Magellan, Mariner

Radiation Effects

Large Dosage (>10^8 Rad)

Medium Dosage (>10^7 Rad)

Low Dose Rate (>10^0 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)

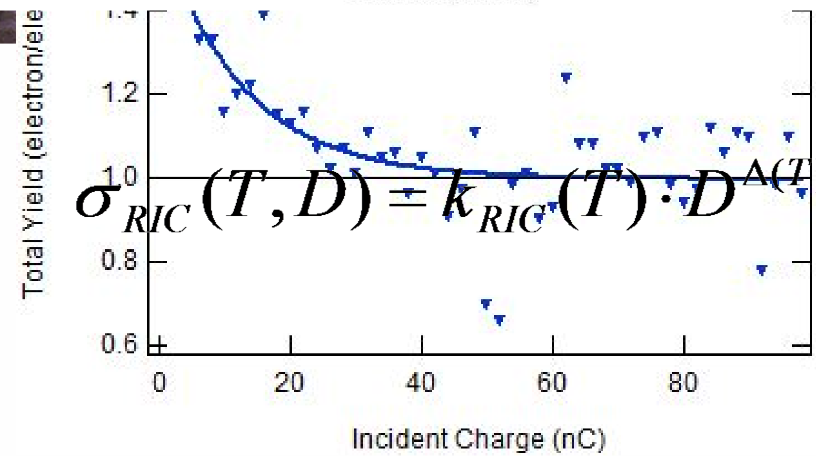
Temperature dependent

Mechanical Modification of Electron Emission Properties

Examples: RBSP, JUNO, JGO/JEO

Caused by bondbreaking and trap creation

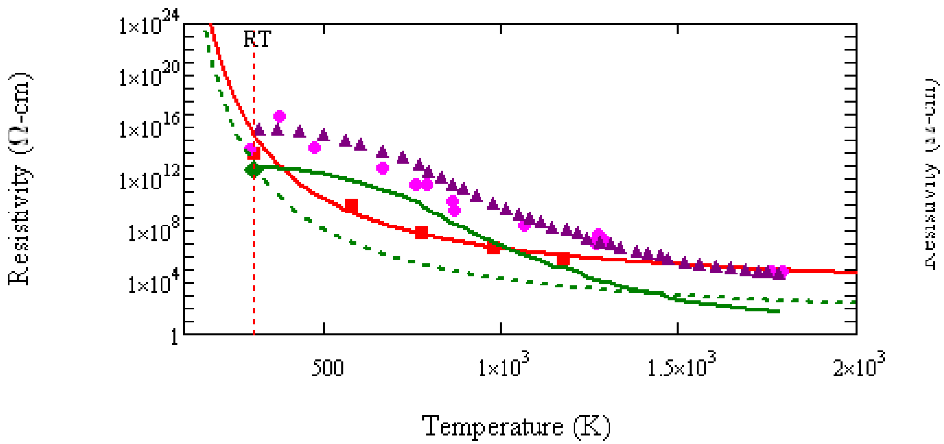
Mechanical and Optical Materials Damage



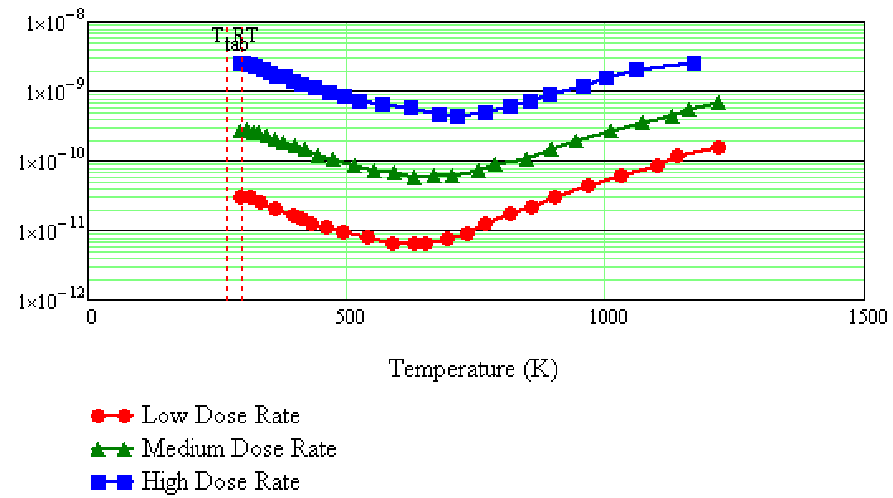
$$\sigma_{RIC}(T,D) = k_{RIC}(T)\cdot D^{\Delta(T)}$$

Combined Temperature and Dose Effects

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

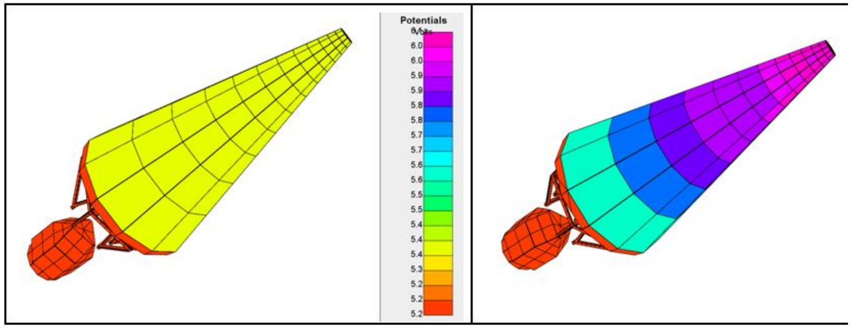
$$\varepsilon_r(T) = \varepsilon_{RT} + \Delta_\varepsilon (T - 298\,K)$$

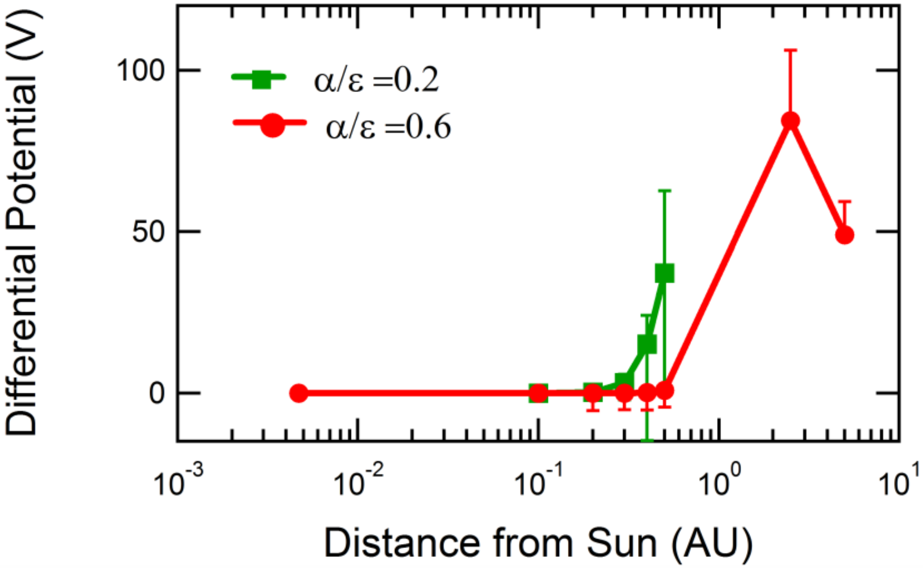
Electrostatic Breakdown

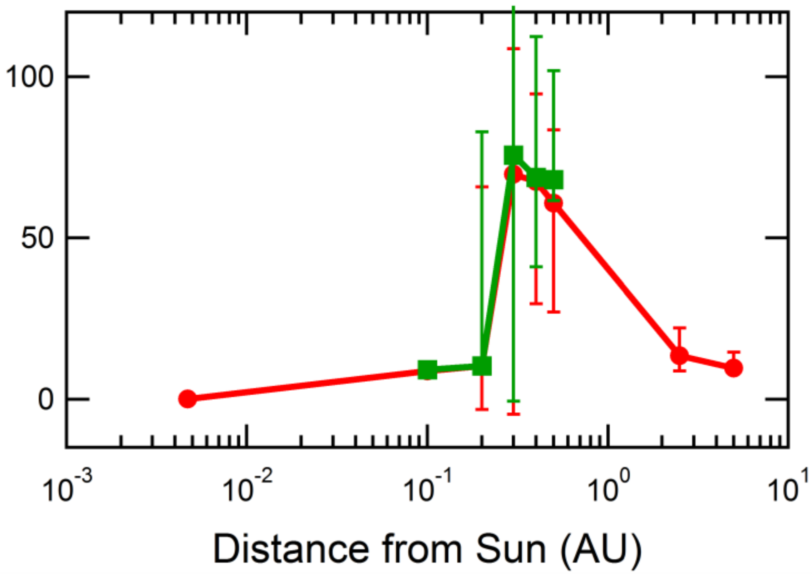
$$E_{ESD}(T) = E_{ESD}^{RT}\, e^{-\alpha_{ESD}(T-298\,K)}$$

Charging Results: Temperature and Dose Effects

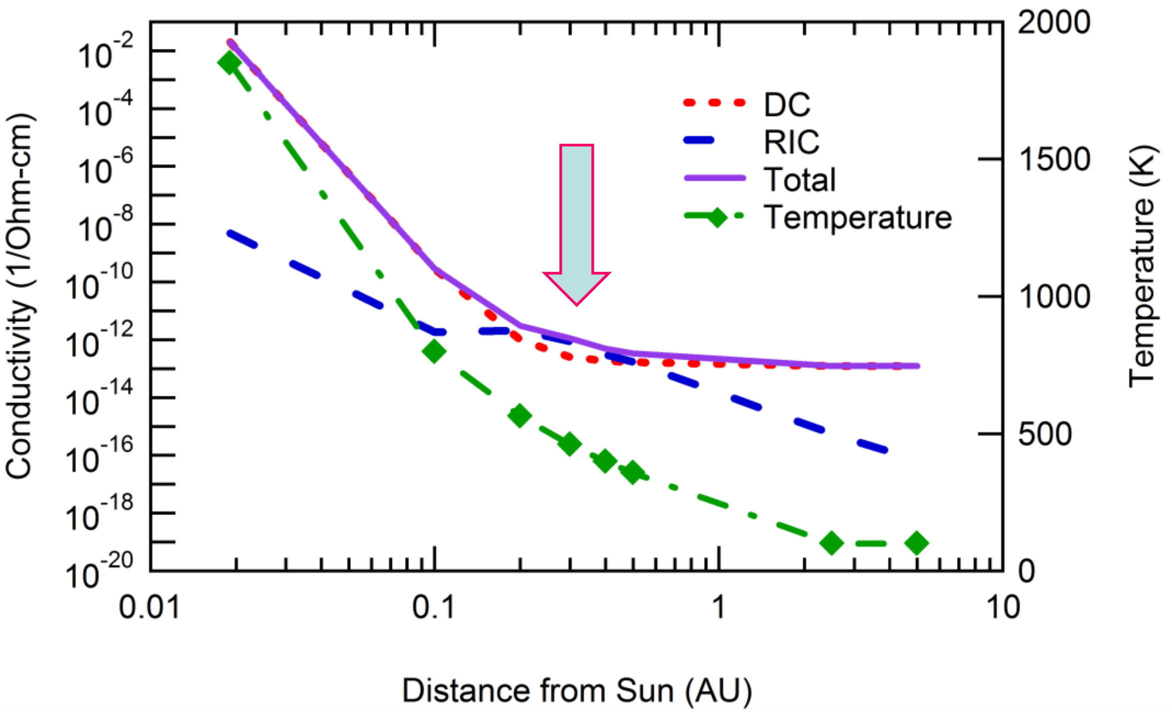
Modeling found a peak in charging at ~0.3 to 2 AU







Explanation of the Temperature and Dose Effects



General Trends

Dose rate decreases as ~r^{-2}
T decreases as ~e^{-r}
σ_{DC} decreases as ~ $e^{-1/T}$
σ_{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

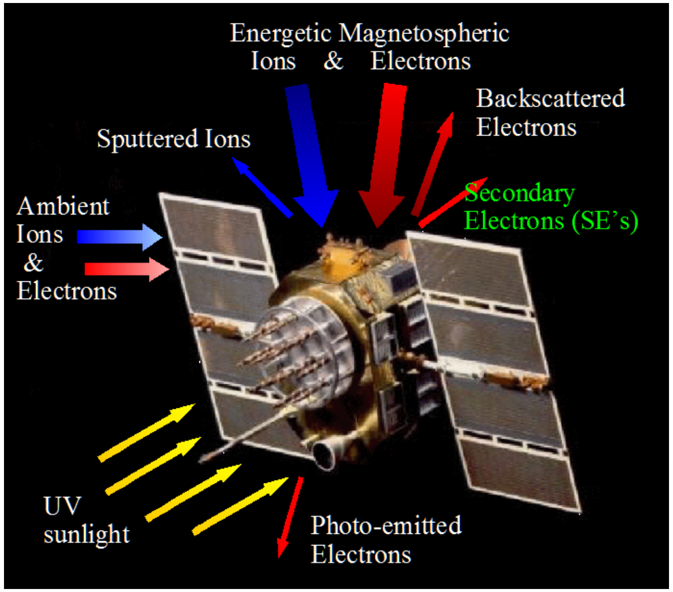
Electron Transport Measurements and Spacecraft Charging

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*

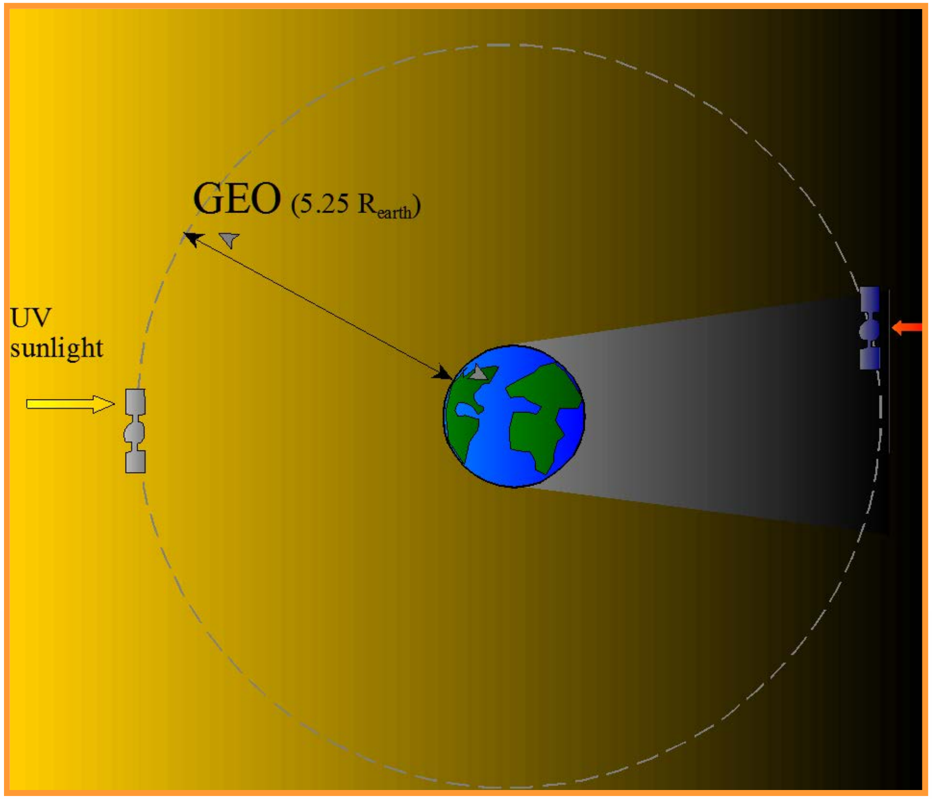


Incident and Emitted Currents that Result in Spacecraft Charging

- Conservation of charge implies:

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

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.

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

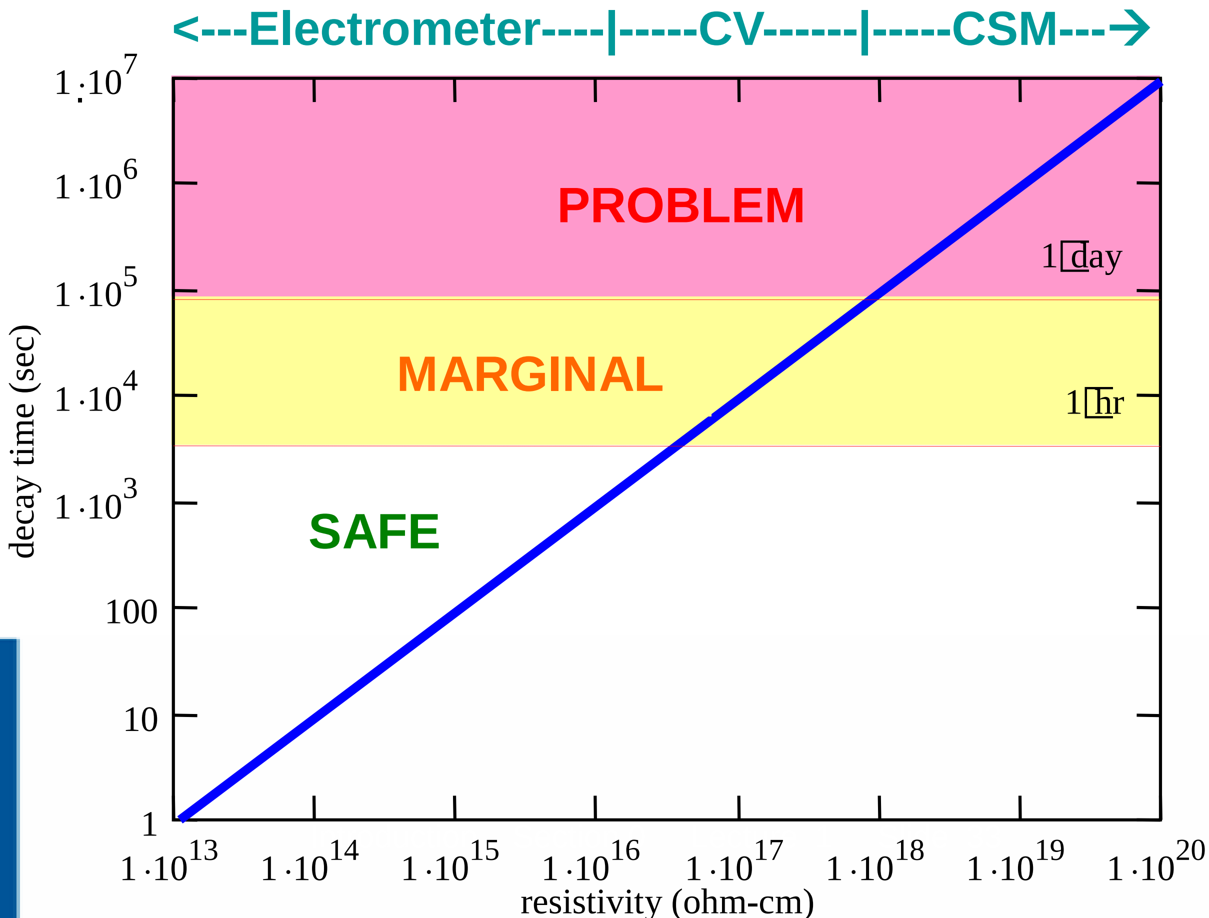
1 hr → ρ•εo ~4•10^{16} Ω-cm

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 <u>Charge Storage Method</u>

1 min → $\rho\cdot\varepsilon_o$ ~$1\cdot10^{15}$ Ω-cm

1 hr → ρ•εo ~4•1016 Ω-cm

1 day → $\rho\cdot\varepsilon_o$ ~$1\cdot10^{18}$ Ω-cm

1 yr → $\rho\cdot\varepsilon_o$ ~$4\cdot10^{20}$ Ω-cm

10 yr → $\rho\cdot\varepsilon_o$ ~$4\cdot10^{21}$ Ω-cm

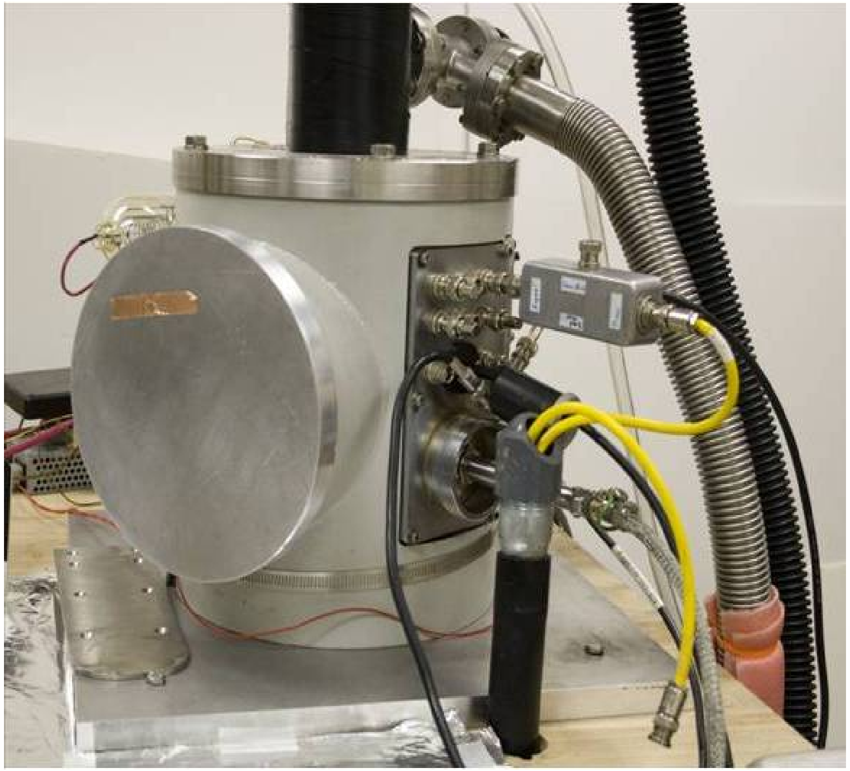
---

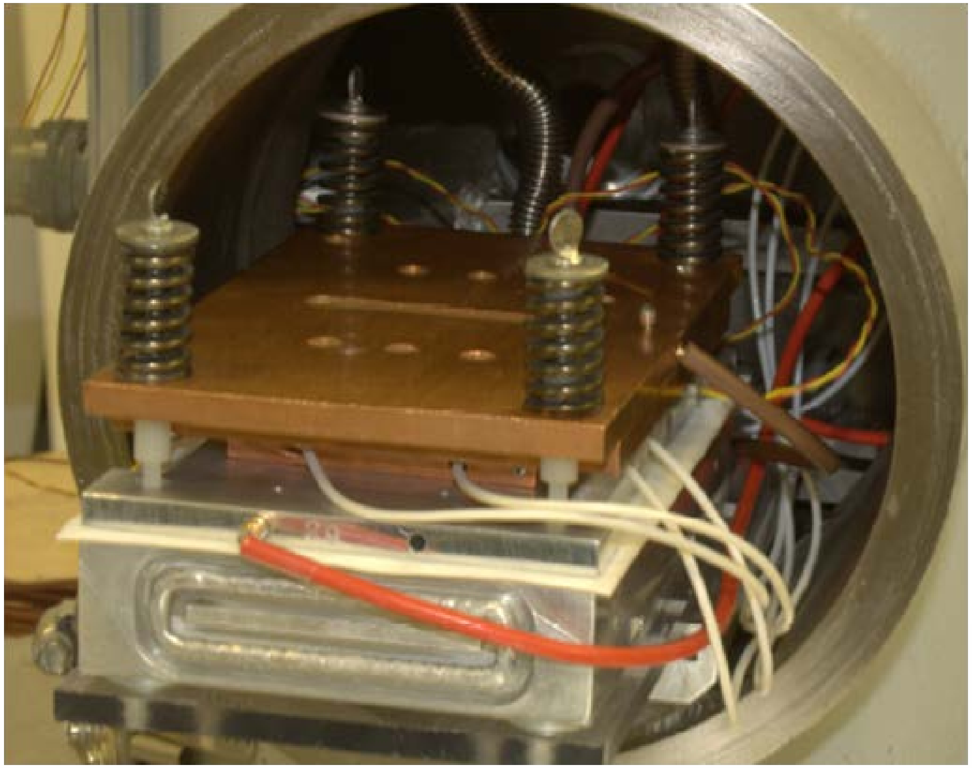
500 yr → ρ•εo ~$1\cdot10^{23}$ Ω-cm

Decay time vs. resistivity base on simple capacitor model.

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

Extremely Low Conductivity



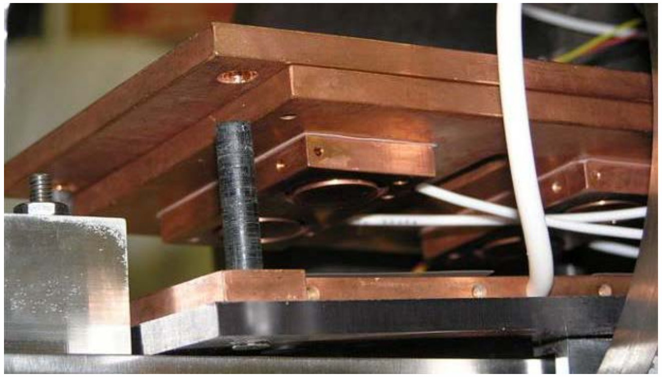


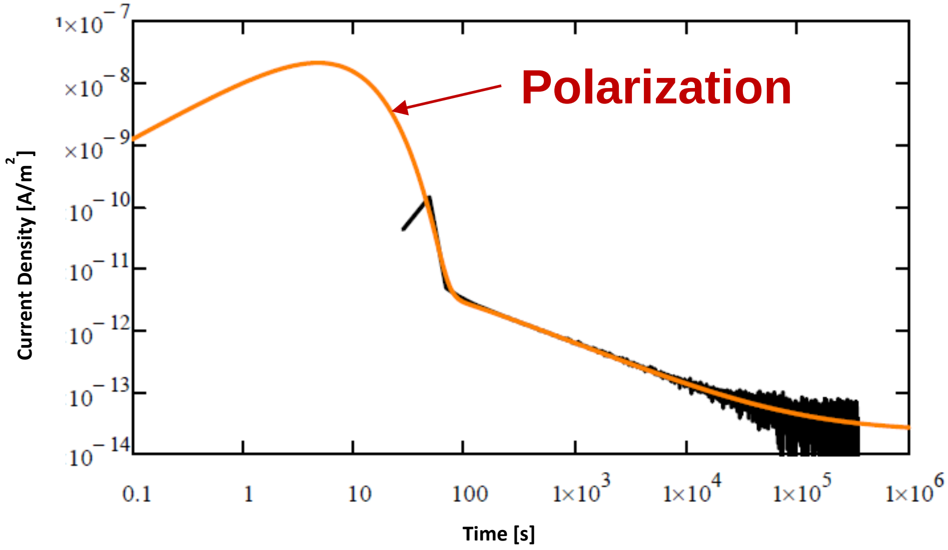
Constant Voltage Conductivity

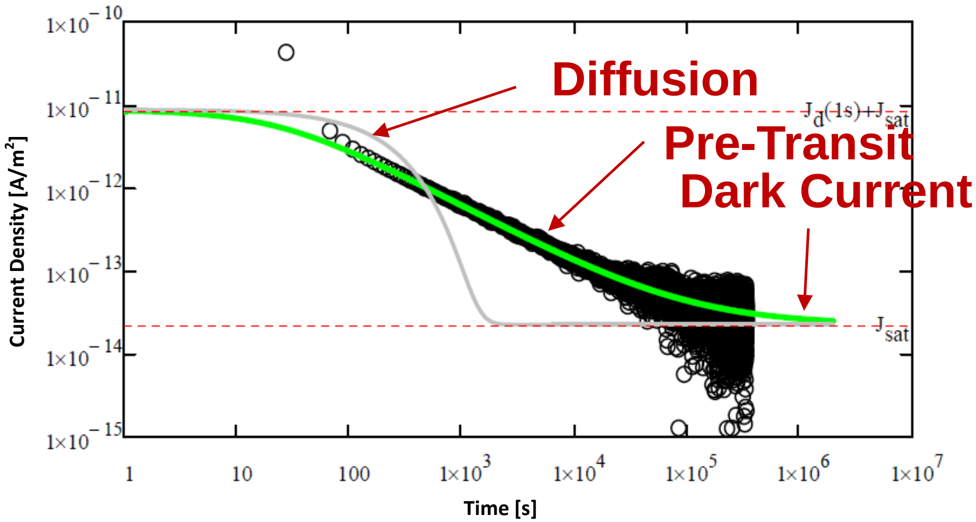
- Time evolution of conductivity
- $<10^{-1}$ s to $>10^{6}$ s
- ±200 aA resolution
- $>5 \cdot 10^{22}$ Ω-cm
- ~100 K <T< 375 K

Constant Voltage Conductivity

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







Conductivity vs Time

AC Polarization Diffusion

Dark Current

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

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 ε_{ST}**
- **Polarization—Rearrangement of bound charge, $\epsilon_r^{\infty}\epsilon_o$ and τ_{pol}**
- **AC conduction—Dielectric response, $\epsilon_r(\nu)\epsilon_o$**

Conductivity vs Time

Dark Current AC Polarization Diffusion

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

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**
- $\sigma_{diffusion}(t) \equiv \sigma_{diffusion}^{o} \cdot t^{-1}$
  diffusion-like conductivity from gradient of space charge spatial distribution.
- $\sigma_{dispersive}(t) \equiv \begin{cases} \sigma_{dispersive}^{o} \cdot t^{-(1-\alpha)} & ;(\text{for } t<\tau_{transit}) \\ \sigma_{transit}(t) \equiv \sigma_{transit}^{o} \cdot t^{-(1+\alpha)} & ;(\text{for } t>\tau_{transit}) \end{cases}$ **broadening of spatial distribution of space charge through coupling with energy distribution of trap states.**
- $\sigma_{RIC}(t;\dot{D},\tau_{RIC}^{1},\tau_{RIC}^{2}) \equiv \sigma_{RIC}^{o}(\dot{D}(t))\left(1-e^{-\tau_{RIC}^{1}/(t-t_{on})}\right)\left(1+(t-t_{off})/\tau_{RIC}^{2}\right)^{-1}$
  radiation induced conductivity term resulting from energy deposition within the material.

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

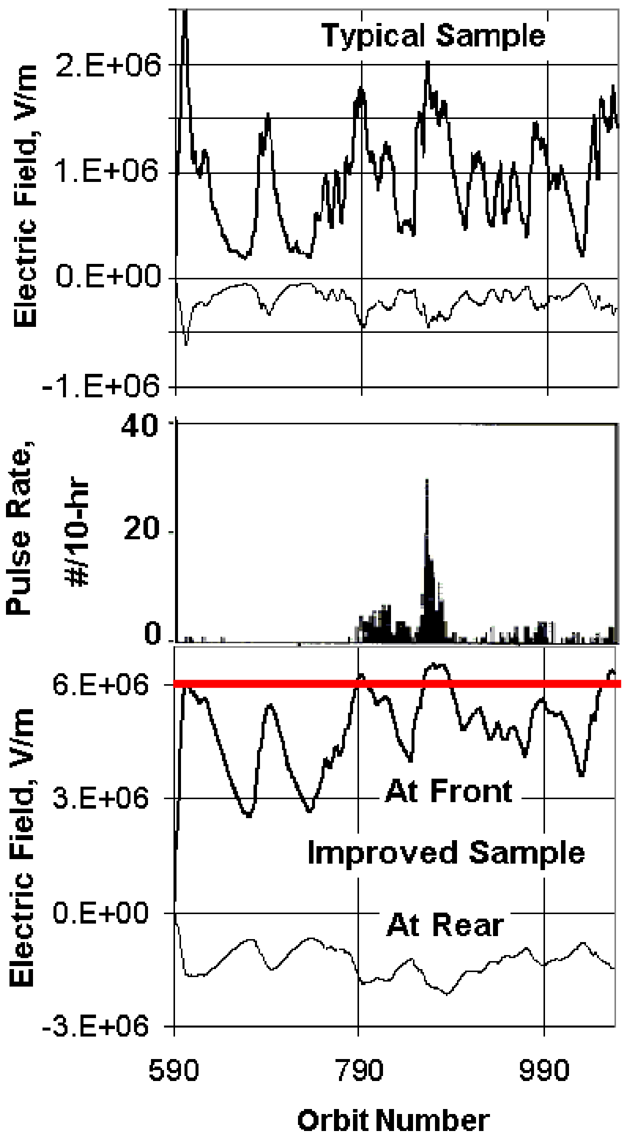
Application to CRESS IDM Pulse Data

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 !!!

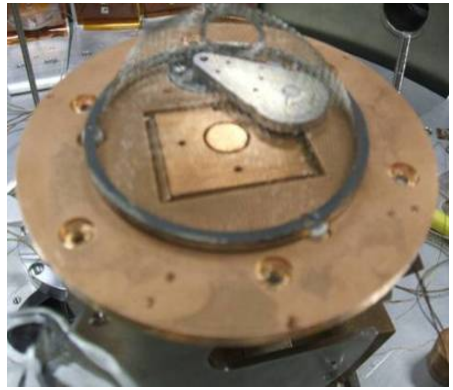
Dark Conductivity	Radiation-Induced Conductivity
typical $=5\text{x}10^{-18}$ $(\Omega\text{-m})^{-1}$	typical = $0.3\text{x }10^{-18}$ $(\Omega\text{-m})^{-1}$
improved $5\text{x}10^{-19}$ $(\Omega\text{-m})^{-1}$	“improved” same as typical
best guess $1.7\text{x}10^{-19}$ $(\Omega\text{-m})^{-1}$	best guess same as typical

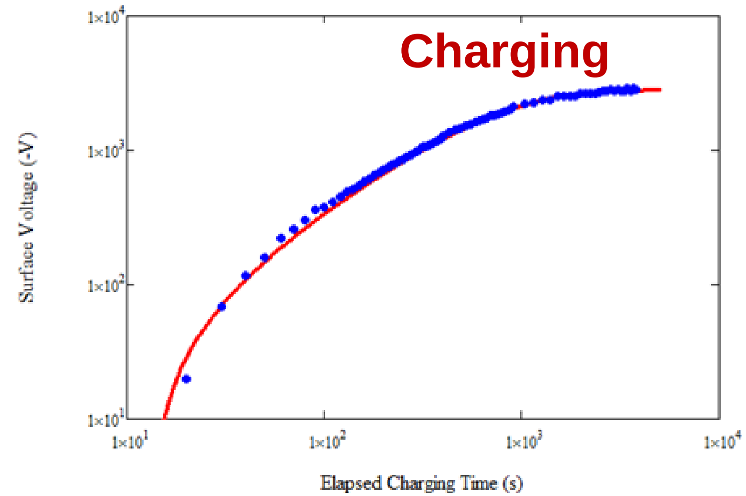


Surface Voltage Charging and Discharging

- **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, α, ε_{ST}**

Instrumentation

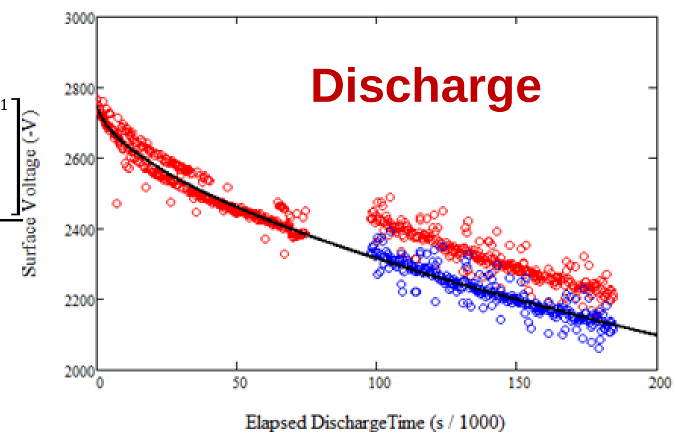




$$\sigma(t)=\sigma_o\left\{1+\left[\frac{\sigma^o_{\text{diffusion}}}{\sigma_o}\right]t^{-1}+\left[\frac{\sigma^o_{\text{dispersive}}}{\sigma_o}\right]t^{-(1-\alpha)}\right\}$$

Charging

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

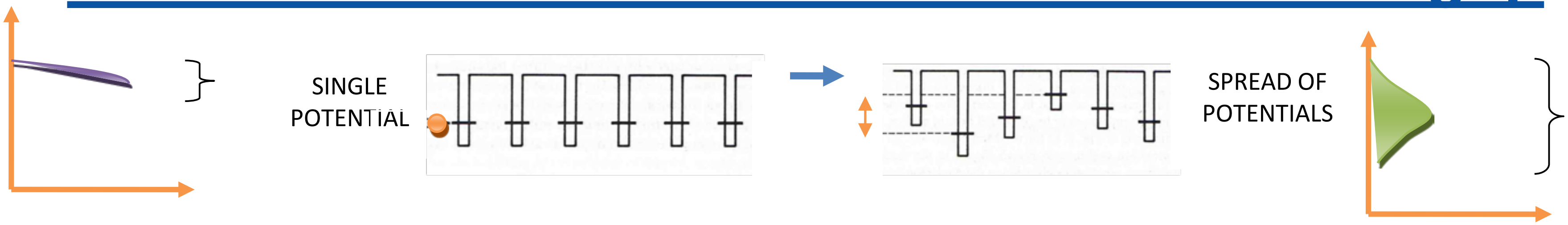


Discharge

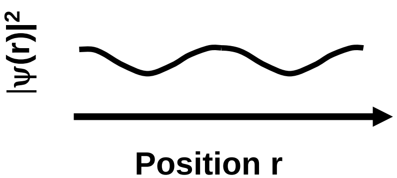
$$V(t)=V_o\,e^{-t\sigma(t)/\epsilon_o\epsilon_r}$$

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

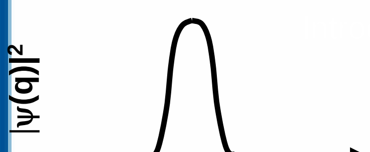
Disorder introduces localized states in the gap

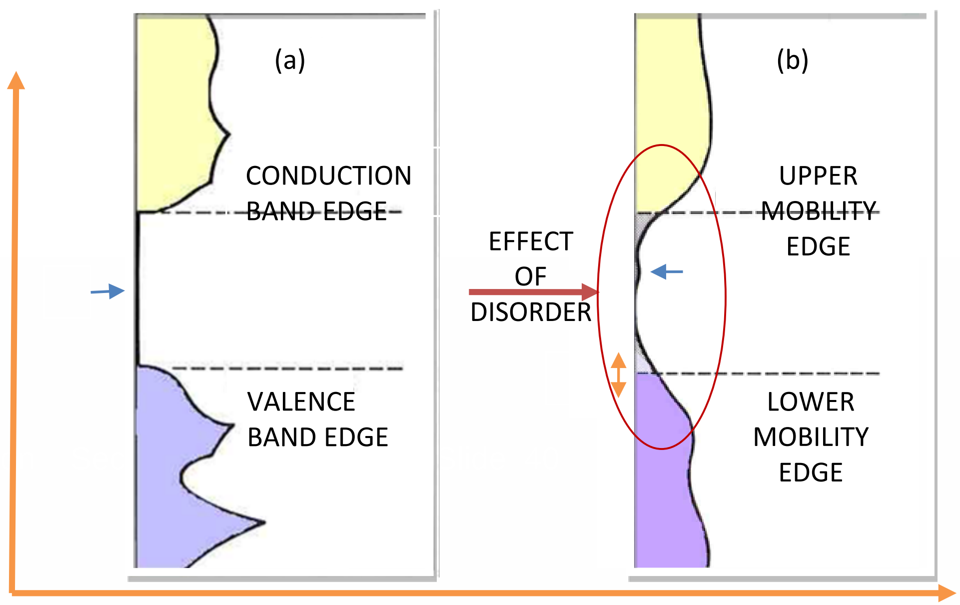


Delocalized in real space

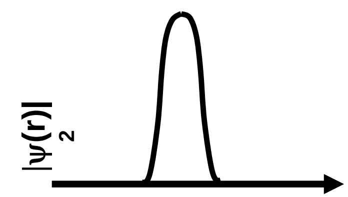


Localized in momentum space

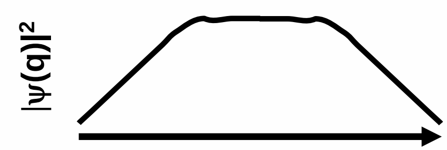




Localized in real space



Delocalized in momentum space



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

Tunneling Between Traps—and Mott Anderson Transitions

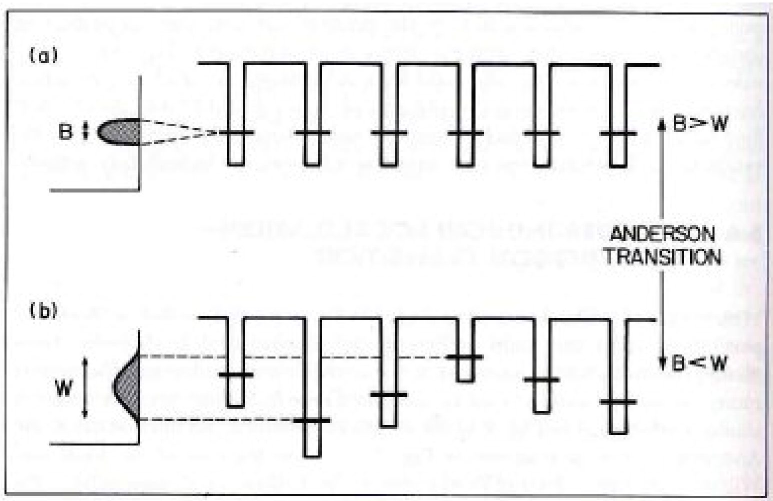


Figure 5.13 One-electron tight-binding picture for the Anderson transition. When the width W of the disorder exceeds the overlap bandwidth B, disorder-induced localization takes place.

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

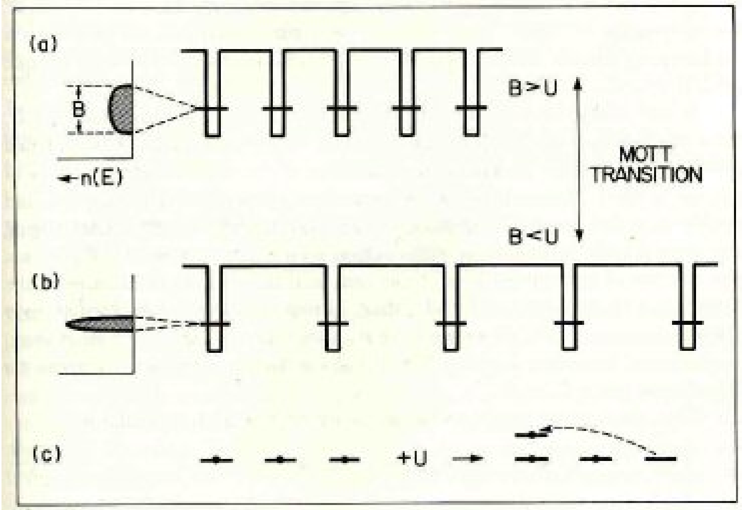


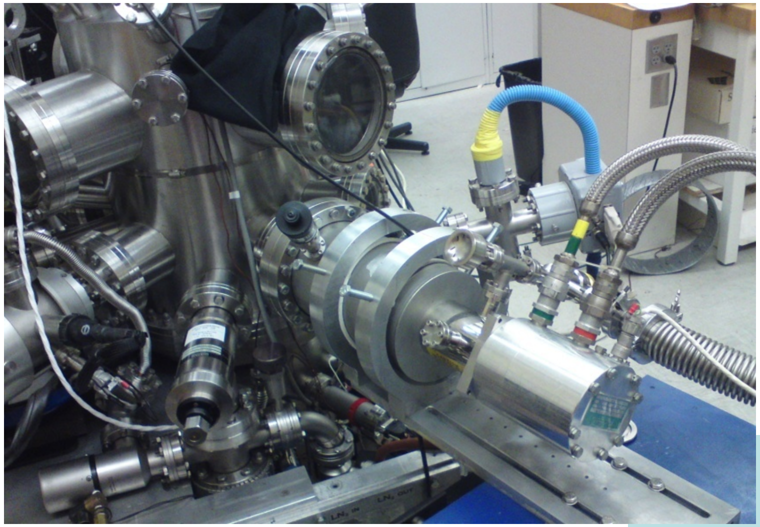
Figure 5.12 Schematic picture for the Mott transition. When the electron bandwidth B is decreased (by increased atom–atom separation) sufficiently to be smaller than the intrasite electron–electron energy U, correlation-induced localization takes place.

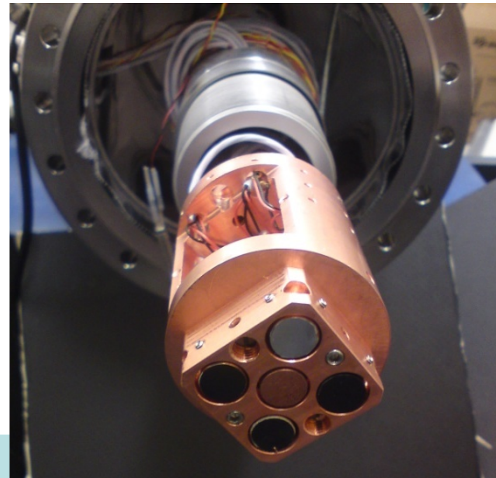
Mott transition between extended Bloch states and localized states caused by variations in well spacing which affects tunneling between states.

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

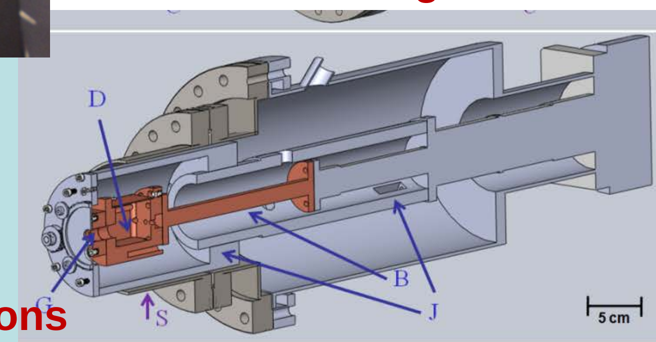
Nobel Prize 1977 to Sir Nevill Mott and P.W. Anderson*, Electronic Structure of Disordered Systems*

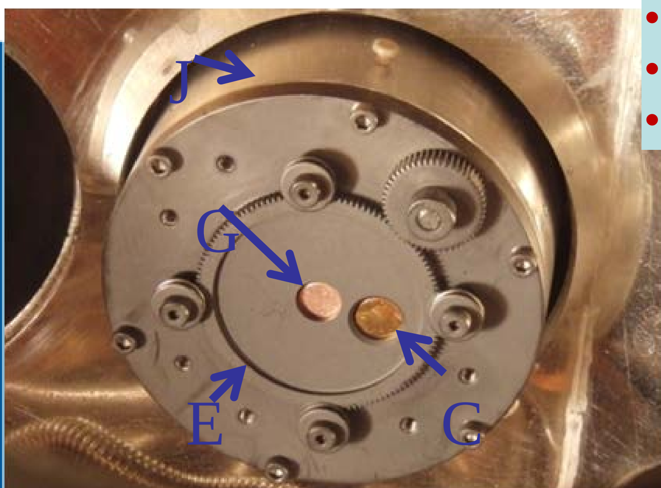
Low Temperature Cryostat





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

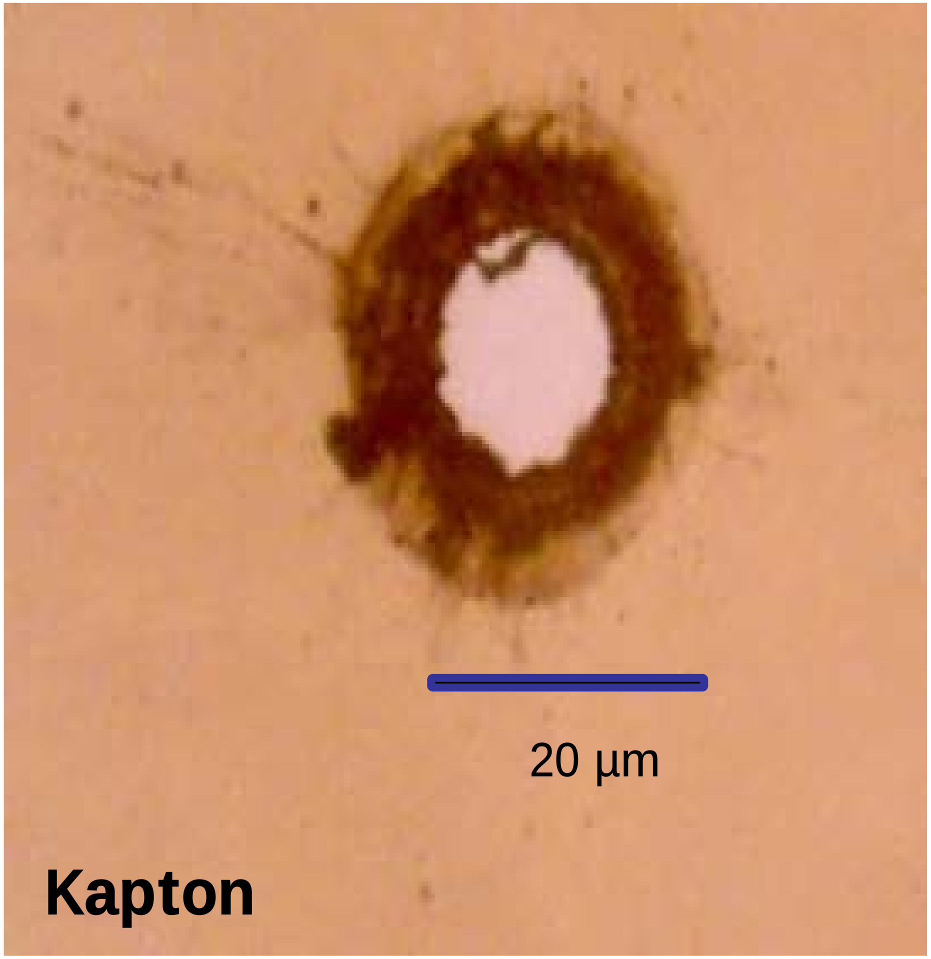
Sample Mount
B Sample Pedestal
C Sample
D Sample Mount
E Sample Mask Selection Gear
F Interchangeable Sample Holder
G *In situ* Faraday Cup
H Spring –Loaded Electrical Connections
I Temperature Sensor
J Radiation Shield

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



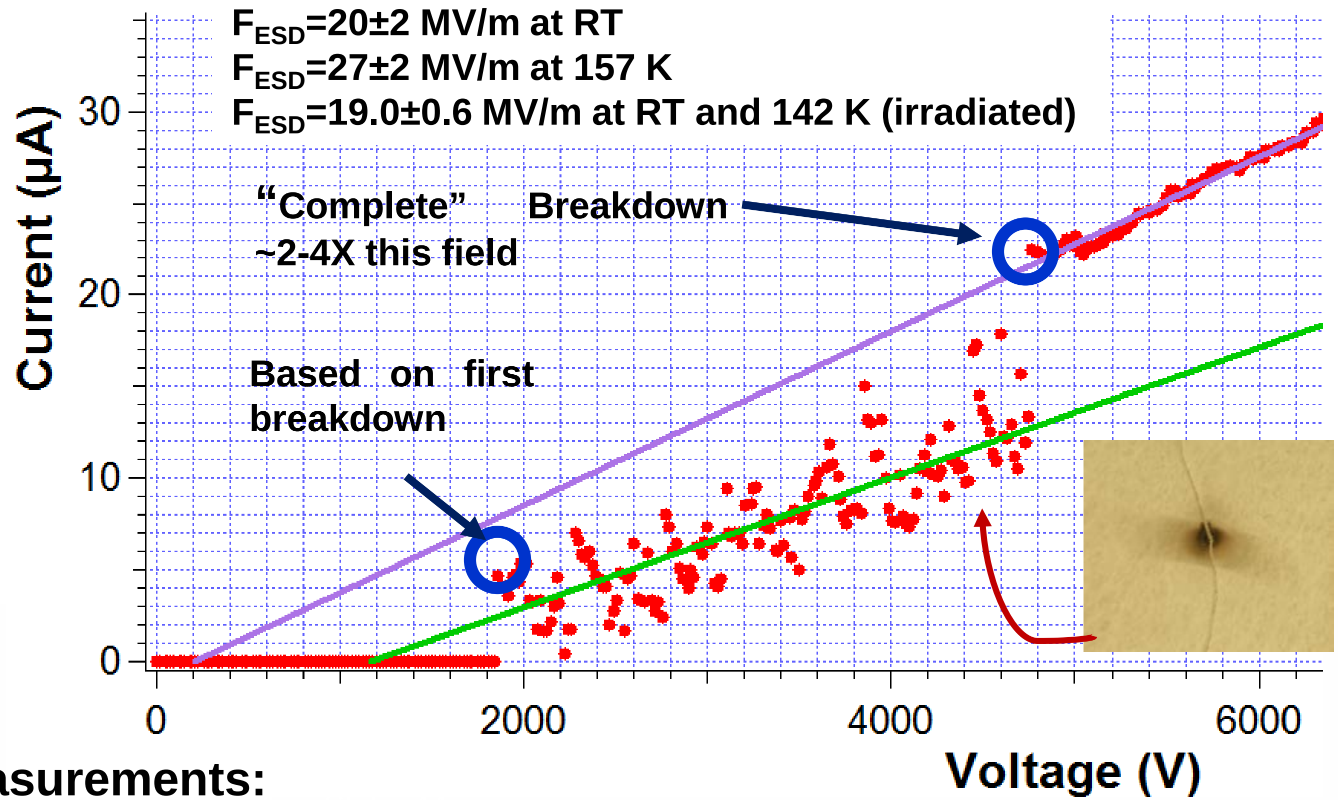
F_{ESD} Breakdown: Dual (Shallow and Deep) Defect Model

Yields:

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

Separate these with T dependence

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



Breakdown field measurements:

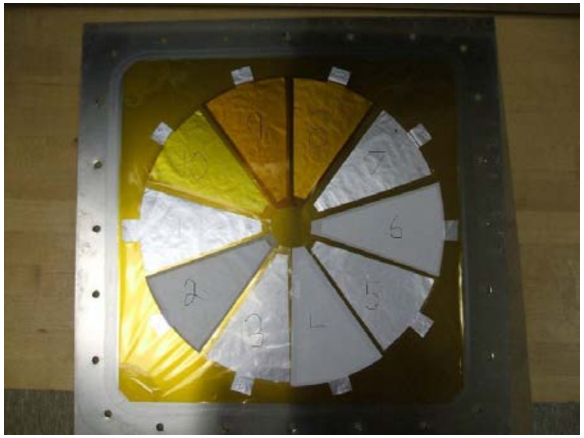
$$N_{def}\,\Delta G_{def} = \frac{\varepsilon_0\varepsilon_r}{2}\cdot(F_{ESD})^2$$

Endurance time measurements:

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

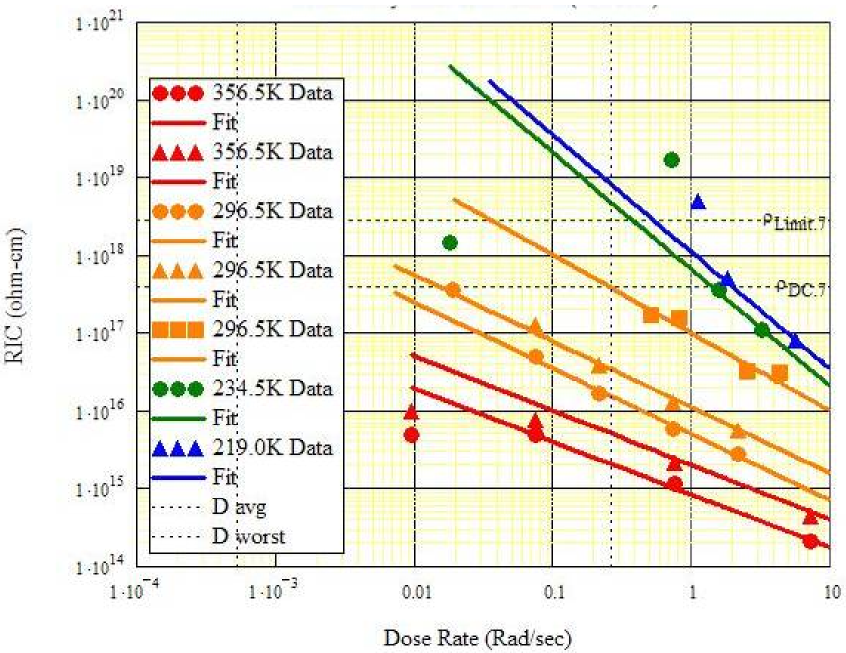
Radiation Induced Conductivity Measurements

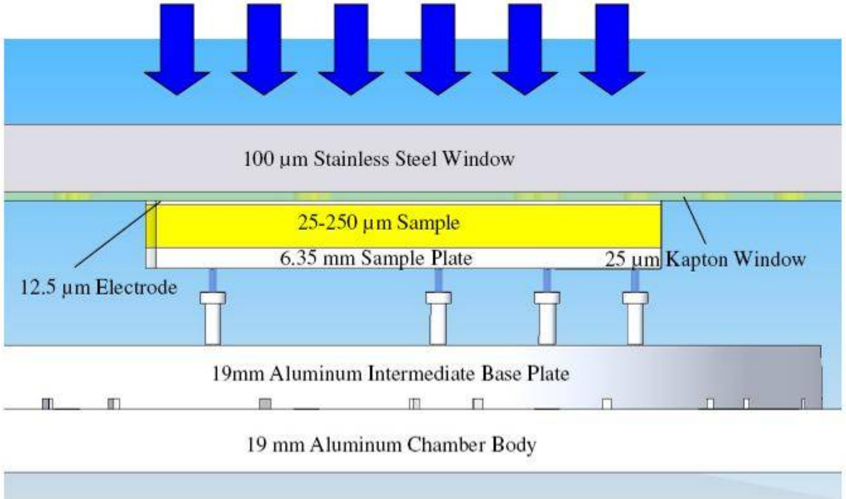
RIC chamber uses a combination of charge injected by a biased surface electrode with simultaneous injection by a pulsed penetrating electron.



Top view of samples on window

RIC Chamber





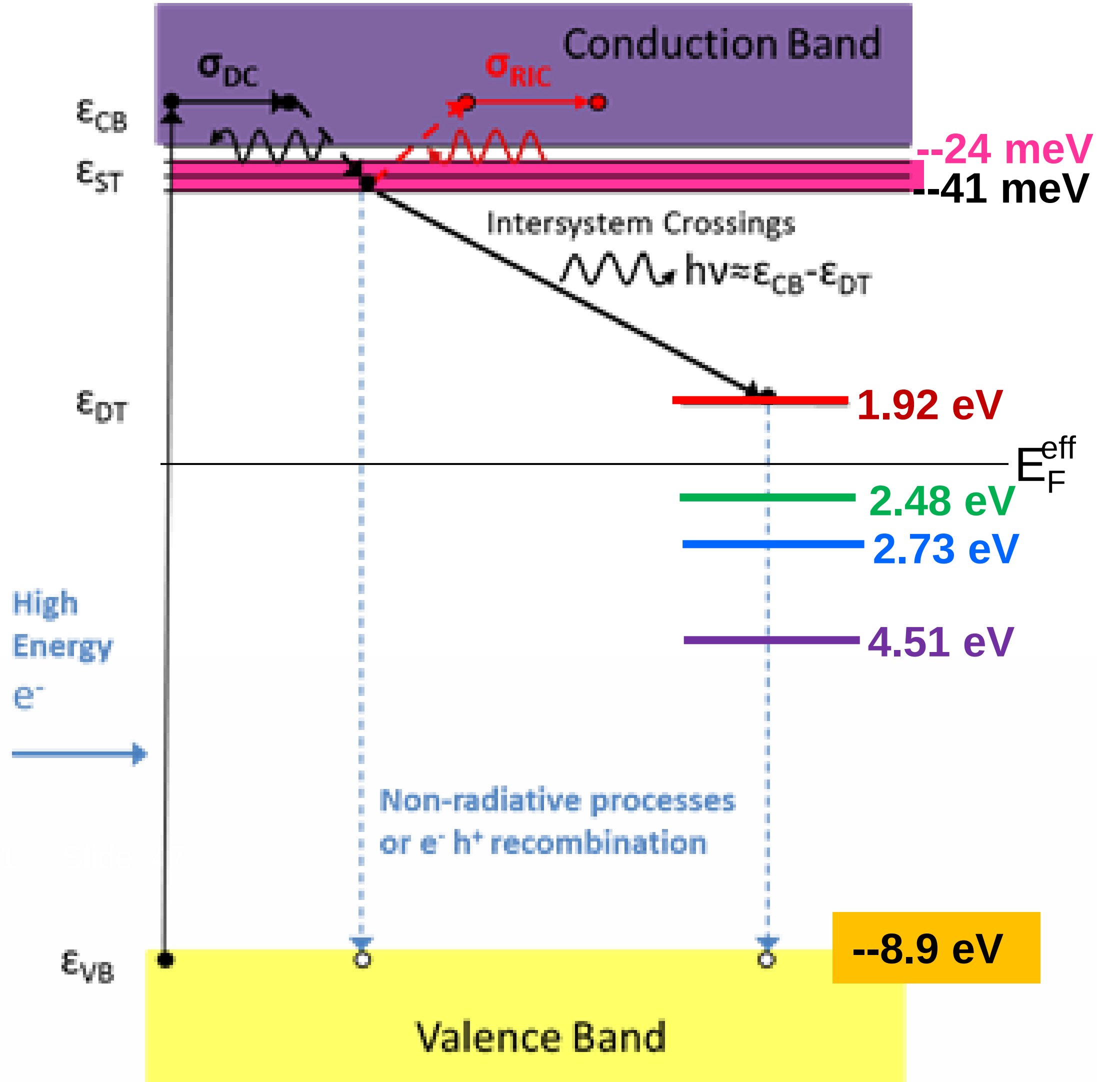
Sample stack cross section

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.



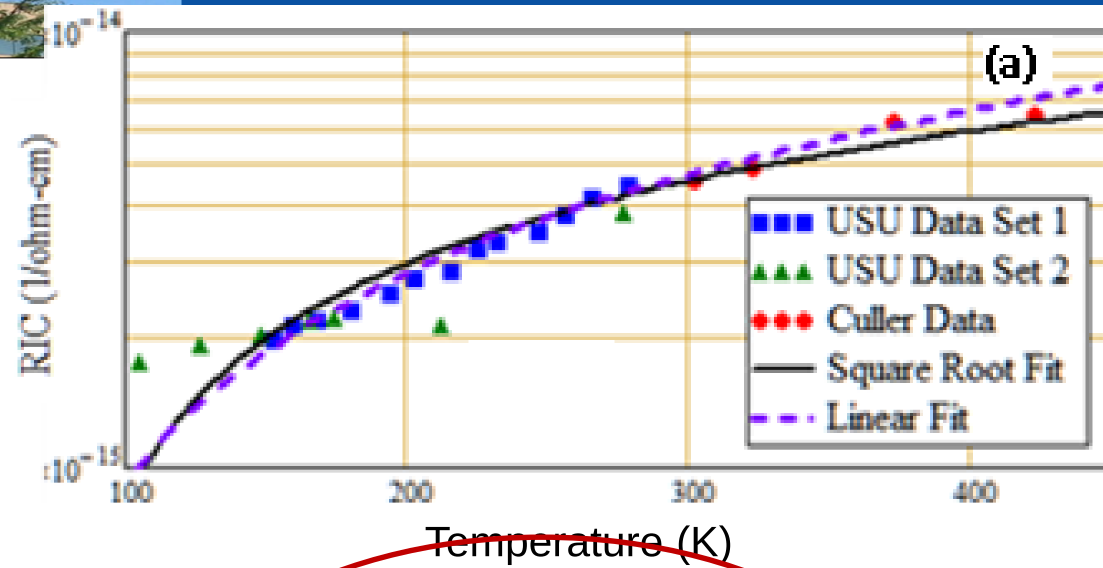
RIC T-Dependence

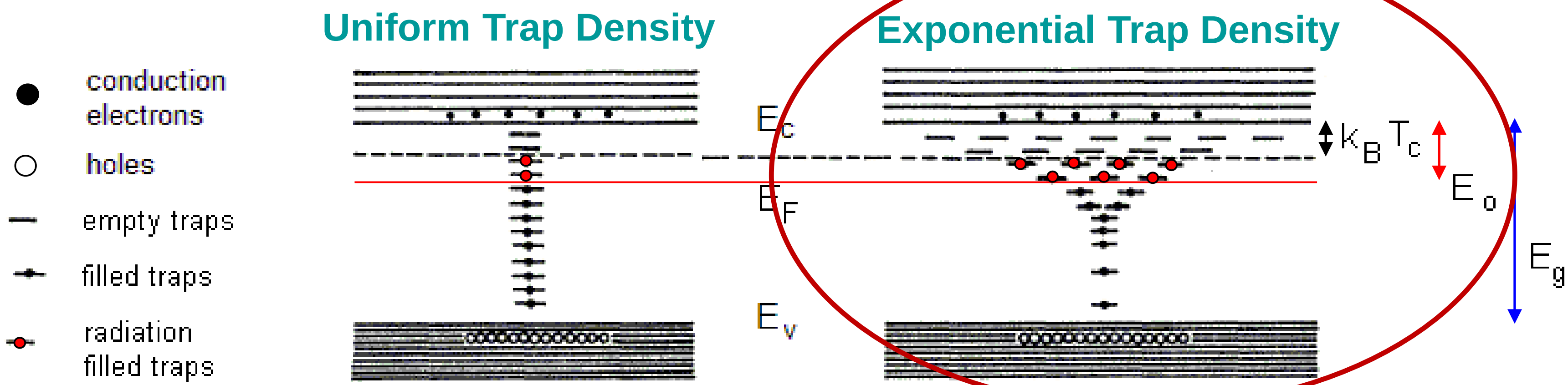
Shallow Trap DOS Profile

Exponential DOS Below E_c

Effective Fermi Level

E_F^{eff} = 24 meV



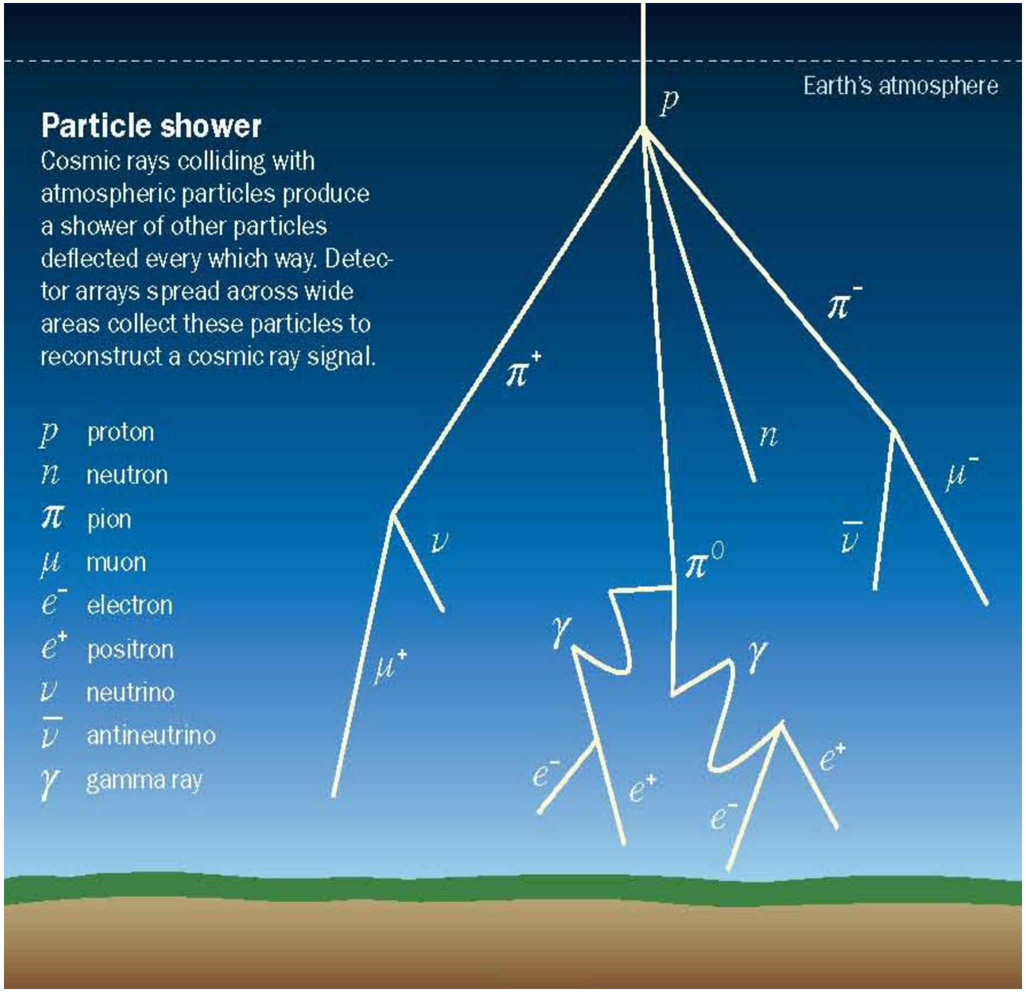


$$\sigma_{RIC}(T,D) = k_{RIC}(T)\cdot D^{\Delta(T)}$$

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

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

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.

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

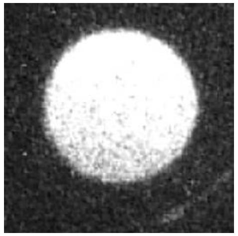
Large Open Structure
Large fluxes
Minimal shielding

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

Complex, Sensitive Hardware
Large sensitive optics
Complex, cold electronics

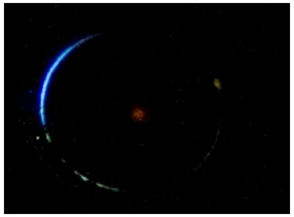
Diversity of Emission Phenomena in Time Domain

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



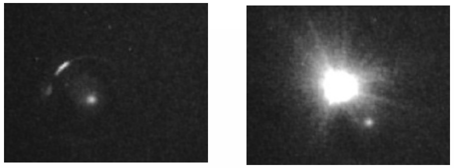
Surface Glow

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



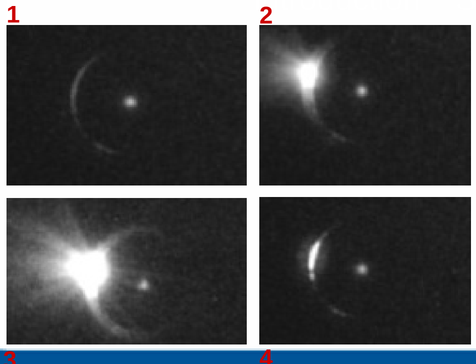
Edge Glow

Similar to Surface Glow, but present only at sample edge



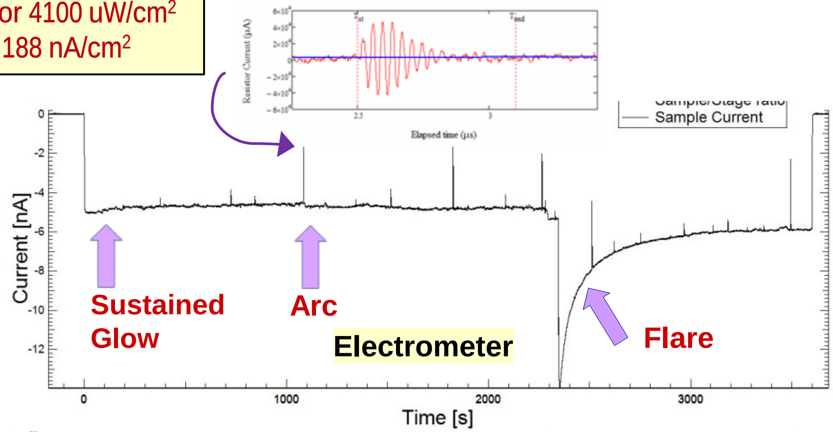
"Flare"

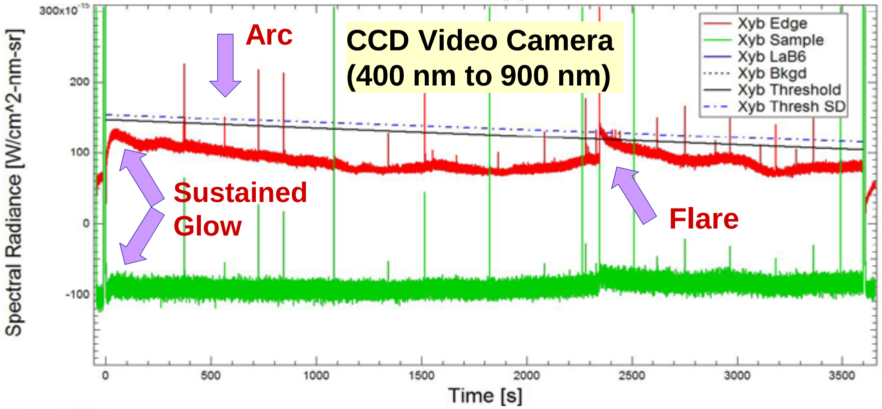
2-20x glow intensity
Abrupt onset
2-10 min decay time

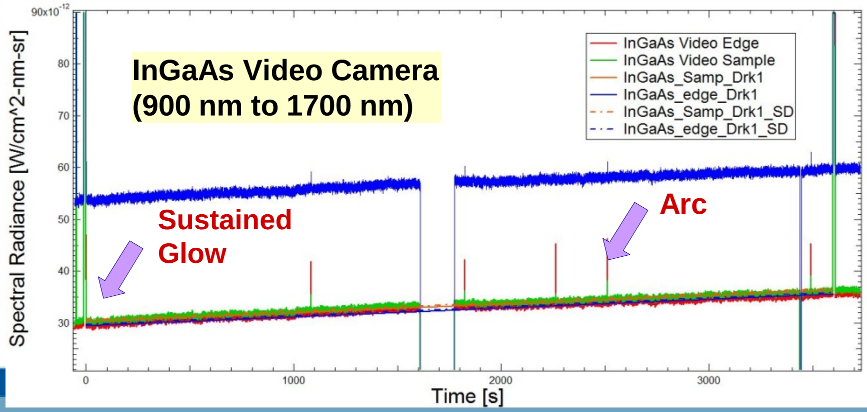


Arc

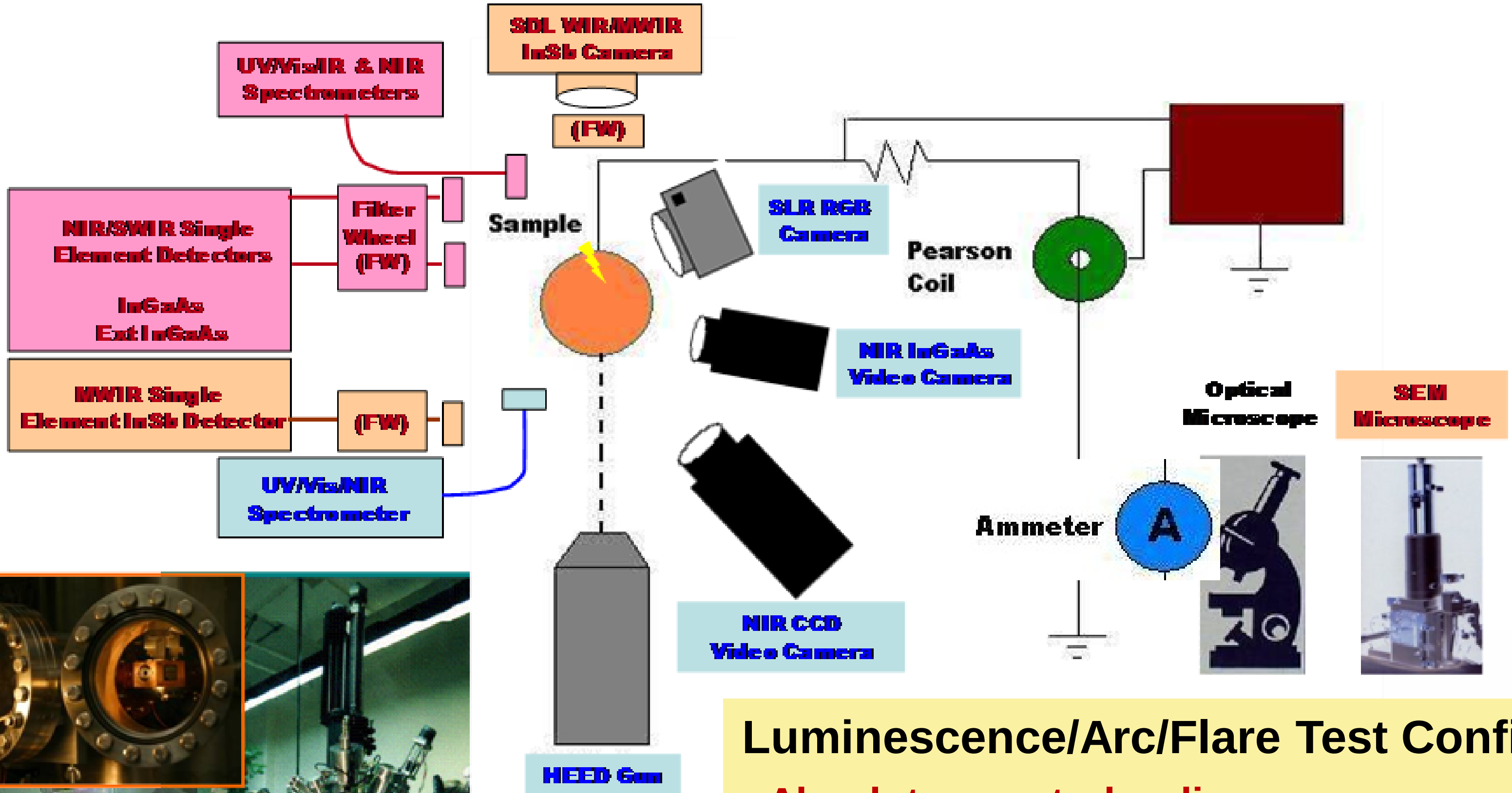
Relatively very high intensity
10-1000X glow intensity
Very rapid <1 us to 1 s

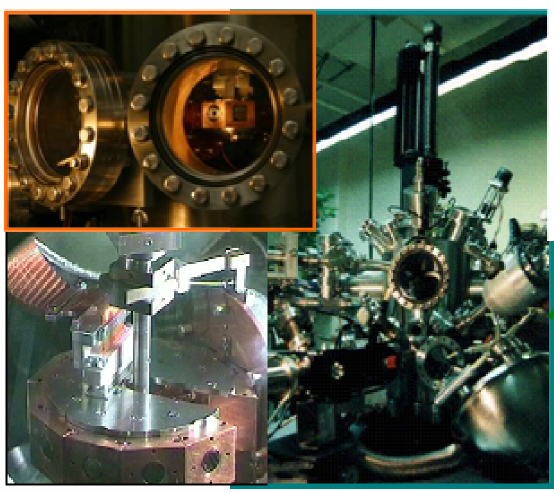






Photon Emission Measurements





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

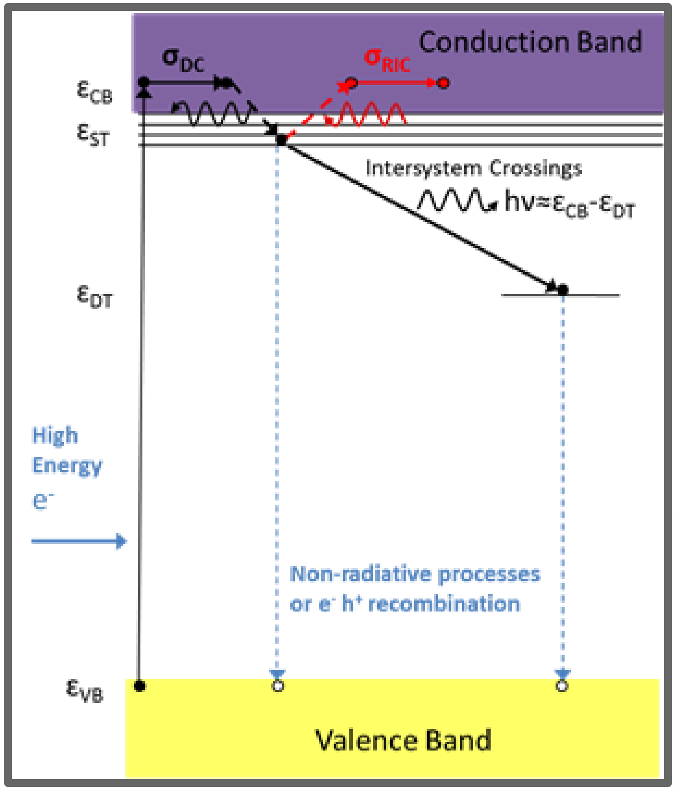
Cathodoluminescence—Deep and Shallow Trap DOS

Cathodoluminescence intensity (α emitted power)

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

Dose rate (α adsorbed power)

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

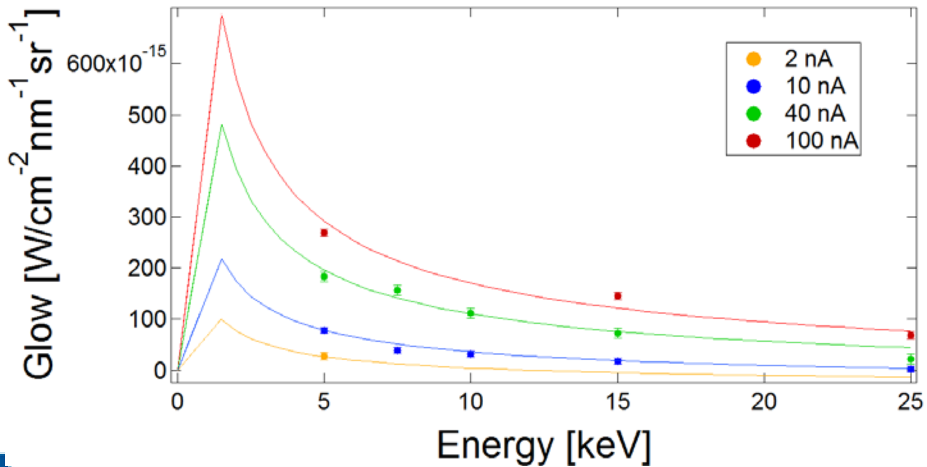


J_b: incident current density — T: temperature
E_b: incident beam energy — λ: photon wavelength
q_e: electron charge — ρ_m: mass density
ε_{ST}: shallow trap energy — $R(E_b)$: penetration range
D_{sat}: saturation dose rate — L: Sample thickness

Cathodoluminescence—E_b and Range Dependence

Incident Beam Energy

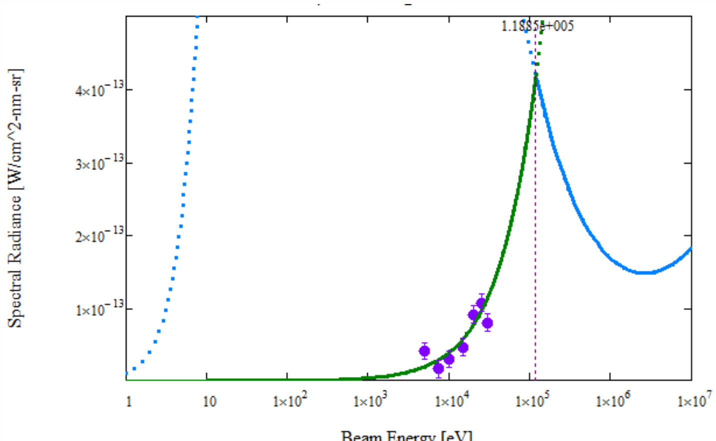
$$\dot{D}(J_b, E_b) = \frac{\boxed{E_b}\, J_b[1-\eta(\boxed{E_b})]}{q_e \rho_m} \times \begin{cases} [1/L] & ; R(E_b) < L \\ [1/R(\boxed{E_b})] & ; R(E_b) > L \end{cases}$$



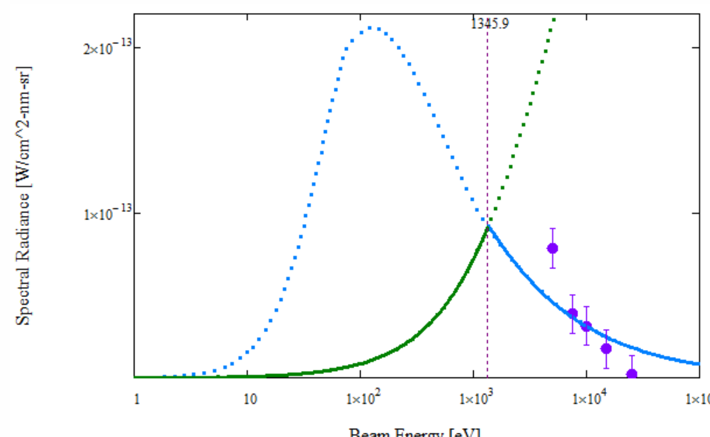
Nonpenetrating Radiation {R(E_b) < L}: all incident power absorbed in coating and intensity and dose rate are linear with incident power density

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

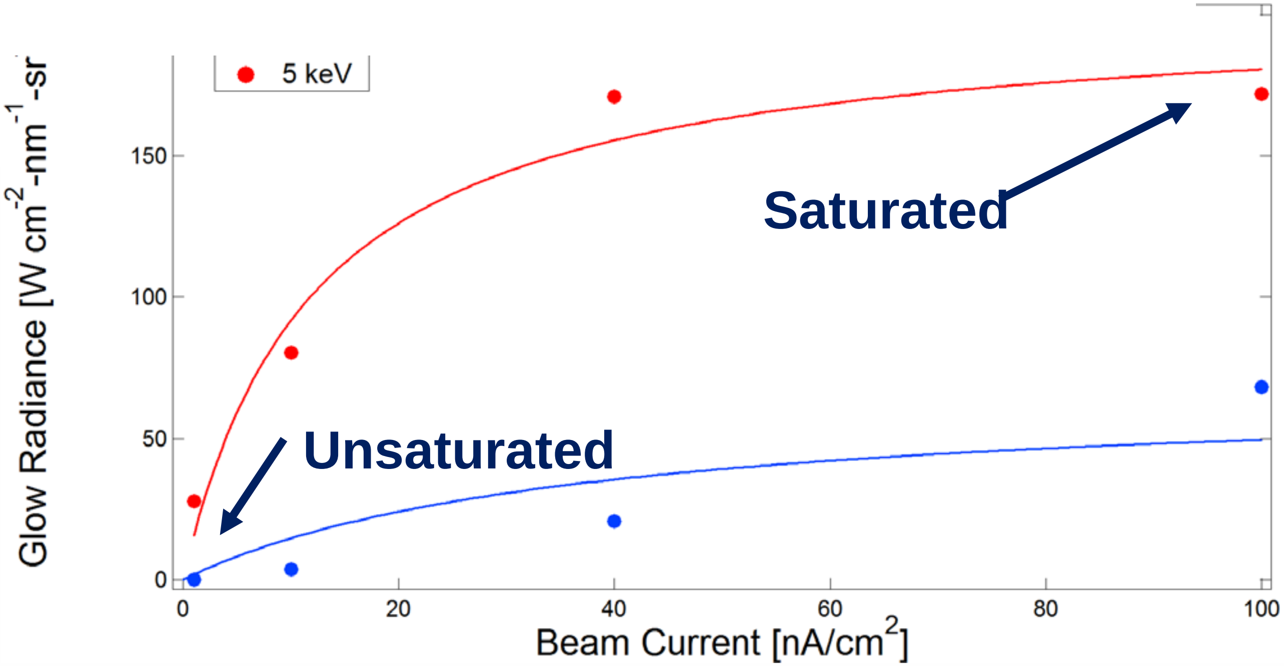
Cathodoluminescence—J_b and Dose Dependence

Cathodoluminescence intensity (α emitted power)

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

Dose rate (α adsorbed power)

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



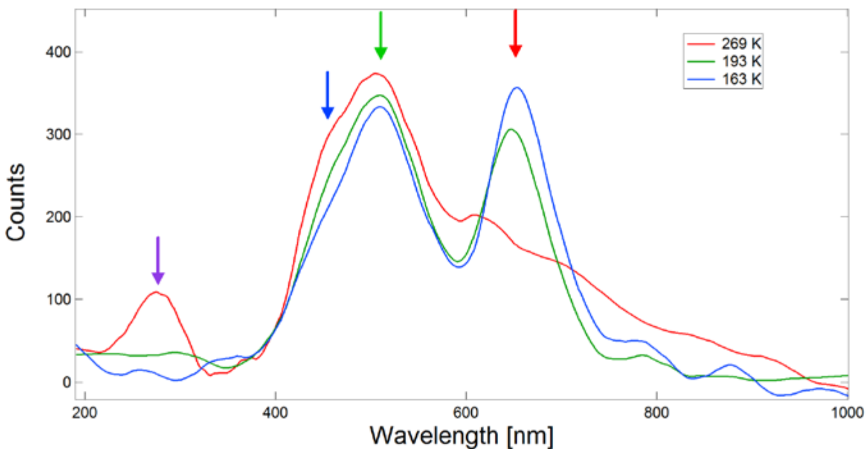
$\dot{D}_{sat}$

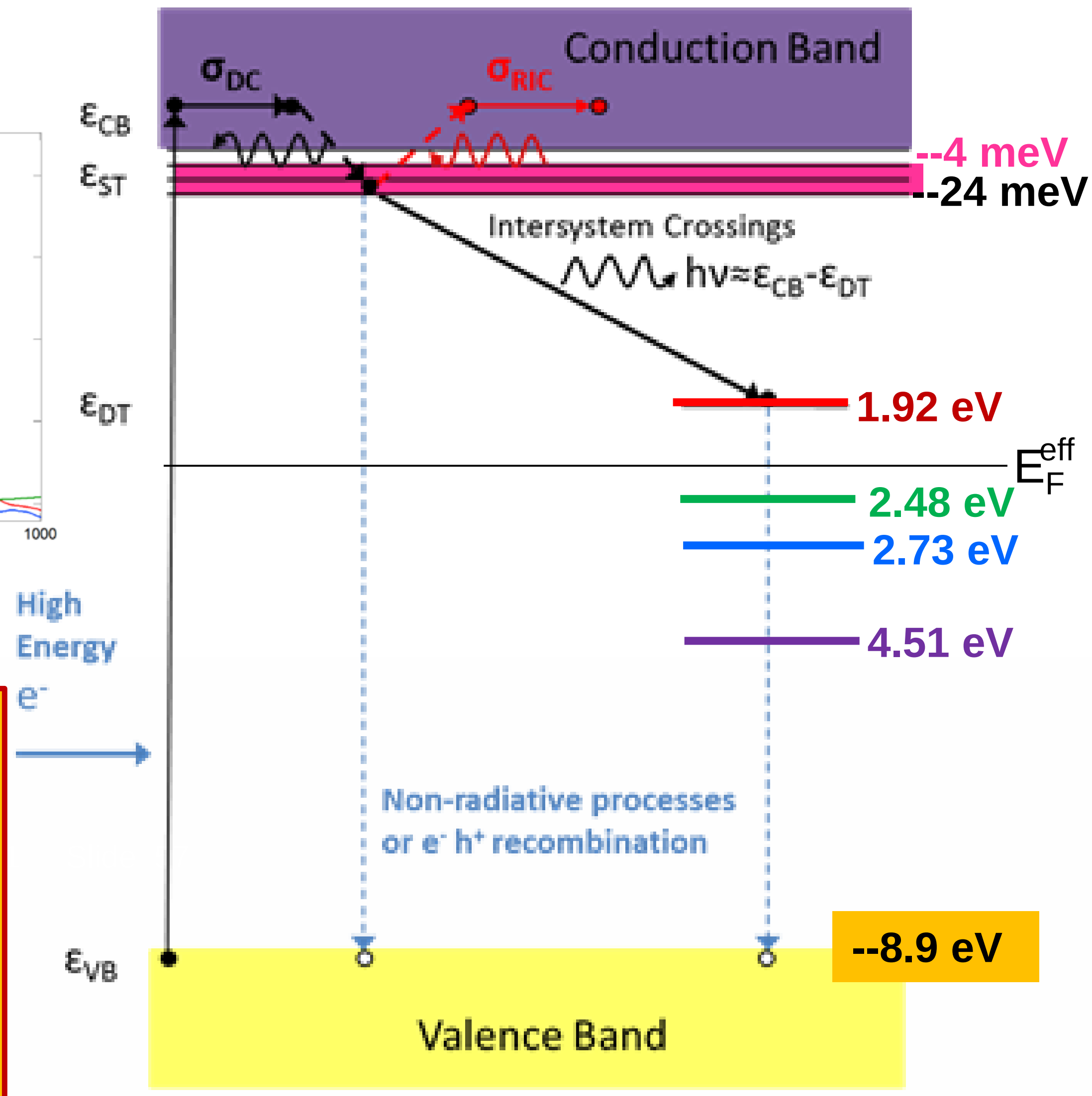
Measure of charge required to fill traps.

~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

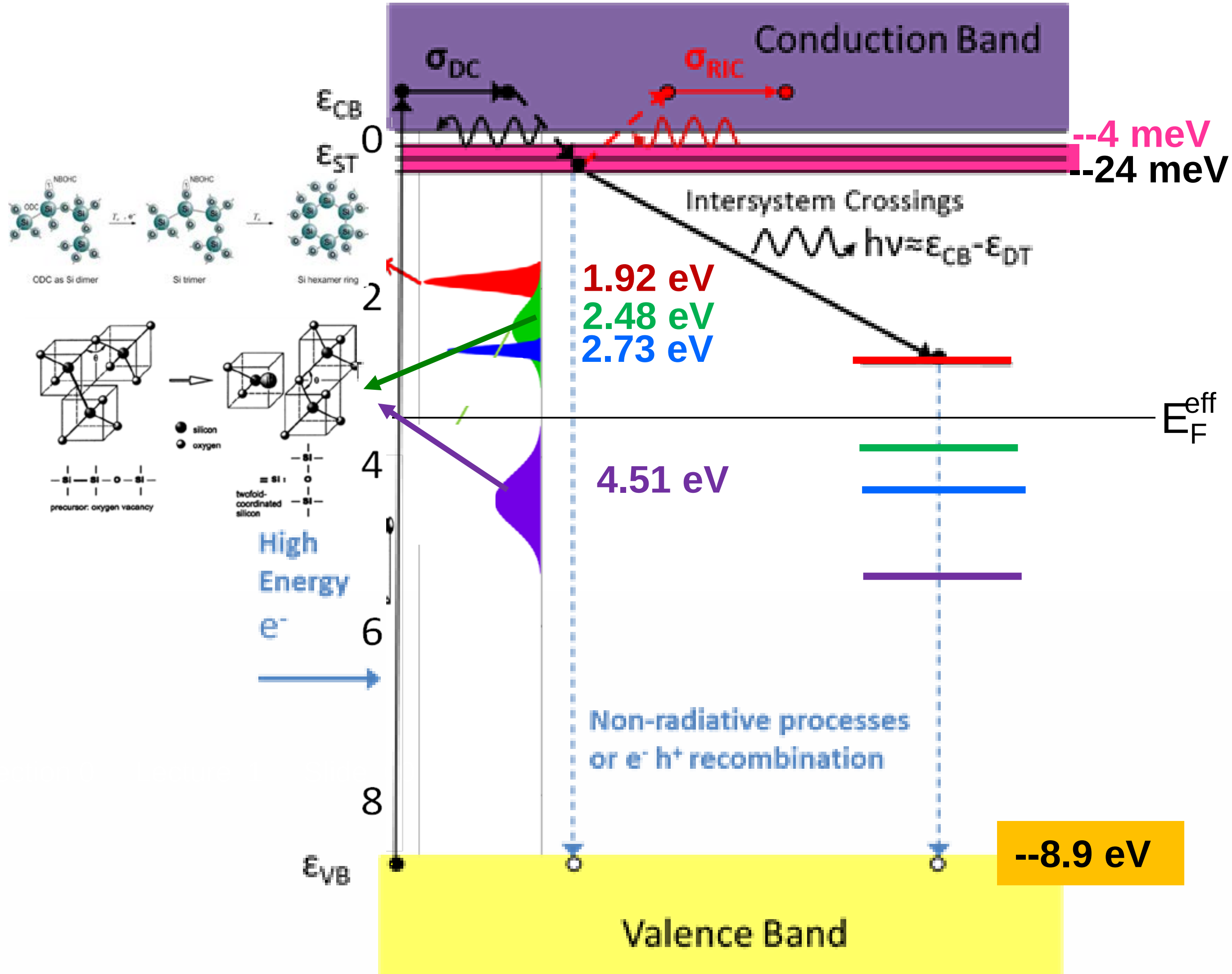
A Path Forward for Dynamic Materials Issues

For dynamic materials issues in spacecraft charging:

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

- Development of **overarching theoretical models**

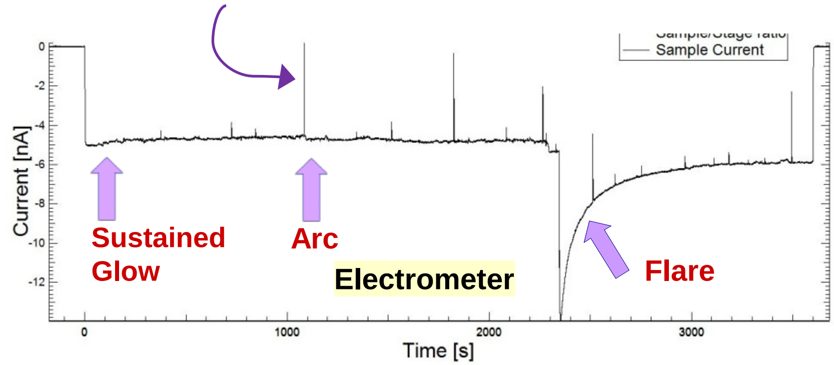
allow extension of measurements made over limited ranges of environmental parameters to make predictions for broader ranges encountered in space.

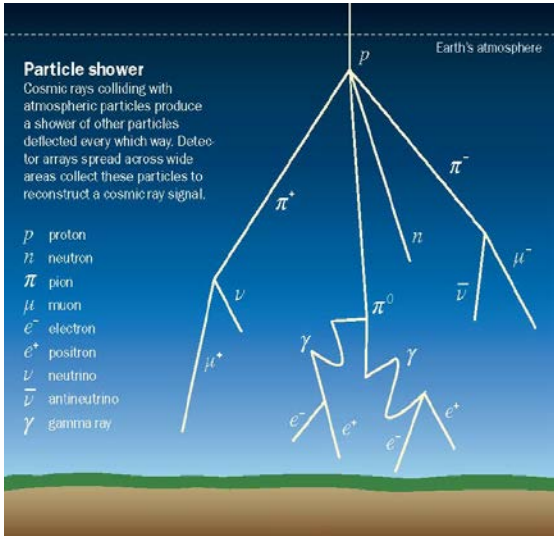


Does Cosmic Background Radiation Explain "Flares"

"Flare"

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

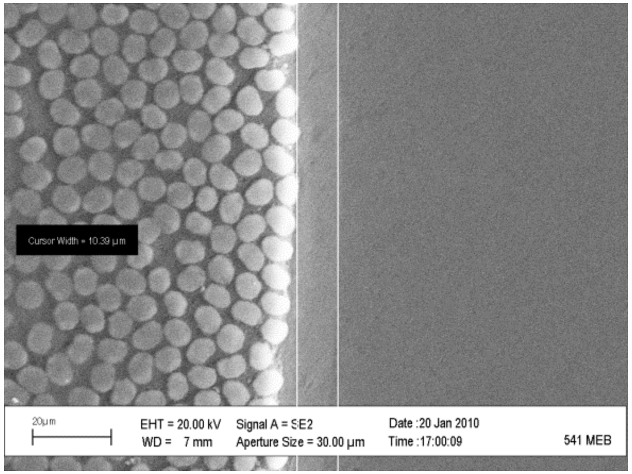




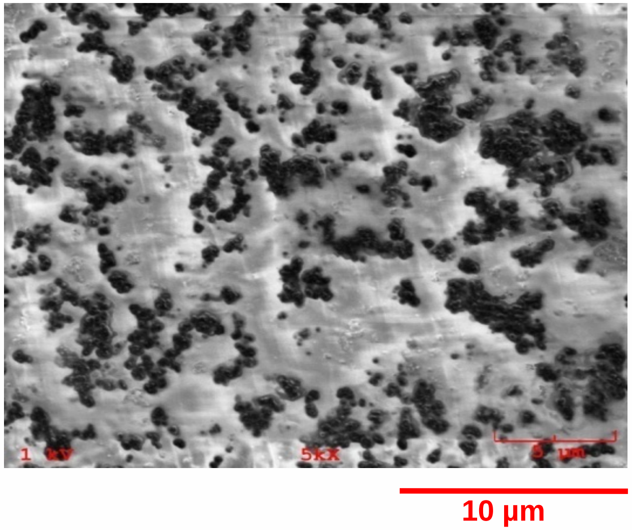
The Next Case: Multilayer/Nanocomposite Effects???

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

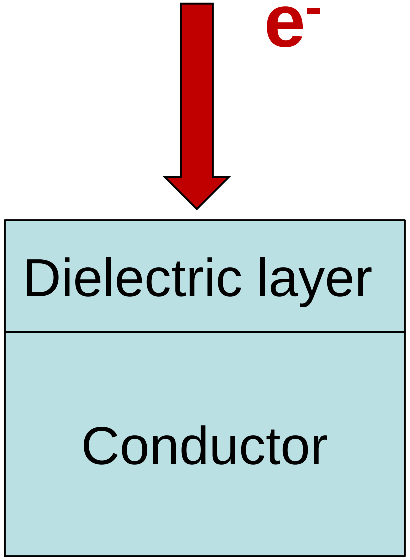
Time Scales
- Deposition times
- Dissipation times
- Mission duration



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



Black Kapton™ (C-loaded PI)



Thin ~100 nm disordered SiO_2 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:

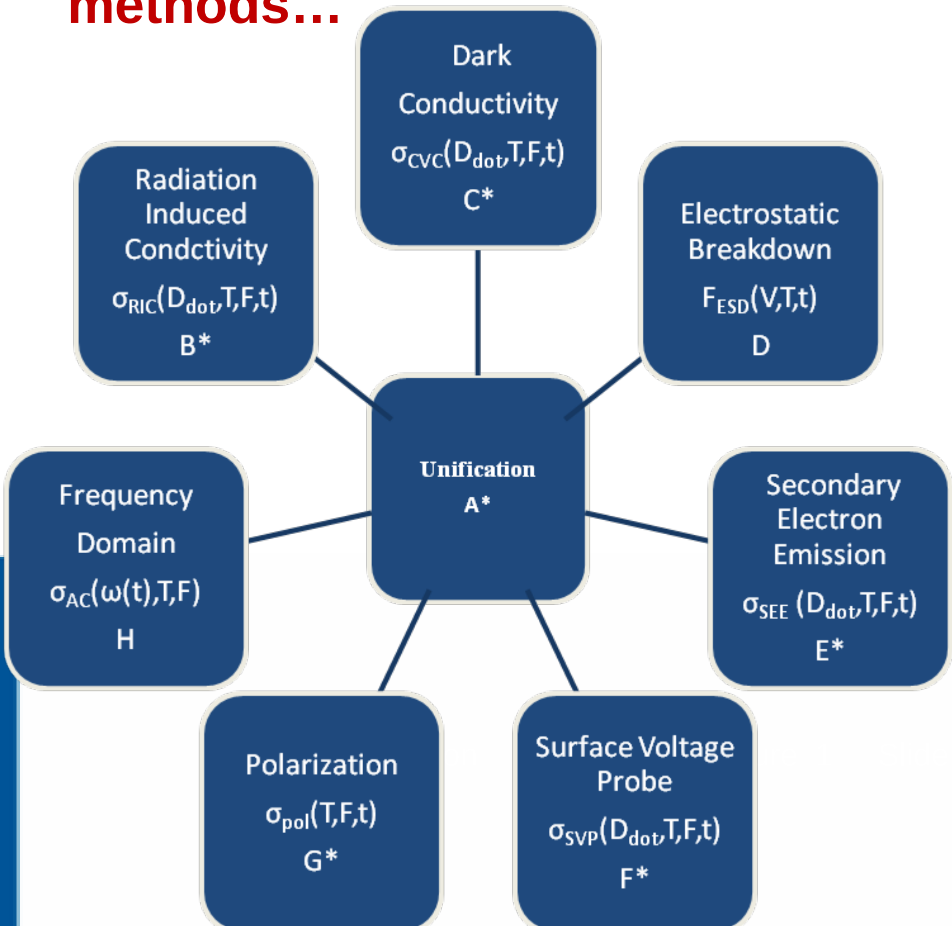
- **Myriad spacecraft materials**
- **New, evolving materials**
- **Many materials properties**
- **Wide range of environmental conditions**
- **Evolving materials properties**
- **Feedback, with changes in materials properties affecting changes of environment**

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

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

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

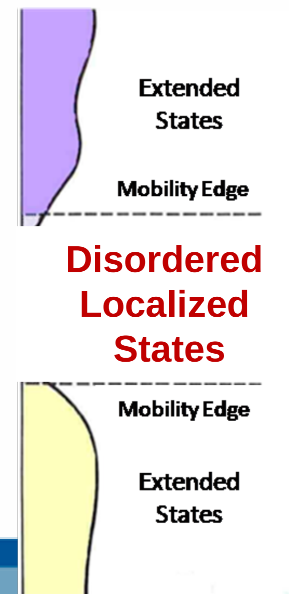
$$\frac{\partial n_{tot}(z,t)}{\partial t} - \mu_e \frac{\partial}{\partial z}[n_e(z,t)F(z,t)] - q_e D \frac{\partial^2 n_e(z,t)}{\partial z^2} = N_{ex} -$$

$$\alpha_{er}\, n_e(z,t) n_{tot}(z,t) + \alpha_{et}\, n_e(t)[N_t(z) - n_t(z,t)]$$

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

$$\frac{dn_t(z,\varepsilon,t)}{dt} = \alpha_{et} n_e(z,t)[N_t(z,\varepsilon) - n_t(z,\varepsilon,t)] -$$

$$\alpha_{te} N_e \exp\left[-\frac{\varepsilon}{kT}\right] n_t(z,\varepsilon,t)$$



…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!)