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Evolution of Materials Properties and the Space Plasma Environment through Interactions and the Dynamics of Spacecraft Charging

JR Dennison

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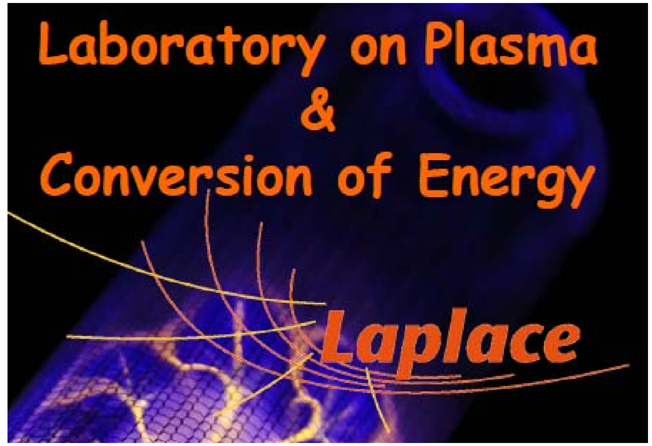
MATERIALS PHYSICS GROUP



Toulouse, France
27 June, 2013

Evolution of Materials Properties and the Space Plasma Environment through Interactions and the Dynamics of Spacecraft Charging

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Logan, Utah USA

Utah State University Materials Physics Group

Yellowstone, NP

Tetons, NP

~~Arcs~~ Arches, NP

Grand Canyon, NP

Logan, Utah

Acknowledgements

Support & Collaborations

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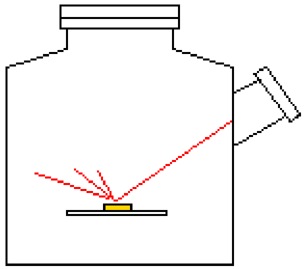
Johns Hopkins App. Phys. Lab
Orbital
USU Space Dynamics Lab

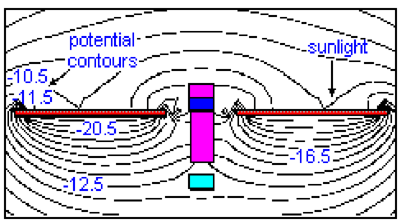
National Research Council
SpaceMasters Program

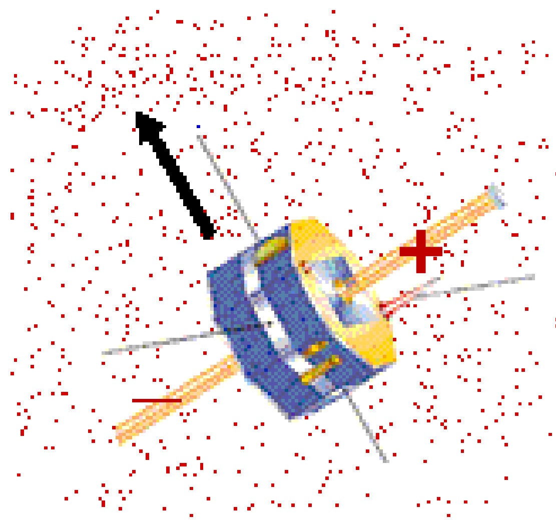
USU Materials Physics Group

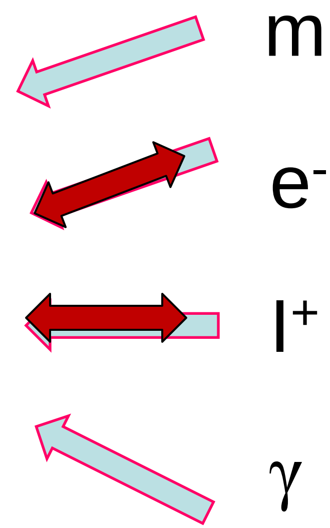
A simplified approach to spacecraft charging modeling…



Materials Properties







Spacecraft Potential Models

Satellite Moving through Space

Space Plasma Environment

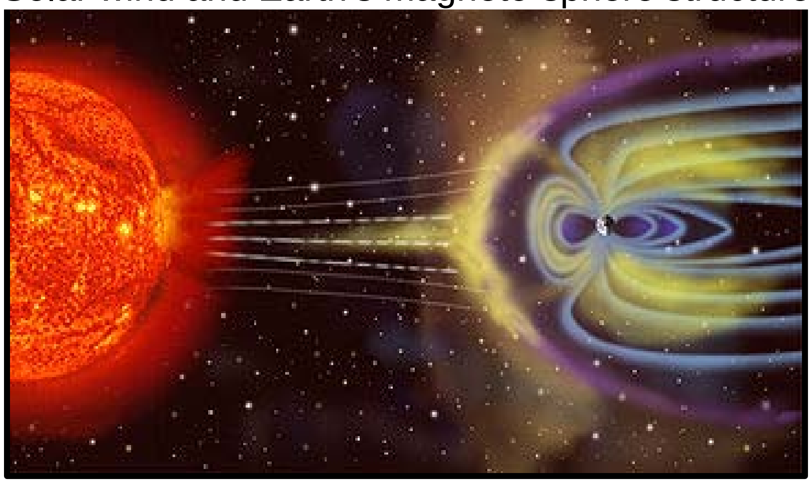
This results in a complex dynamic interplay between space environment, satellite motion, and materials properties

The Space Environment

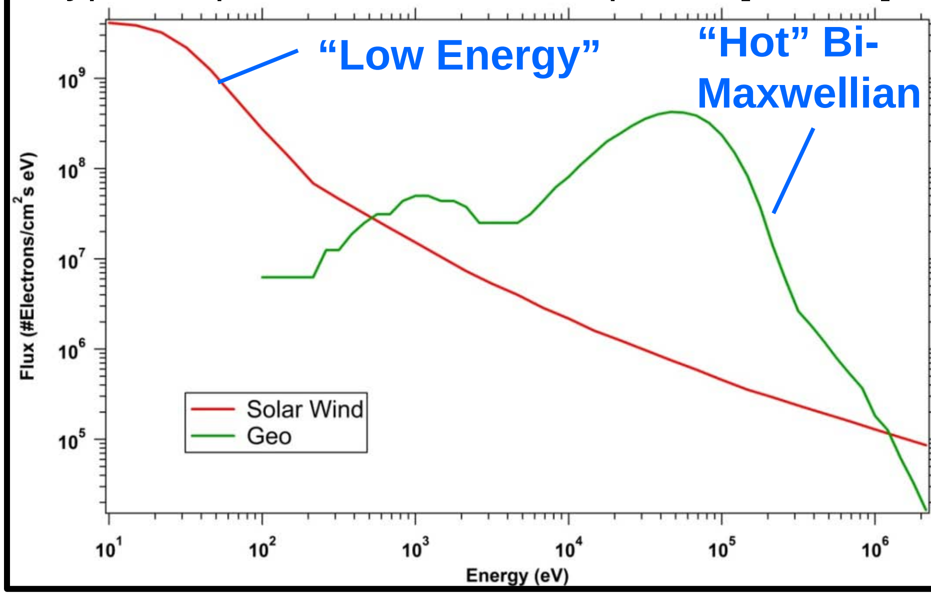
Dynamics of the space environment and satellite motion lead to dynamic spacecraft charging (min to decades)

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

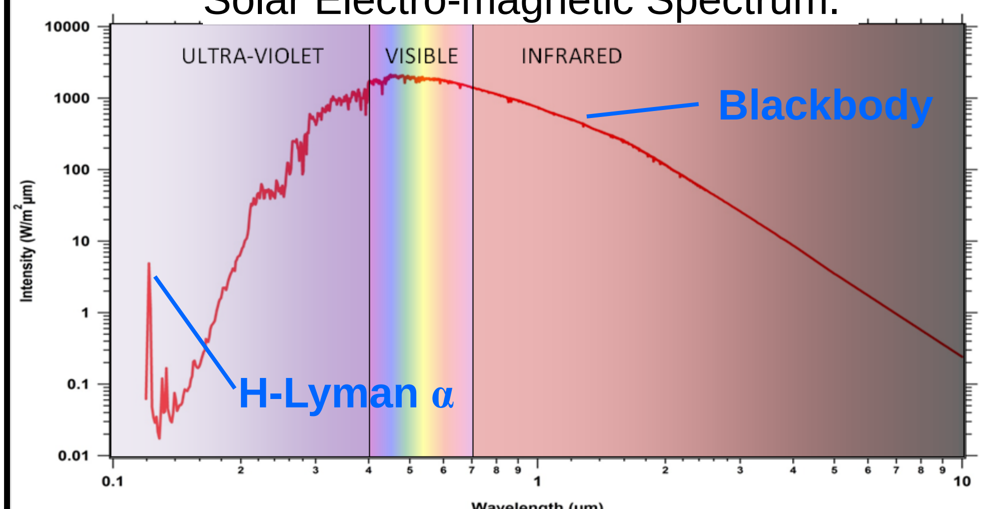
Solar wind and Earth's magneto-sphere structure.



Typical Space Electron Flux Spectra [Larsen].



Solar Electro-magnetic Spectrum.



Incident fluxes of:

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

What do you need to know about the materials properties?

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STATIC Charging codes such as NASCAP-2K or SPENVIS 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 $\langle Z_{eff} \rangle$	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·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

Focus of the Materials Physics Group—Dynamic Materials Properties

Specific focus of our work is the change in materials properties as a function of time, position, energy, and charge:

- **Time (Aging), t**
- **Position (xy,z)**
  - **Charge distributions, Q(z,t)**
  - **Surface voltage, ΔV(xy,t)**
- **Energy**
  - **Temperature, k_B T**
  - **Deposited Energy (Dose), D**
  - **Power Deposition (Dose) Rate, Ď**
- **Charge**
  - **Accumulated Charge, ΔQ or ΔV(Q, ΔV,D,Ď,t)**
  - **Charge Profiles, Q(xy,z,t)**
  - **Charge Rate (Current), Ǒ(xy,z,t)**
  - **Conductivity Profiles, σ(z,t,Q,Ǒ,D,Ď)**
  - **Electron emission (e^-, I^+, Γ)**
- **Light emission**
  - **Cathodoluminescence $I_Γ$(t,xy,Q,D,Ď)**
  - **Arcing $I_Γ$(t,xy,Q,D,Ď), $Ǒ_Γ$(t,xy,z,Q,D,Ď)**

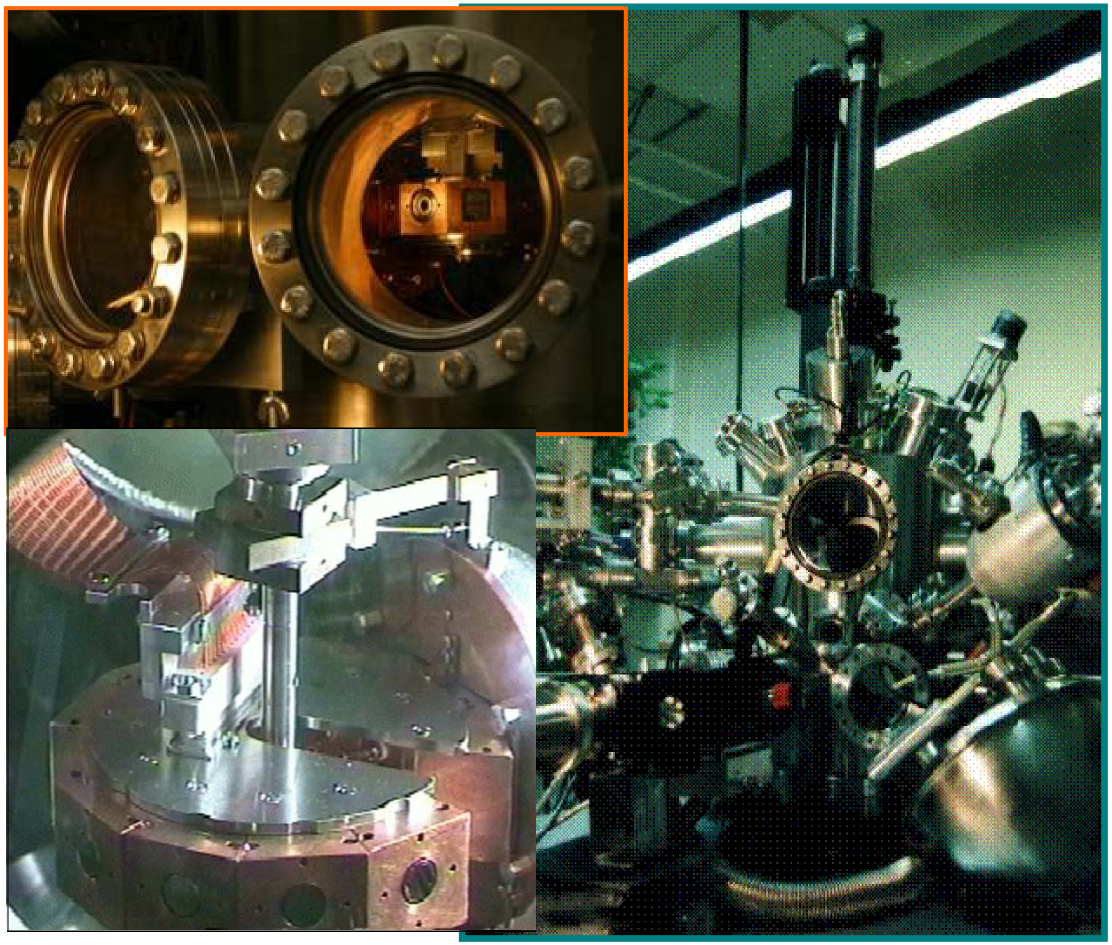
Materials Physics Group Measurement Capabilities

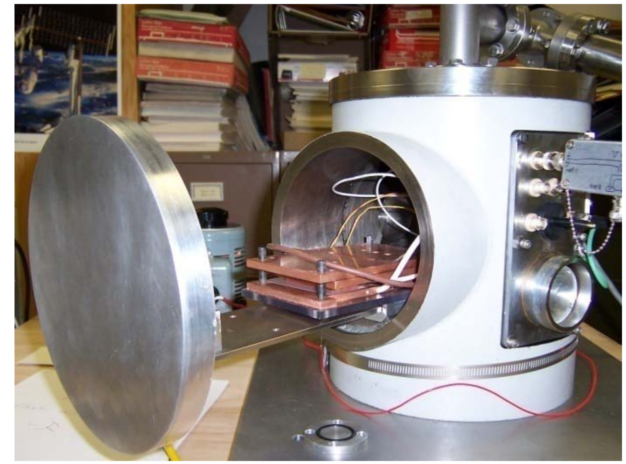
Electron Emission
Ion Yield

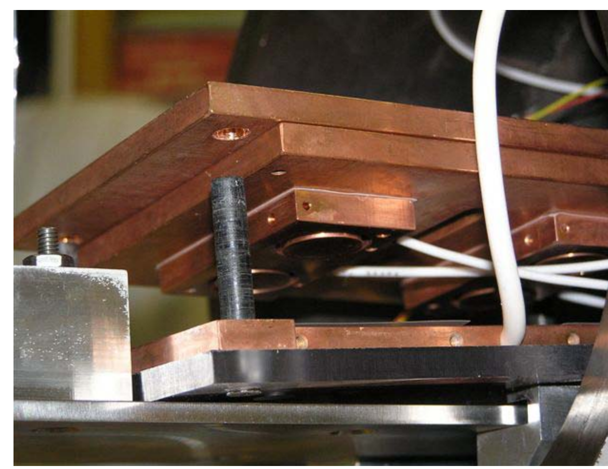
Photoyield
Luminescence

Conductivity
Electrostatic Discharge

Radiation Induced Cond.
Radiation Damage





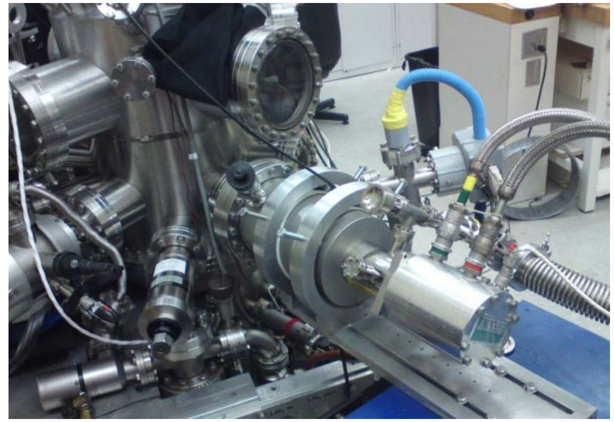


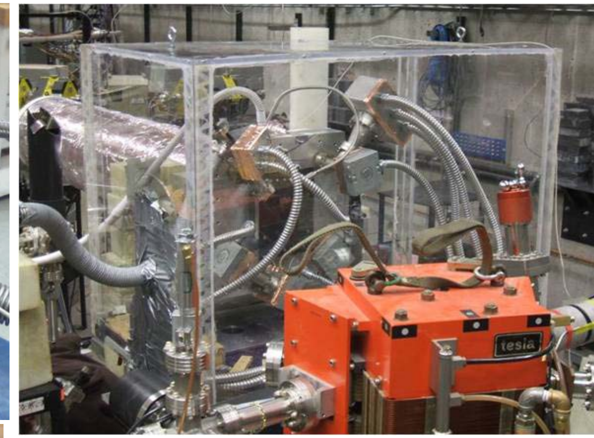
Dependence on: Time, Pressure, Temperature, Charge, E-field, Dose, Dose Rate

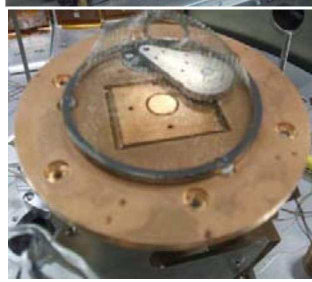
USU Experimental Capabilities

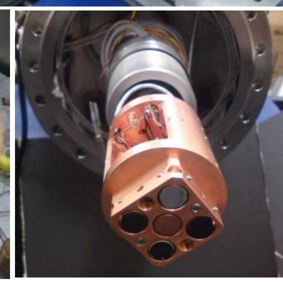
Absolute Yields

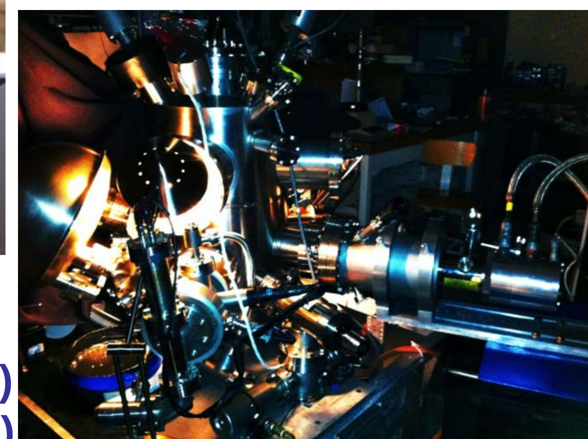
- SEE, BSE, emission spectra , (<20 eV to 30 keV)
- Angle resolved electron emission spectra
- Photoyield (~160 nm to 1200 nm)
- Ion yield (He, Ne, Ar, Kr, Xe; <100 eV to 5 keV)
- Cathodoluminescence (200 nm to 5000 nm)
- No-charge “Intrinsic” Yields
- T (<40 K to >400 K)











Other Capabilities

- Conductivity (<10^{-22} [ohm-cm]$^{-1}$)
- Surface Charge (<1 V to >15 kV)
- ESD (low T, long duration)
- Radiation Induced Conductivity (RIC)
- Evolution of internal charge distributions (PEA)
- Multilayers, contamination, surface modification
- Radiation damage
- Modeling
- Sample Characterization

Instrumentation Overview

Sadly (for an experimentalist) there is no time for this!

(Perhaps you will ask a question)

Examples of Dynamical Change in Materials

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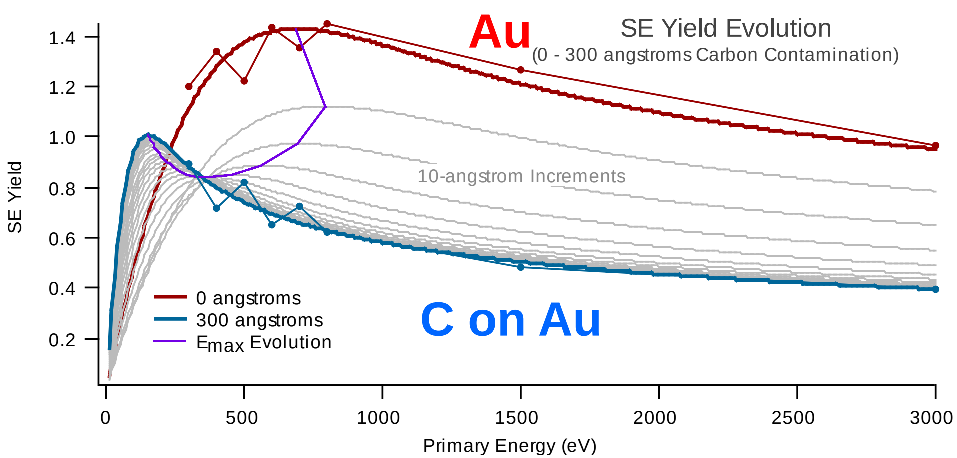
I. Contamination and Oxidation
II. Reflectivity as a Feedback Mechanism
III. Radiation Effects (and t)
IV. Temperature Effects (and t)
V. Radiation and Temperature Effects
VI. Charge Accumulation Effects
VII. Multilayer/Nanocomposite Effects

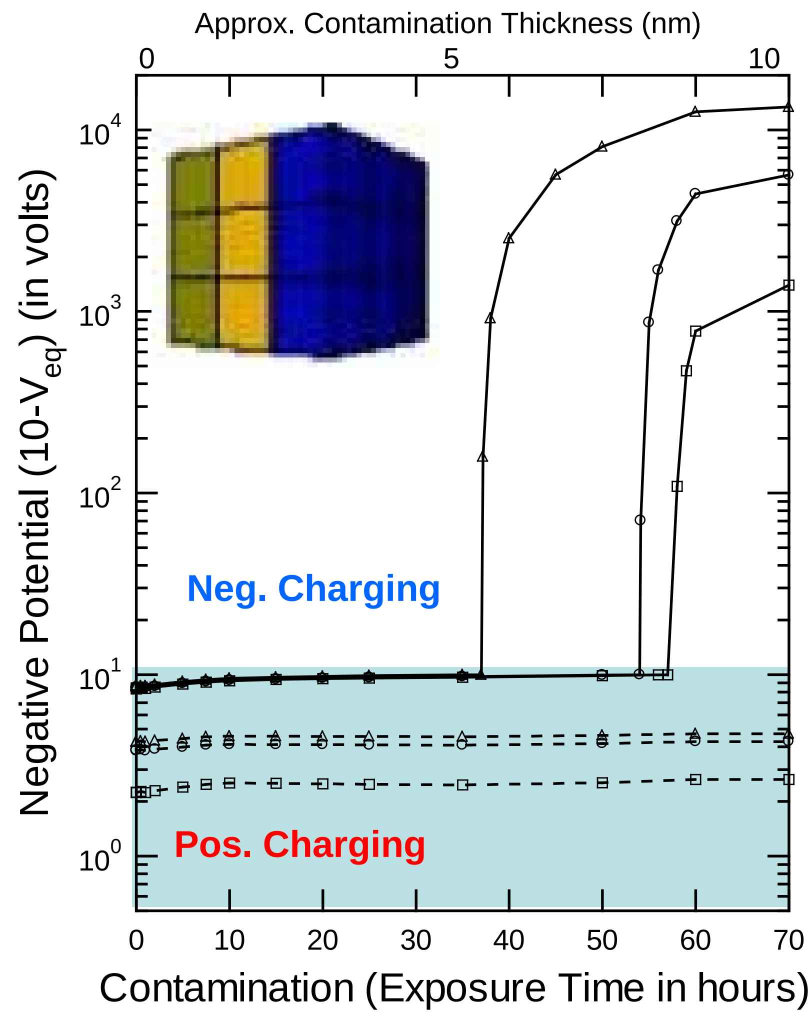
Case I: Evolution of Contamination and Oxidation

Build up of C contamination on Au by long-duration, high current keV electron beam

Common to SEM work



Davies, Kite, and Chang



"All spacecraft surfaces are eventually carbon…"

--C. Purvis (lead for NASCAP)

Threshold differential charging at ~5 nm of contamination!!!

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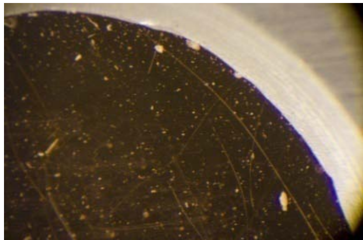
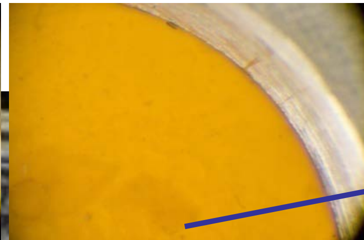
Case I: Evolution of Contamination and Oxidation



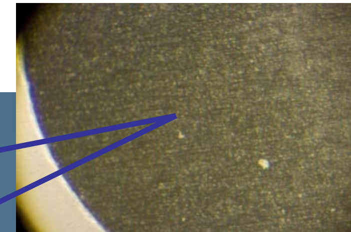


Before

After

Kapton

AO and UV degradation
(AO fluence standard)

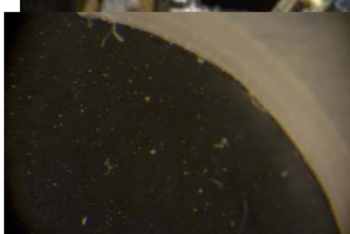


Before

After

Ag

AO degradation
(AO fluence standard)

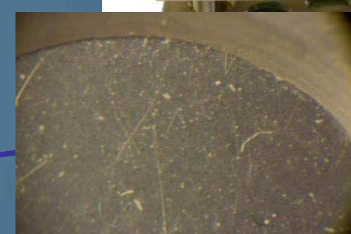


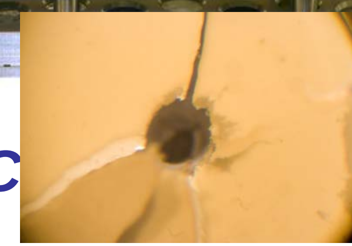
Before

After

Black Kapton

Surface modified by AO, UV





C 6

Before

After

Al coated PET

AO, UV and particle impact!

Dennison, Evans and Prebola, IEEE-TPS 2012.

168 Sample with 18 mon exposure on ISS

Ram, wake and "layered" exposure to: AO, UV, vacuum, ΔT

Case II: Reflectivity as a Feedback Mechanism

Reflectivity changes with surface contamination, oxidation and roughness

Reflect→Charging→Contamination

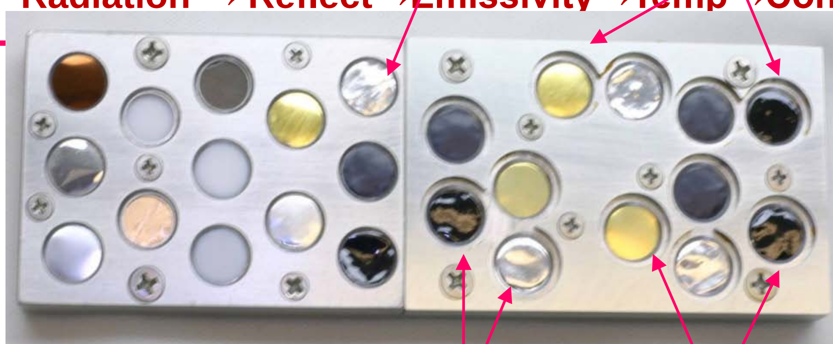
Reflect→Emissivity→Temp→Contamination

Charging→ Reflectivity

Radiation → Reflect→Emissivity→Temp→Contamina

Grounded Guard Plate

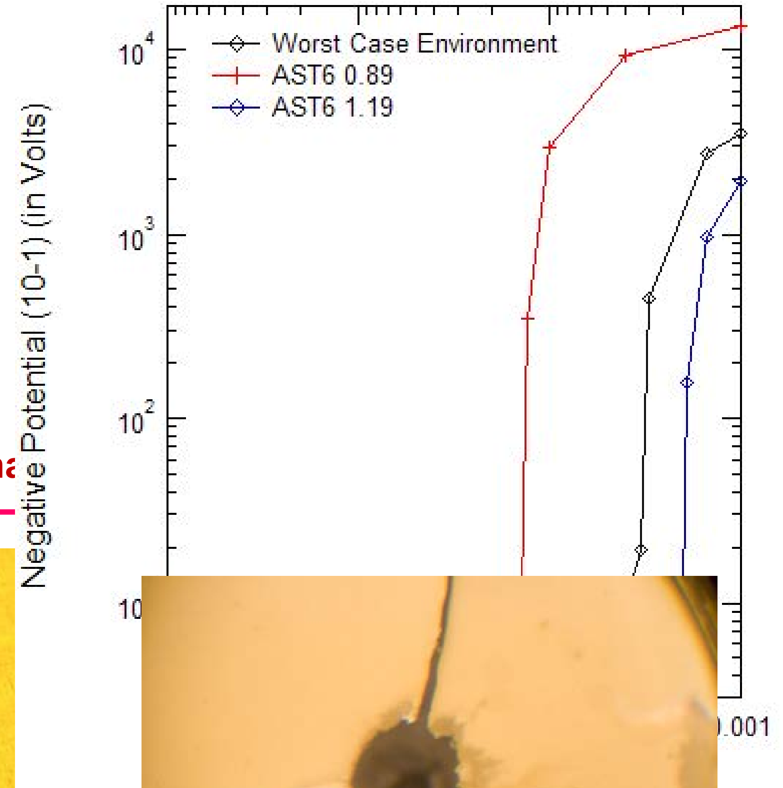
-5 VDC

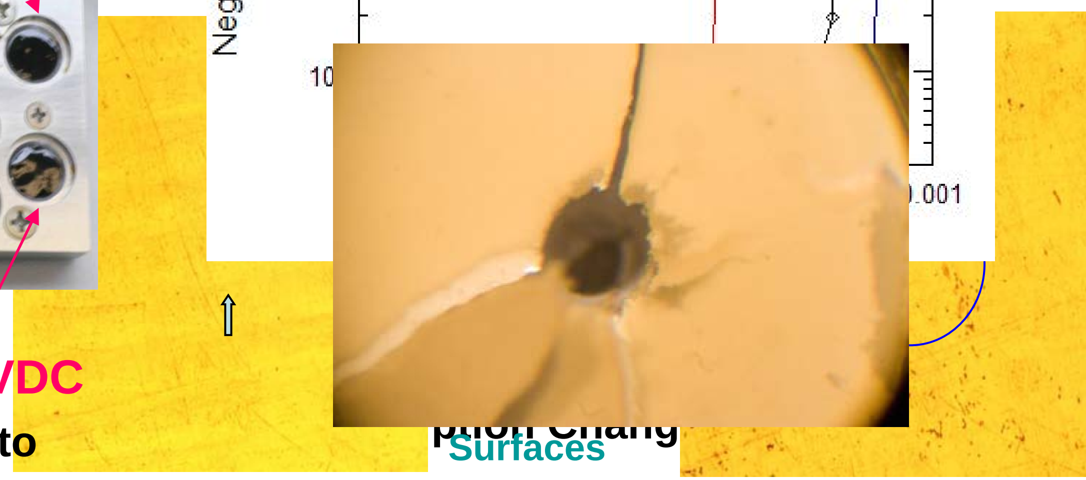


+5 VDC

-15 VDC

4 samples held a constant potential to test charge enhanced contamination





See Lai & Tautz, 2006 & Dennison 2007

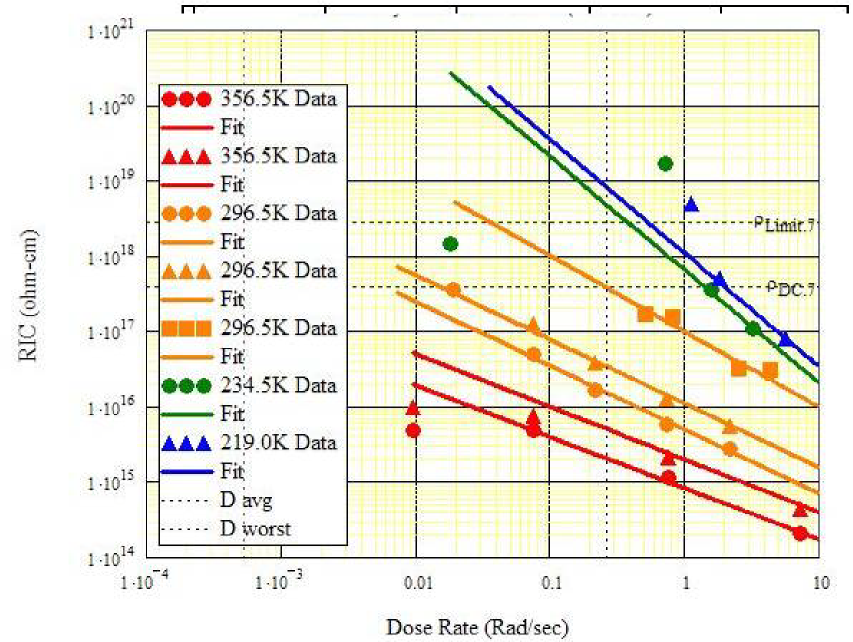
Radiation Damage (Color Change) of PET

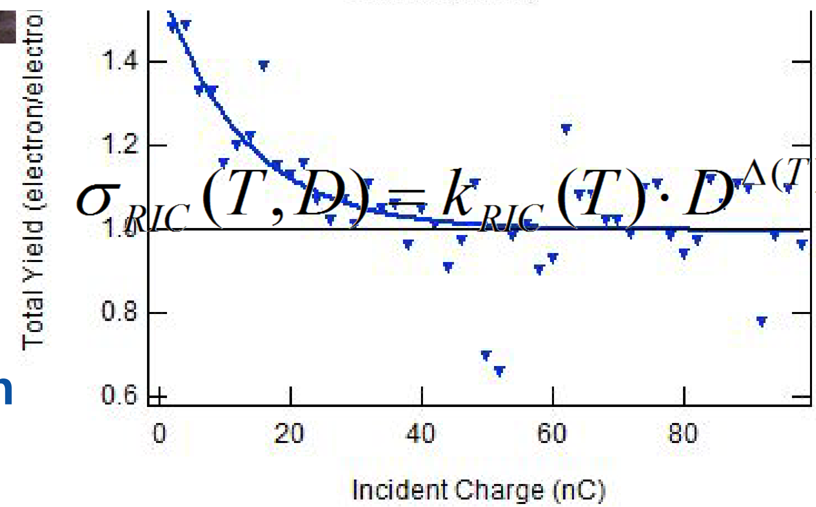
Case III: Radiation Effects

Large Dosage (>10^8 Rad)

Medium Dosage (>10^6 Rad)

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





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

Examples: RBSP, MMS, JUNO, JGO/JEO

Examples: JWST, SPP, Comm Sats.

Examples: RBSP, JUNO, JGO/JEO

Mechanical Modification of Electron Transport and Emission Properties

Radiation Induced Conductivity (RIC)

Mechanical and Optical Materials Damage

Temperature dependant trap filling and depletion

Caused by trap creation and filling

Caused by bond breaking and trap creation

(Hoffmann & Sim)

(Gillespie & Sim)

Case IV: Temperature Effects

Strong T Dependence for Insulators

Charge Accumulation

- Electron Emission
- Charge Recombination

Charge Transport

- Conductivity
- RIC
- Permittivity
- Electrostatic Discharge

Examples:

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

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

Inner Planetary Mission
SPM, Ulysses, Magellan, Mariner

Case IV: Temperature Effects—A "Perfect Storm"

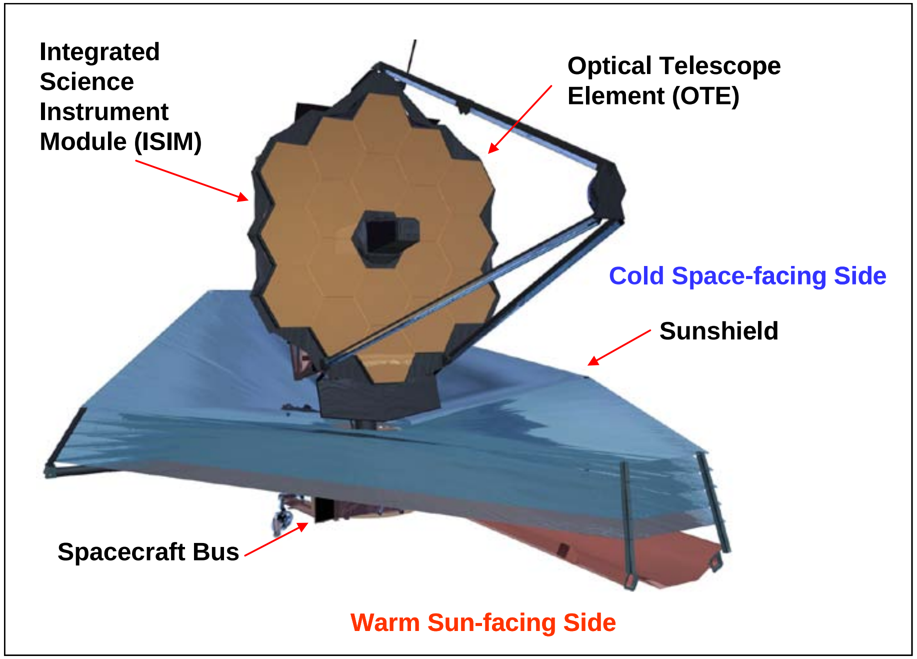
JWST

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

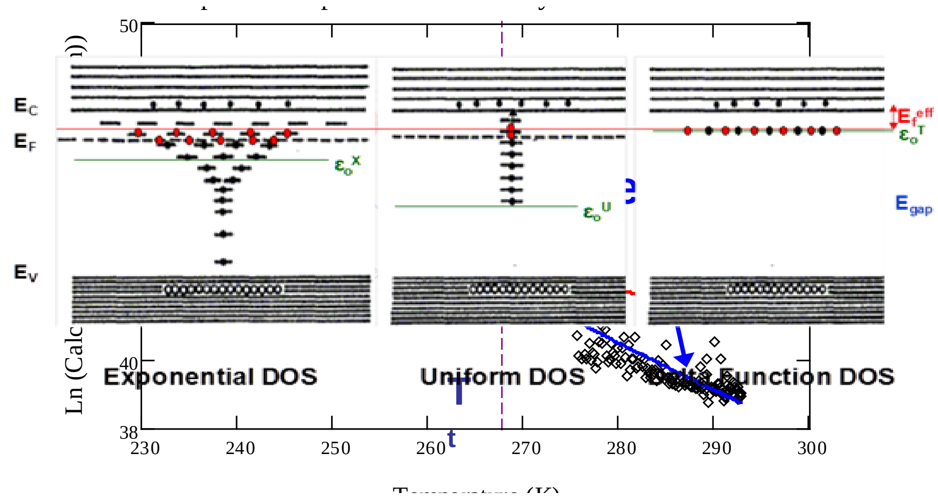


Variation in Flux
Large solar activity variations
In and out of magnetotail

Complex, Sensitive Hardware
Large sensitive optics
Complex, cold electronics

Case IV: Temperature Effects in Charge Transport

Strong T Dependence for Insulators

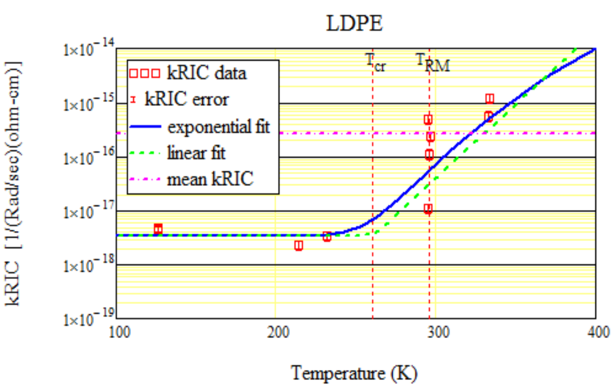


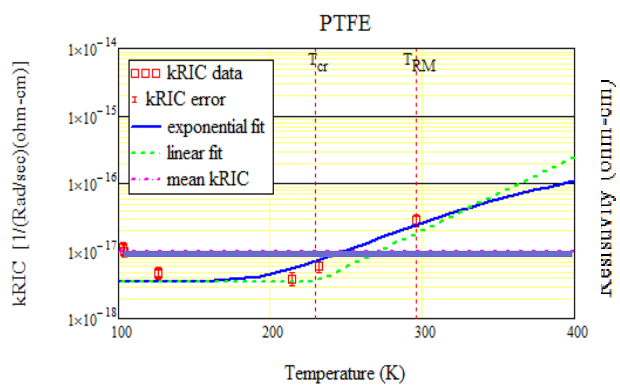
Charge Transport

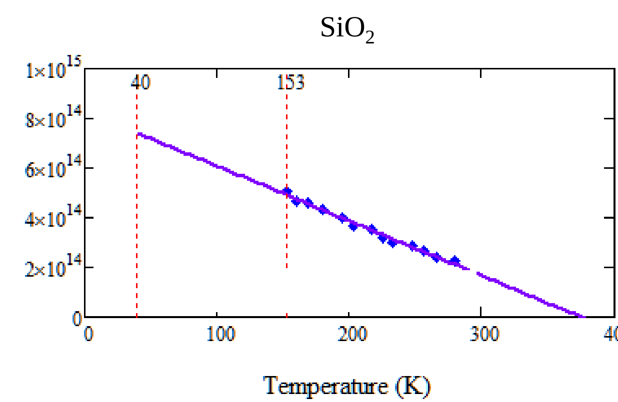
- **Conductivity**
- **RIC**

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

Exponential Trap Density	Uniform Trap Density	Delta Function Trap Density
$\Delta(T) \rightarrow {T_c}/{T+T_c}$	$\Delta(T) \rightarrow 1$	$\Delta(T) \rightarrow 1$
$k(T) \rightarrow k_{RIC1}\left[2\left(\frac{m_e k_B T}{2\pi\hbar^2}\right)^{3/2}\left(\frac{m_e^* m_h^*}{m_e m_e}\right)^{3/4}\right]^{\frac{T}{T+T_c}}$	$k(T) \rightarrow k_{RICo}$	$k(T) \rightarrow k_{RICo}\ T$







Case V: Temperature and Dose Effects

Solar

- *Miss*
- *Mate*

Hoffma

- *Evol*

Doneg

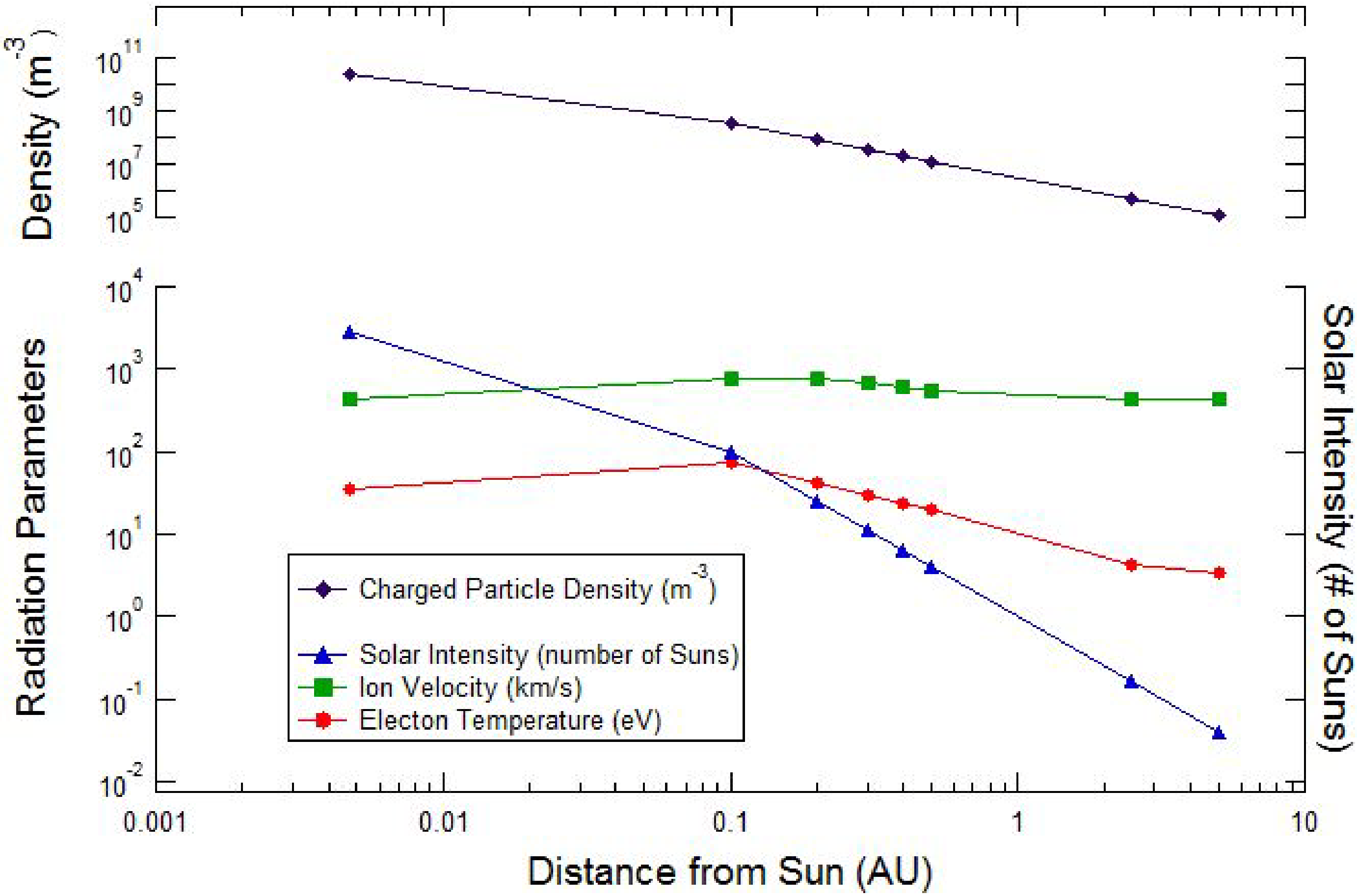
Hoffma

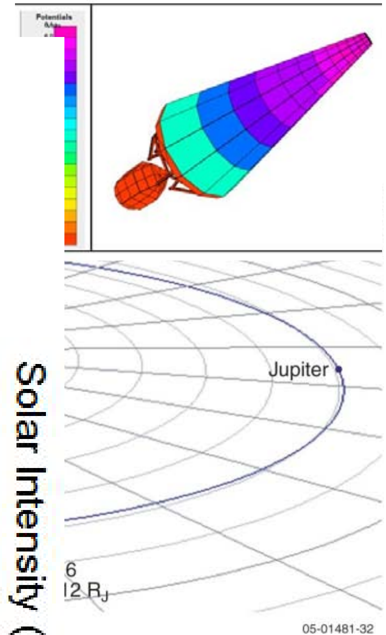
(See

- *Revis*

chargi

(See





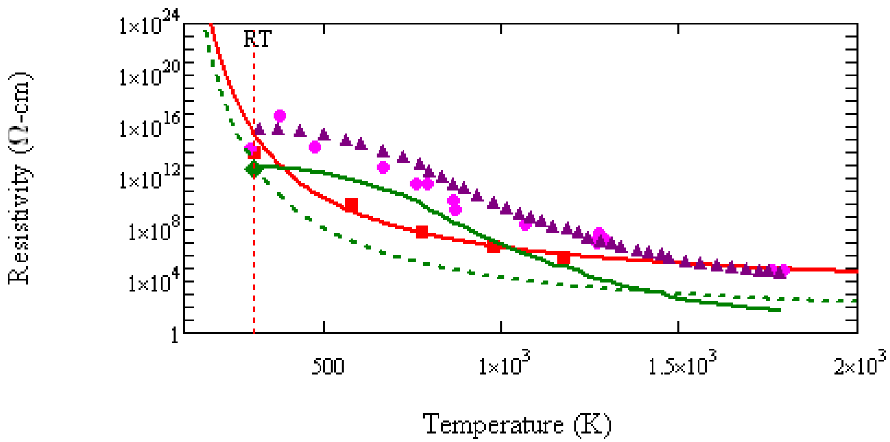
Wide Orbital Range
Earth to Jupiter Flyby
Solar Flyby to 4 R_s

WideTemperature Range
<100 K to >1800 K

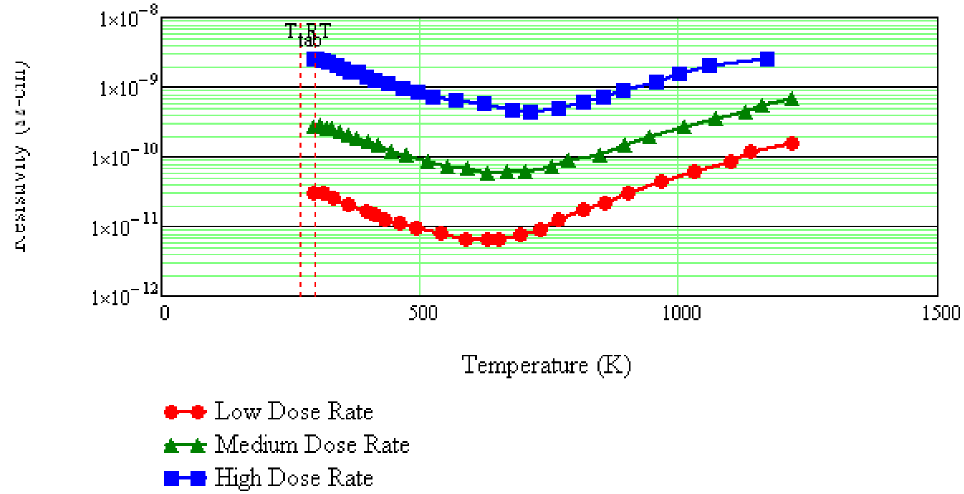
Wide Dose Rate Range
Five orders of magnitude variation!

Case V: 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

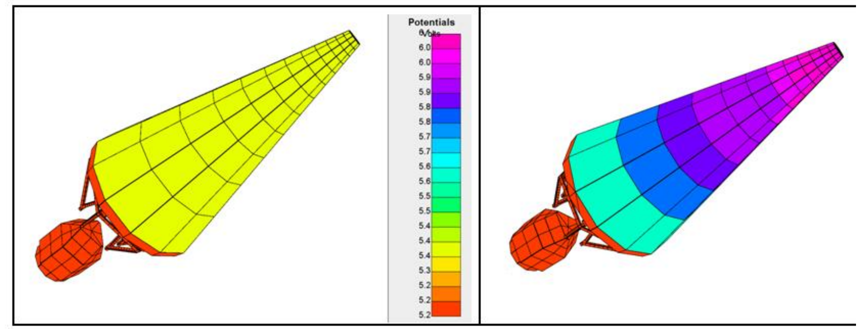
$$\varepsilon_r(T) = \varepsilon_{RT} + \Delta_\varepsilon (T - 298\,K)$$

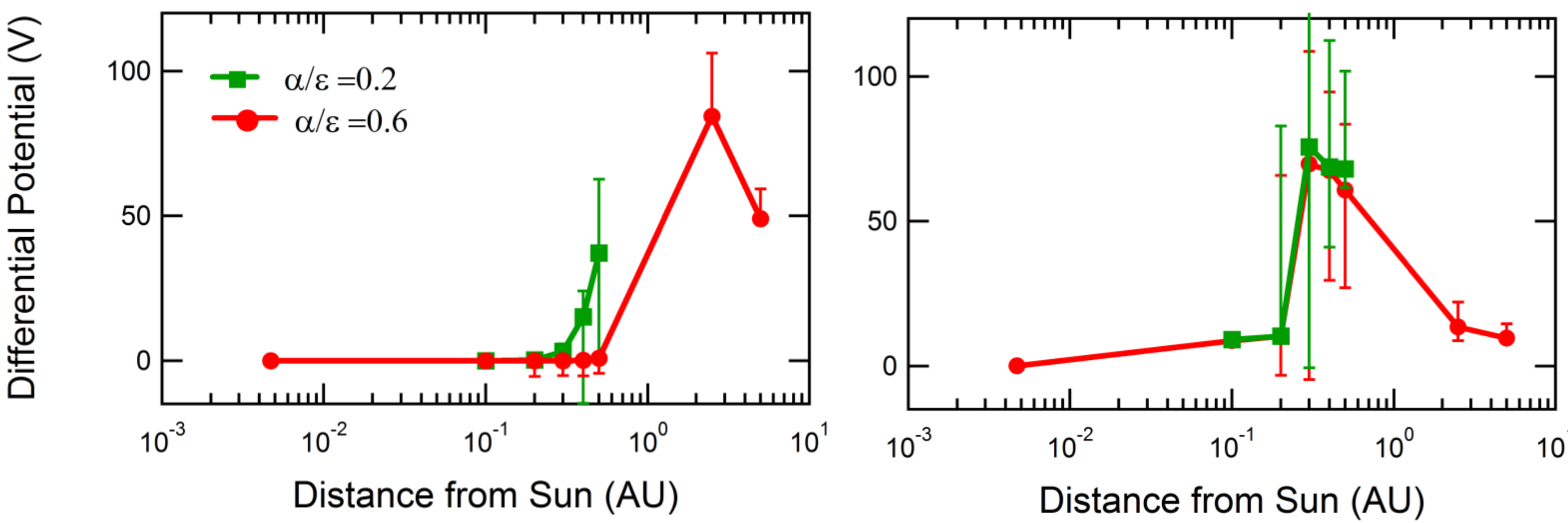
Electrostatic Breakdown

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

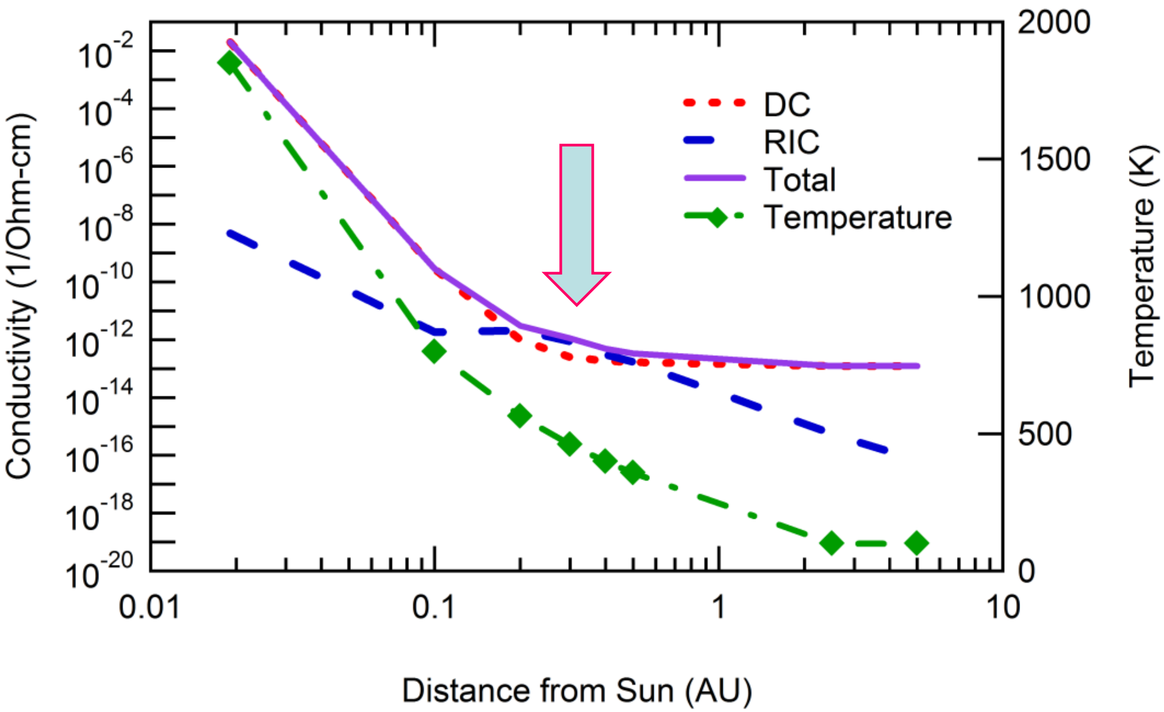
Case V: Temperature and Dose Effects

Charging model using T and r dependant inputs at various orbits predict a peak in charging at ~0.3 to 2 AU





Case V: Temperature and Dose Effects



General Trends

Dose rate decreases as $\sim r^{2}$

T decreases as $\sim e^{-r}$

σ_{DC} ***decreases as*** $\sim e^{-1/T}$

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

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 VI: Charge Effects of Yields, Currents & Surface Voltage

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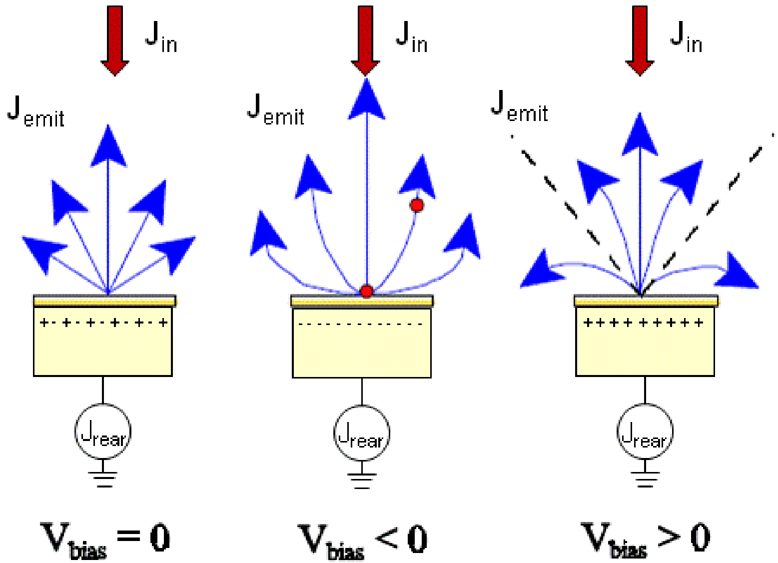
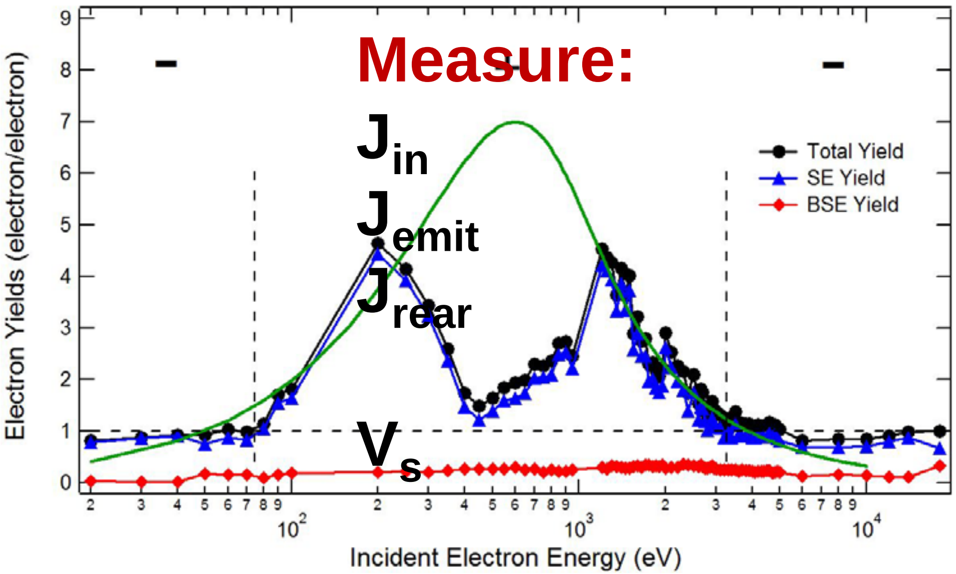
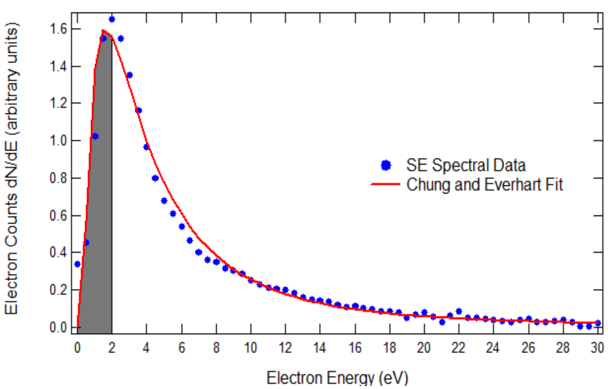
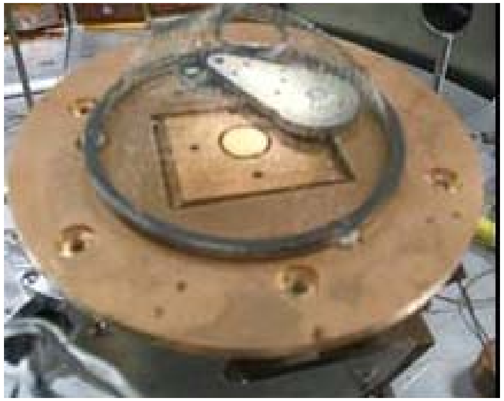
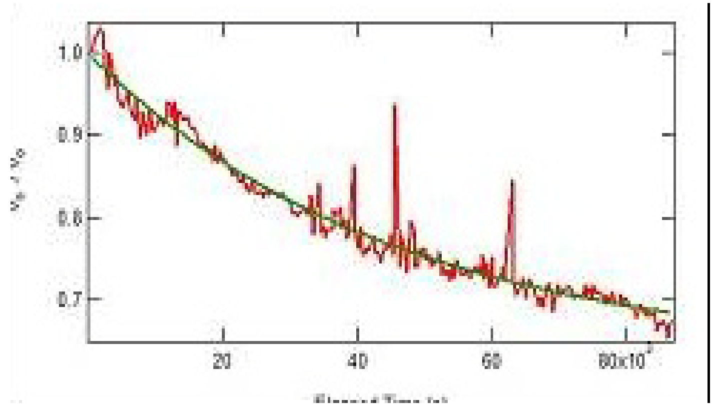








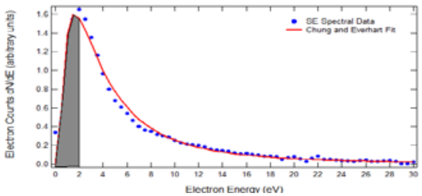


Surface Voltage Relates to “Intrinsic” Yield Model

Combining all the pieces

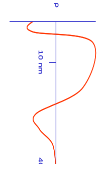
$$\frac{\delta_i(E_o,Q_i)}{\delta_o(E_o)} = \frac{\displaystyle\int_{eV_s(Q_i)}^{50\ eV} \frac{dN(E;E_o)}{dE}\,dE}{\displaystyle\int_{0\ eV}^{50\ eV} \frac{dN(E;E_o)}{dE}\,dE}$$

Physics based model for yield SE recapture as a function of incident fluence



$$V_s = \frac{Q_o(\sigma-1)d}{\varepsilon_o\varepsilon_r A_o} - \frac{\sigma Q_o\lambda_{SE} + Q_o R}{2\varepsilon_o\varepsilon_r A_o}$$

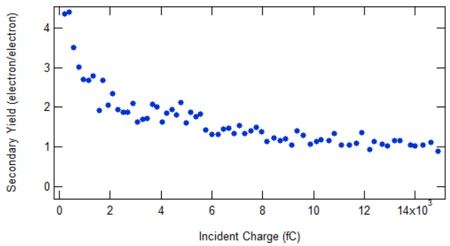
DDLM model for surface potential



Depth profile for net positive charging

$$\sigma(E_o Q) = \eta(E_o) + \delta(E_o Q)$$

Decay curve data



$$\delta(eV_S) = (\sigma_o(E_o) - 1)\cdot\left(1 - \frac{\lambda_{se}}{2\cdot d}\right)\cdot\left(\frac{\dfrac{h(\varepsilon_S)}{h(50\cdot eV)} - 1}{\dfrac{h(0)}{h(50\cdot eV)} - 1}\right) - \left[\eta_o\cdot\left(1 - \frac{\lambda_{se}}{2\cdot d}\right) - \left(1 + \frac{R}{2\cdot d}\right)\right]$$

- Analytic solution for SE yield as V_s changes with J_{in}
- Walden/Wintle model modified for electron beam injection gives:
  - o V_s in terms of J_{in}
  - o J_{rear} in tems of J_{in}

Case VII: Multilayer/Nanocomposite Effects

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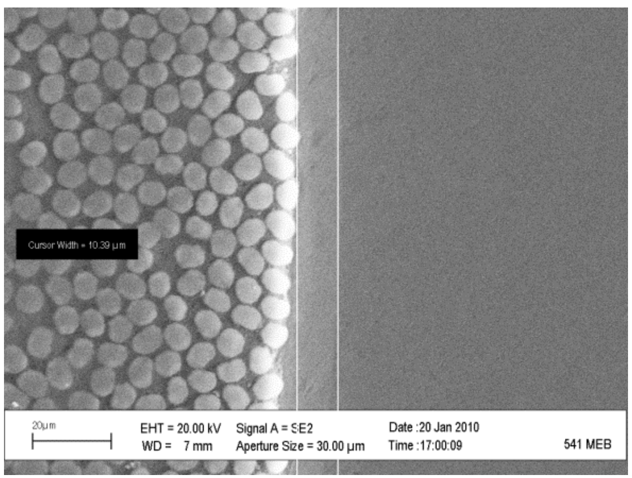
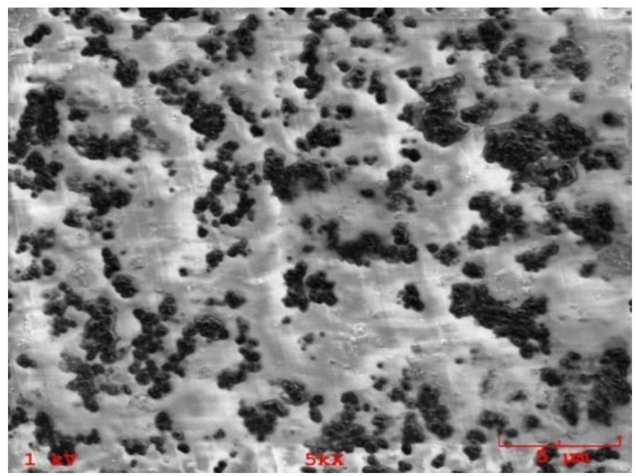
Length Scale
- Nanoscale structure of materials
- Electron penetration depth
- SE escape depth

Time Scales
- Deposition times
- Dissipation times
- Mission duration

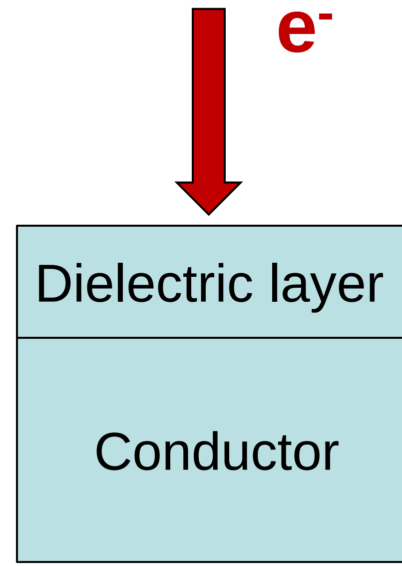


C-fiber composite with thin ~1-10 µm resin surface layer



10 µm

Black Kapton™ (C-loaded PI)



Thin ~100 nm disordered SiO_2 dielectric coating on metallic reflector

Diversity of Emission Phenomena in Black Kapton

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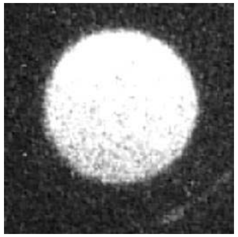
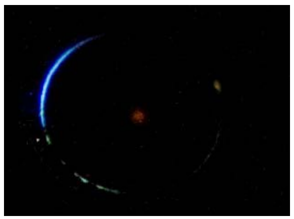
MATERIALS PHYSICS GROUP

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



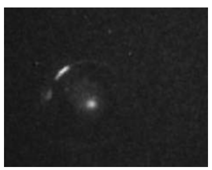
Surface Glow

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



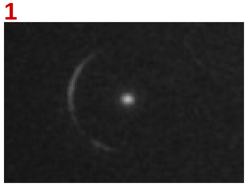
1

2

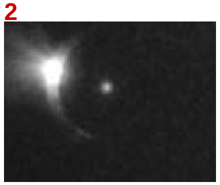
"Flare"

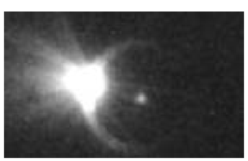
2-20x glow intensity
Abrupt onset
2-10 min decay time

1



2





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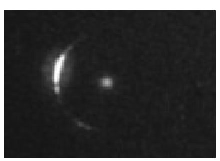
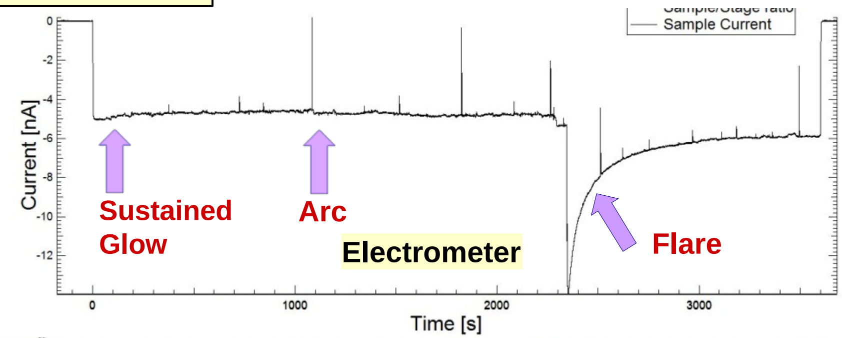
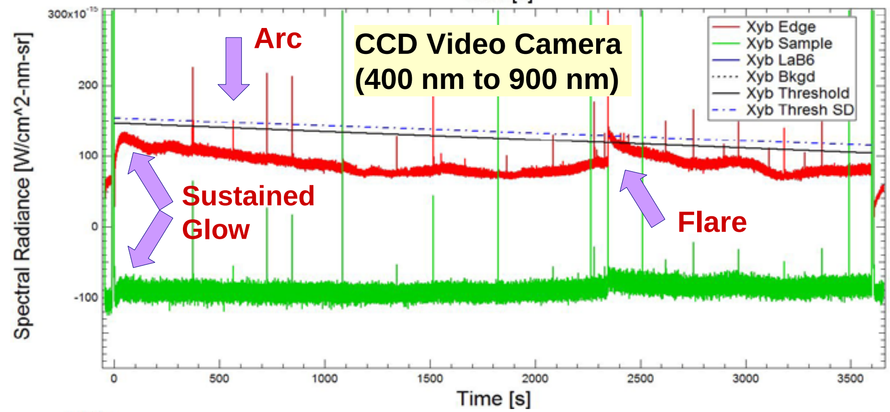


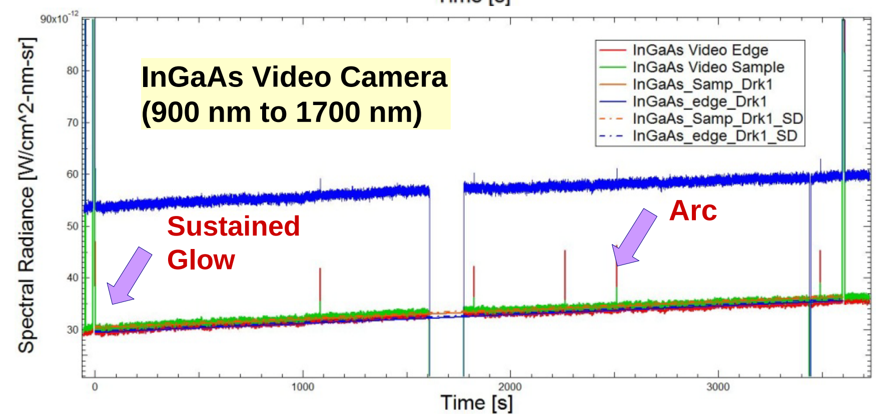
4

Arc

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







Glow Increases with Increasing Flux, Energy and Power

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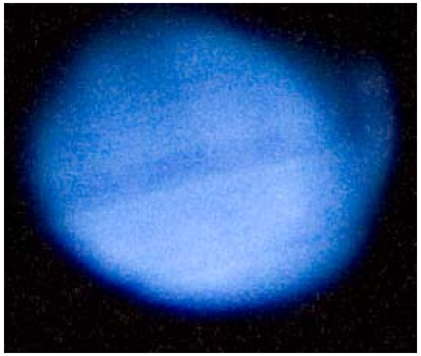
e^- Energy

C Composite

~110 uW/cm^2
~5 nA/cm^2
22 keV
135 K

Run 122



C Composite

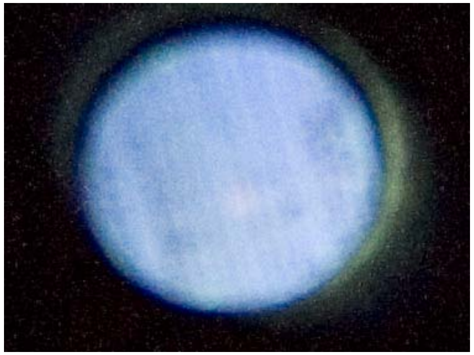
~4100 uW/cm^2
~188 nA/cm^2
22 keV
135 K

Run 122A

C Composite

~35 uW/cm^2
~5 nA/cm^2
7 keV
128 K

Run 121



C Composite

~1300 uW/cm^2
~188 nA/cm^2
7 keV
128 K

Run 121A

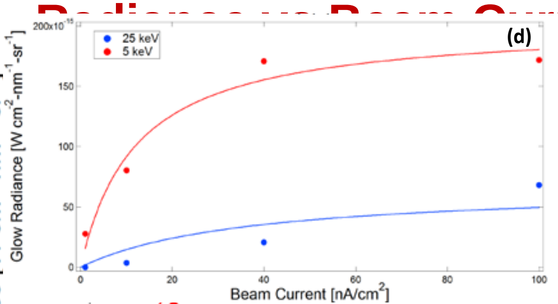
e^- Flux

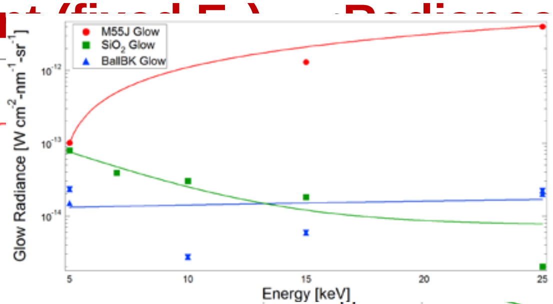
For C-fiber/resin composite Surface Glow, Edge Glow, and Arcing Frequency are all found to increase with:

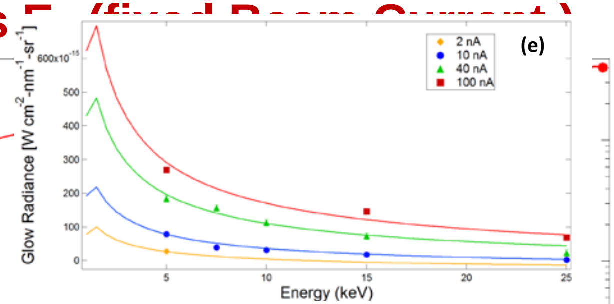
- **increasing incident electron flux and energy**
- **decreasing T**

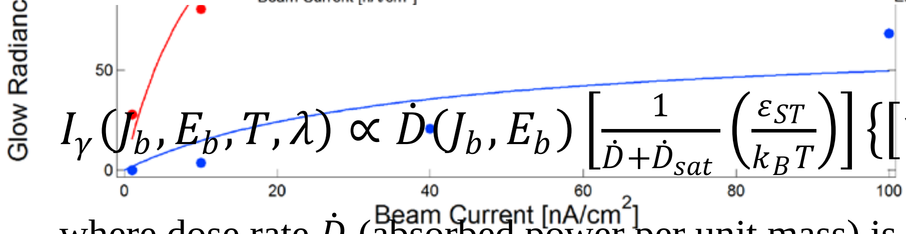
Thickness Dependant Model for Luminescence

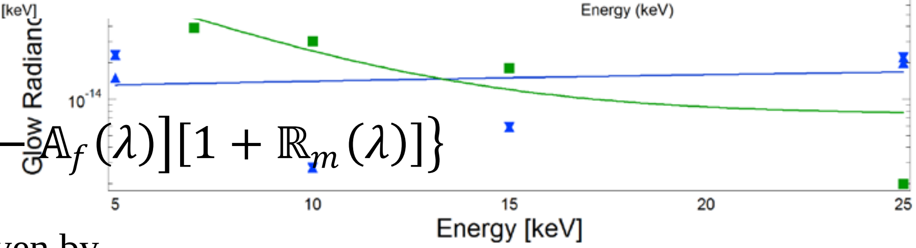
Radiance vs Beam Current (fixed E_b) **Radiance vs E_b (fixed Beam Current)** **Radiance vs E_b (fixed Beam Current)**









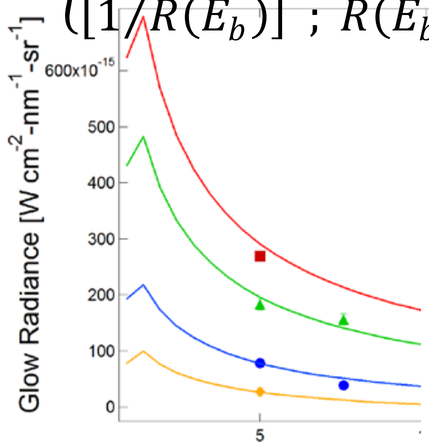


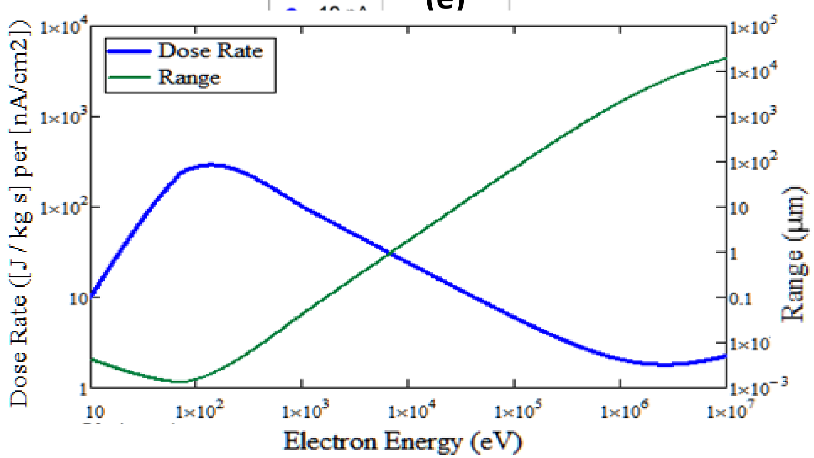
$$I_\gamma(J_b,E_b,T,\lambda) \propto \dot{D}(J_b,E_b)\left[\frac{1}{\dot{D}+\dot{D}_{sat}}\left(\frac{\varepsilon_{ST}}{k_B T}\right)\right]\{[1-\mathbb{A}_f(\lambda)][1+\mathbb{R}_m(\lambda)]\}$$

where dose rate $\dot{D}$ (absorbed power per unit mass) is given by

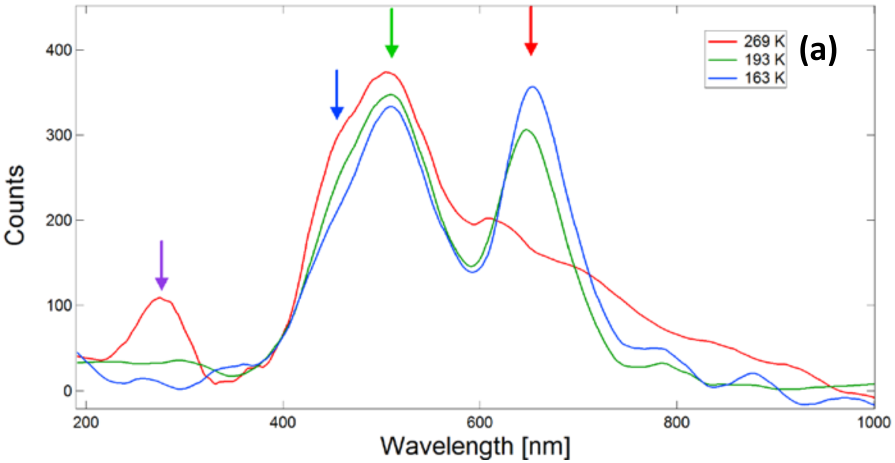
$$\dot{D}(J_b,E_b) = \frac{E_b\, J_b[1-\eta(E_b)]}{q_e \rho_m} \times \begin{cases} [1/L] & ;\ R(E_b) < L \\ [1/R(E_b)] & ;\ R(E_b) > L \end{cases}$$

Radiance vs E_b (fixed Beam Current)



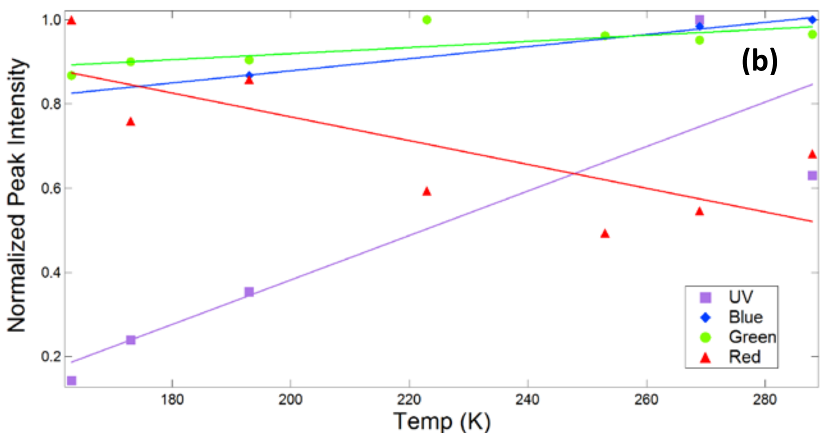


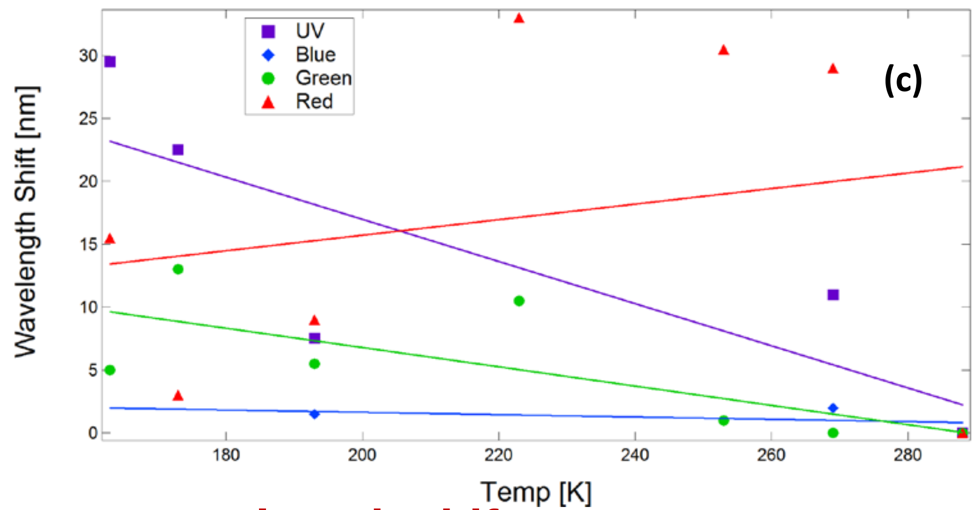
Measured Cathodoluminescence Spectra for Fused Silica



Spectra vs T

Four peaks evident





Peak Intensity vs T

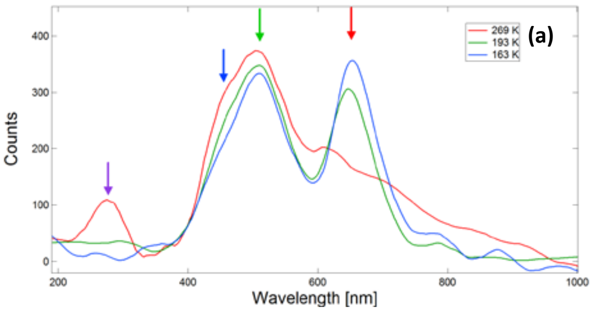
Red decreases with increasing T
Others increases with increasing T

Wavelength shift vs T

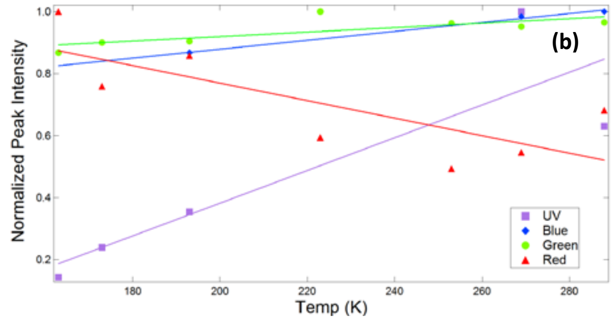
Red increases with increasing T
Purple decreases with increasing T

Model for Luminescence Intensity in Fused Silica

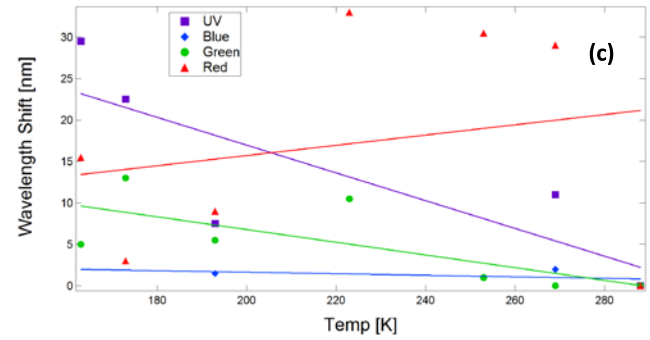
Spectra vs T

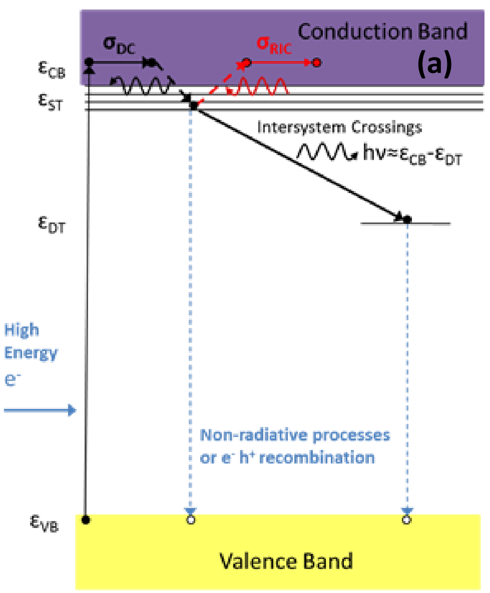


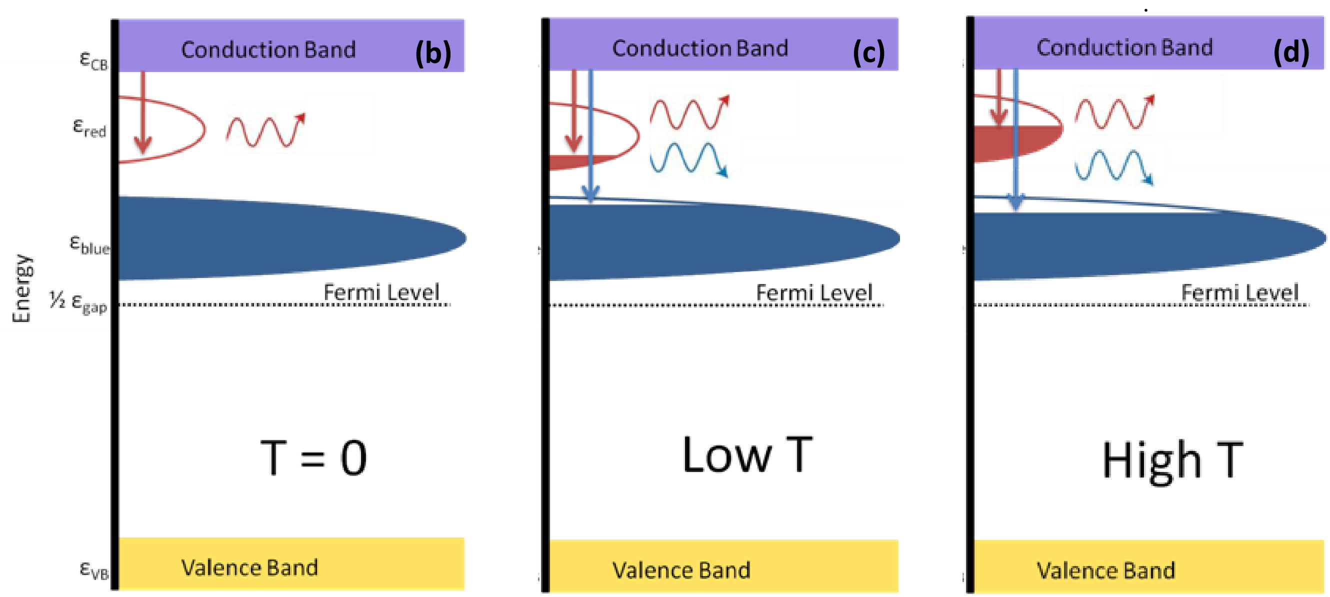
Peak Intensity vs T



Wavelength shift vs T







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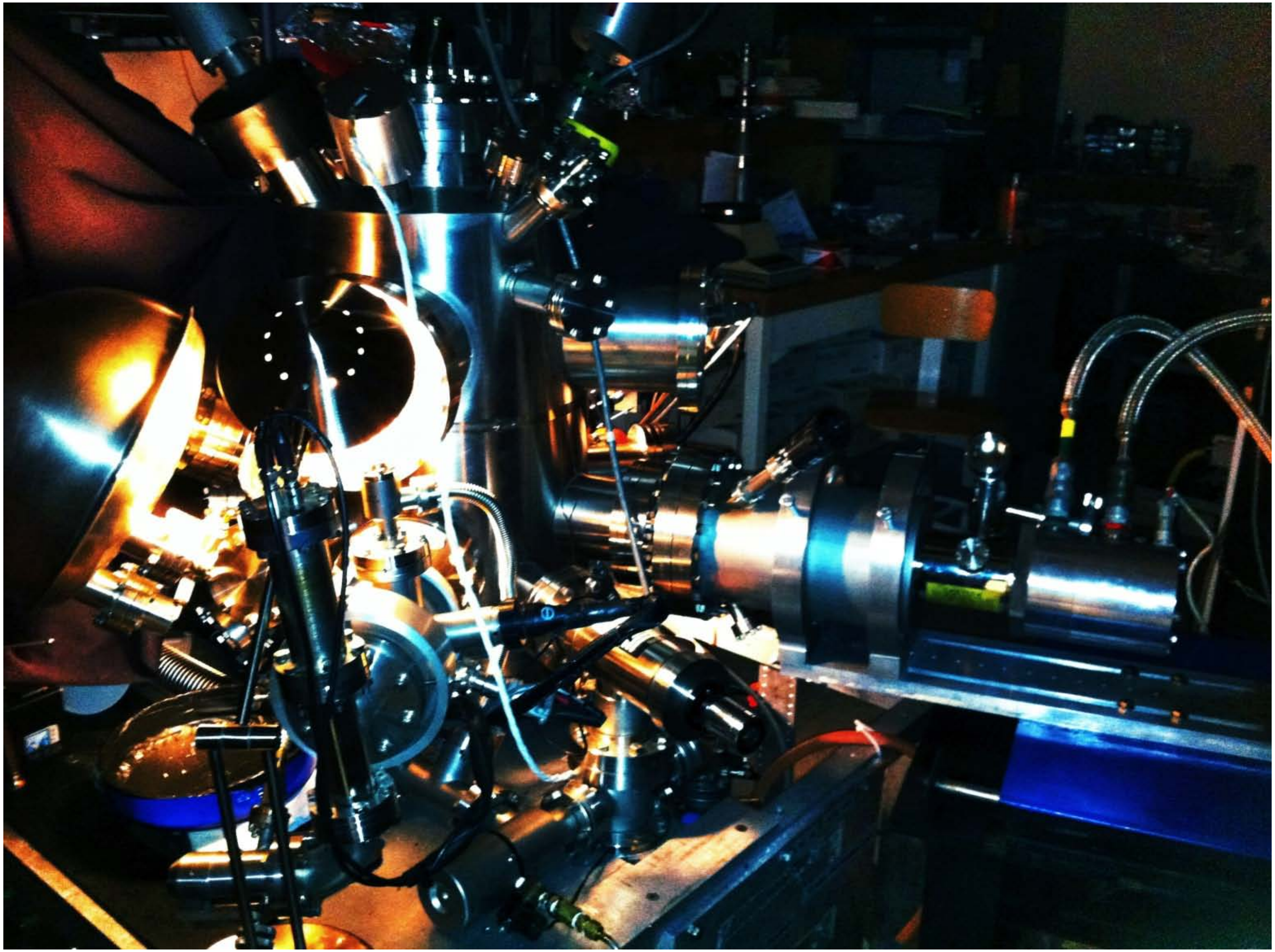
Conclusions

- Complex satellites require:
    - Complex materials configurations
    - More power
    - Smaller, more sensitive devices
    - More demanding environments
- 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
- Environment/Materials Modification feedback mechanisms can cause many new problems
- Understanding of the microscale structure and transport mechanisms are required to model dynamic materials properties for dynamic spacecraft charging models

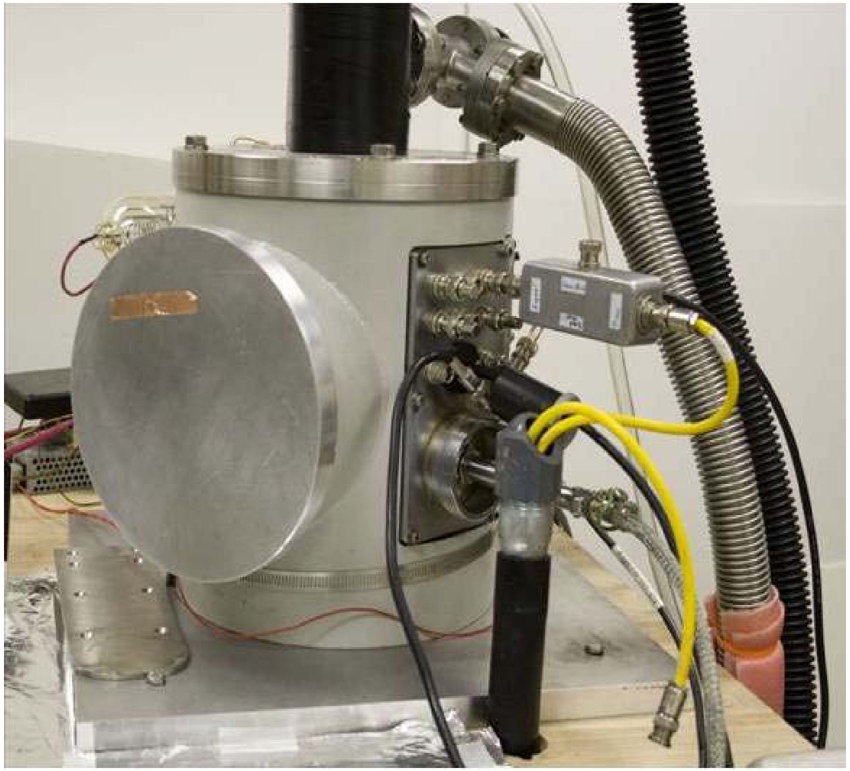
End with a Bang

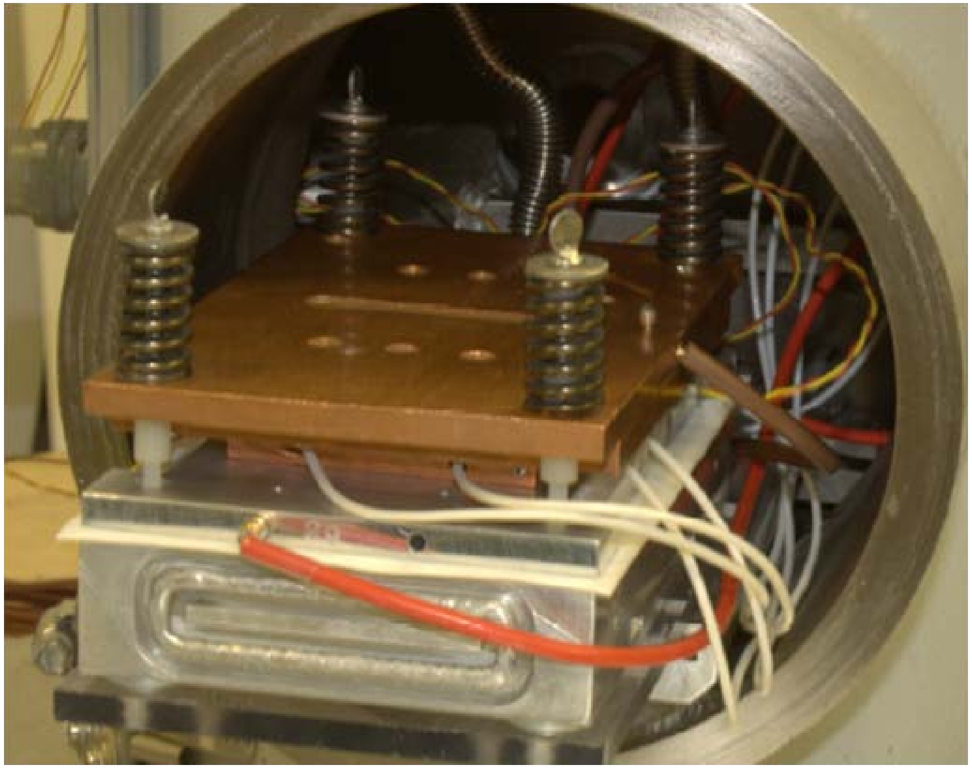


Supplemental Slides

Instrumentation Overview

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

Absolute Electron Yields

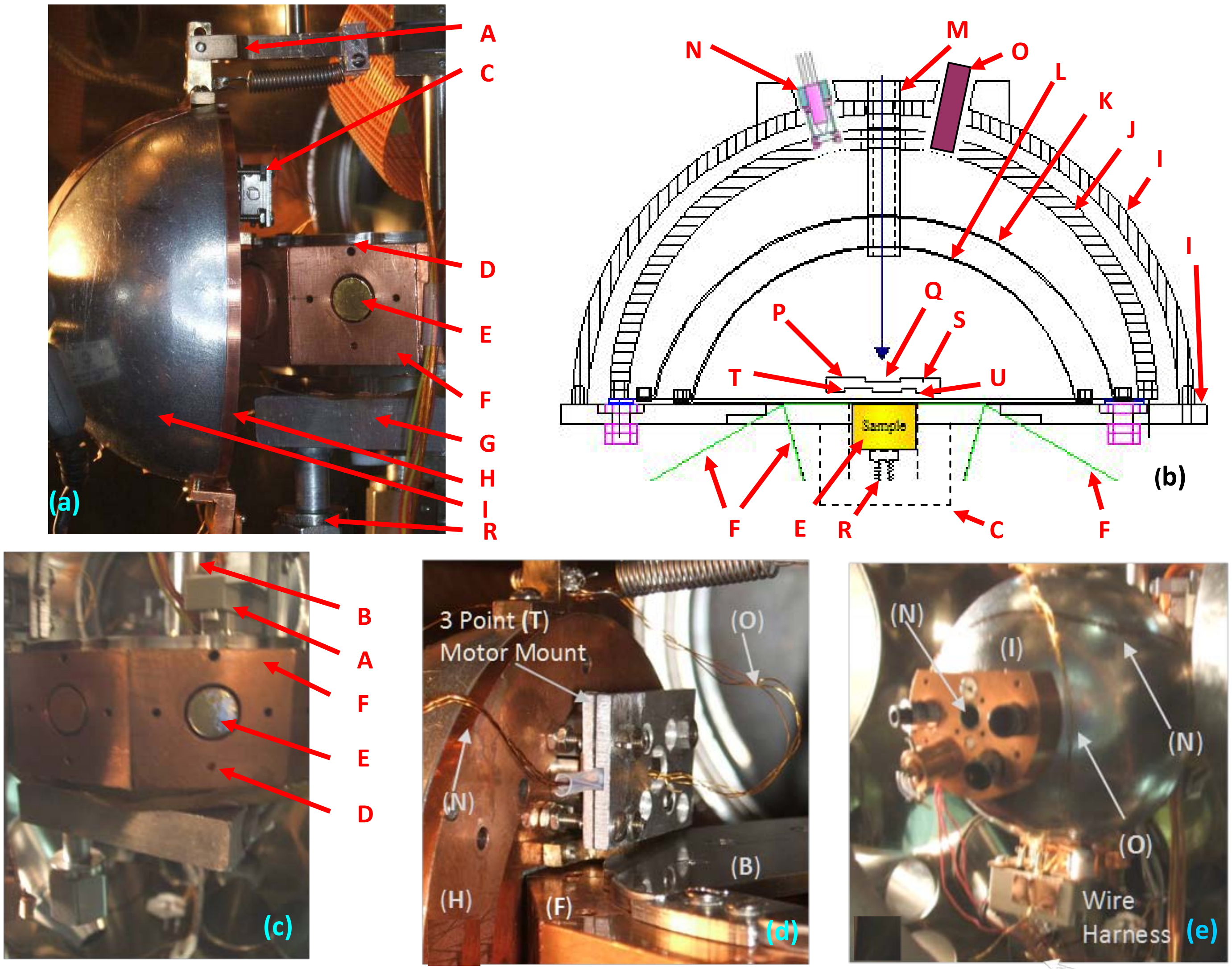


Fig. 2. **Hemispherical Grid Retarding Field Analyzer (HGRFA).** *(a) Photograph of sample stage and HGRFA detector (side view). (b) Cross section of HGRFA. (c) Photograph of sample stage showing sample and cooling reservoir. (d) Side view of the mounting of the stepper motor. (e) Isometeric view of the HGRFA detailing the flood gun, optical ports, and wire harness.*

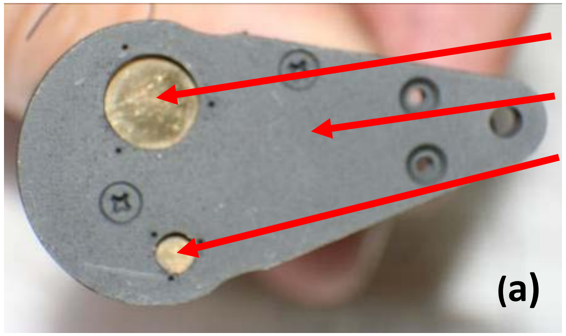
Hemispherical Grid Retarding Field Analyzer Electron Emission Detector

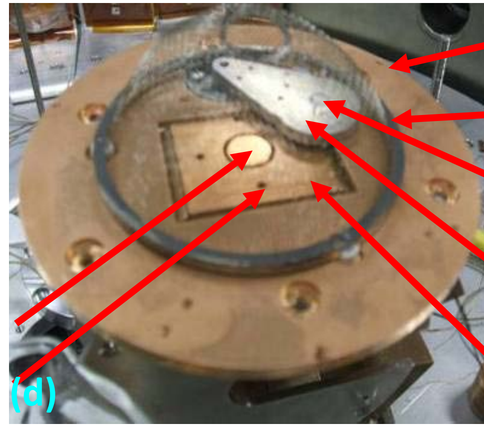
- **Works with incident:**
  - o 20 eV to 30 keV electrons
  - o ~100 eV to 5 keV ions
  - o ~0.5 eV to 7 eV photons

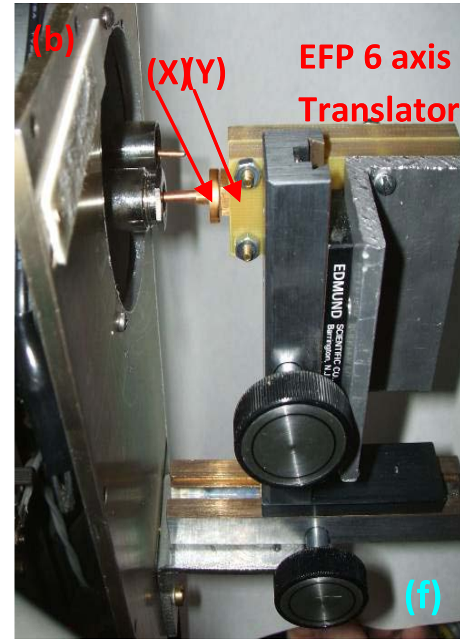
- **Precision absolute yield**
  - o ~1-2% accuracy with conductors
  - o ~2-5% accuracy with insulators
  - o measures all currents
  - o in situ cabsolute calibration

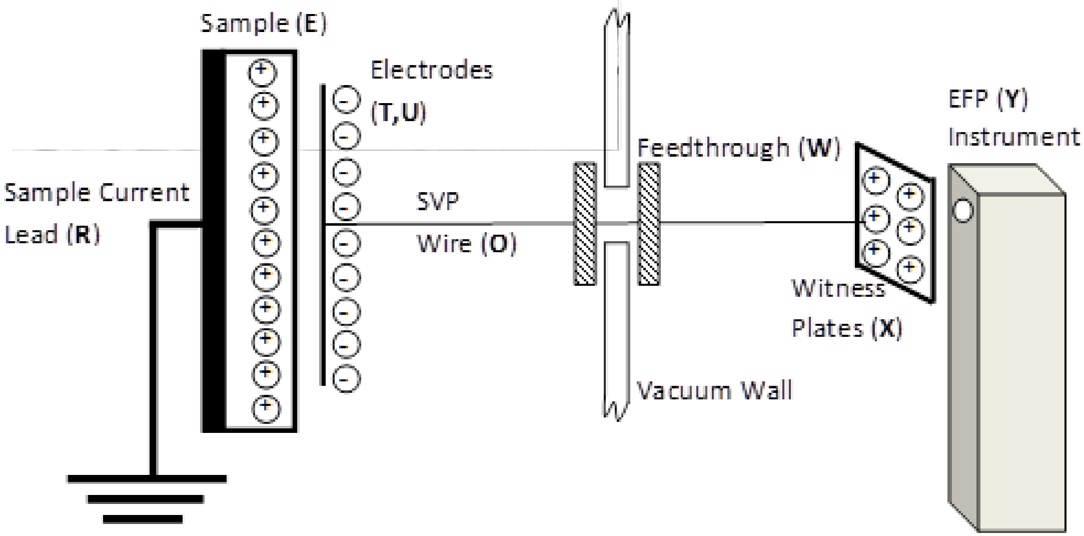
- **low energy e^- and UV charge neutralization**
- ***in situ* surface voltage probe**
- **multiple sample stage**
- **~100 K < T < 400 K**

Surface Voltage Probe





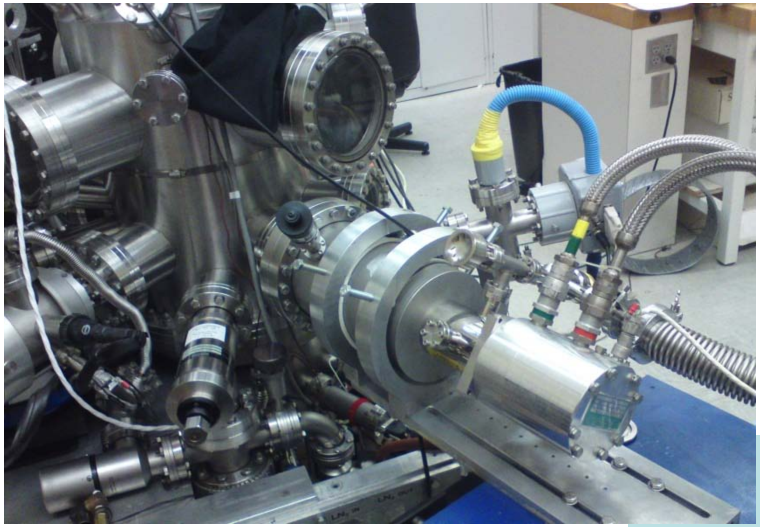


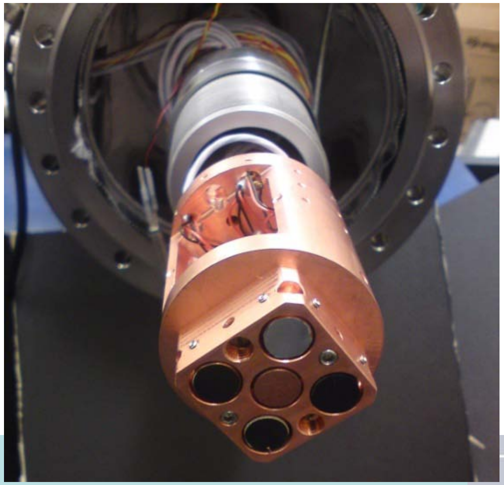


Surface Voltage Probe

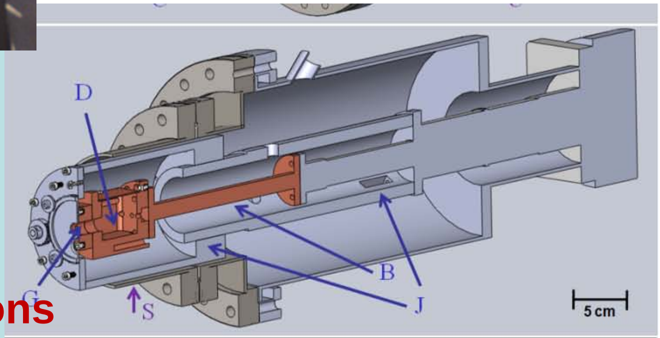
- Inside SEE HGRFA
- ~0.5 V to 15 kV range
- ±0.5 V resolution
- Arc scan
- ~7 s min scan time

Low Temperature Cryostat



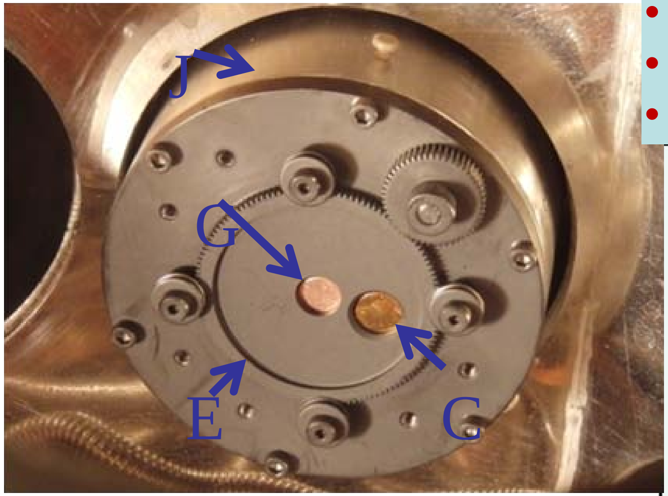


Used with:
- **Constant Voltage Cond.**
- **RIC**
- **SEE/BSE**
- **Cathodoluminescence**
- **Arcing**
- **Surface Voltage Probe**



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

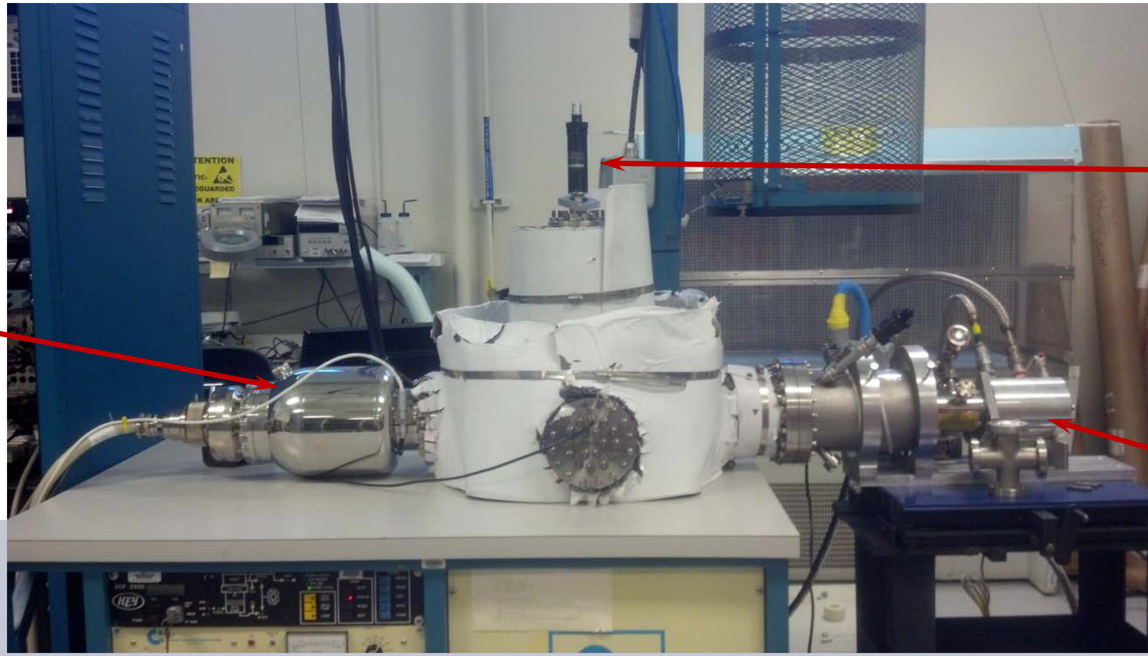
Analysis Components
K UV/Vis/NIR Reflectivity Spectrometers
L CCD Video Camera (400-900 nm)
M InGaAs Video Camera (800-1200 nm)
N InSb Video Camera (1000-5000 nm)
O SLR CCD Camera (300-800 nm)
P Fiber Optic Discrete Detectors
Q Collection Optics

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

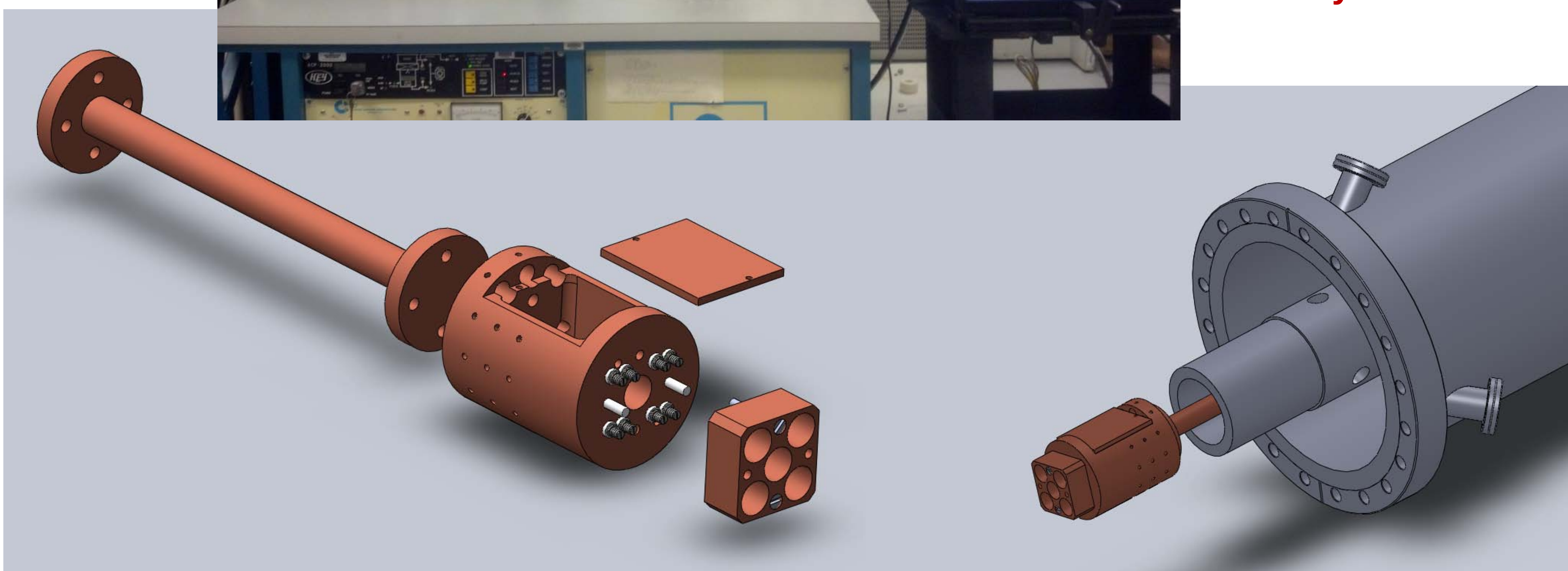
Closed-System Helium Refrigerator Sample Stage Mounting

High Energy Electron Gun

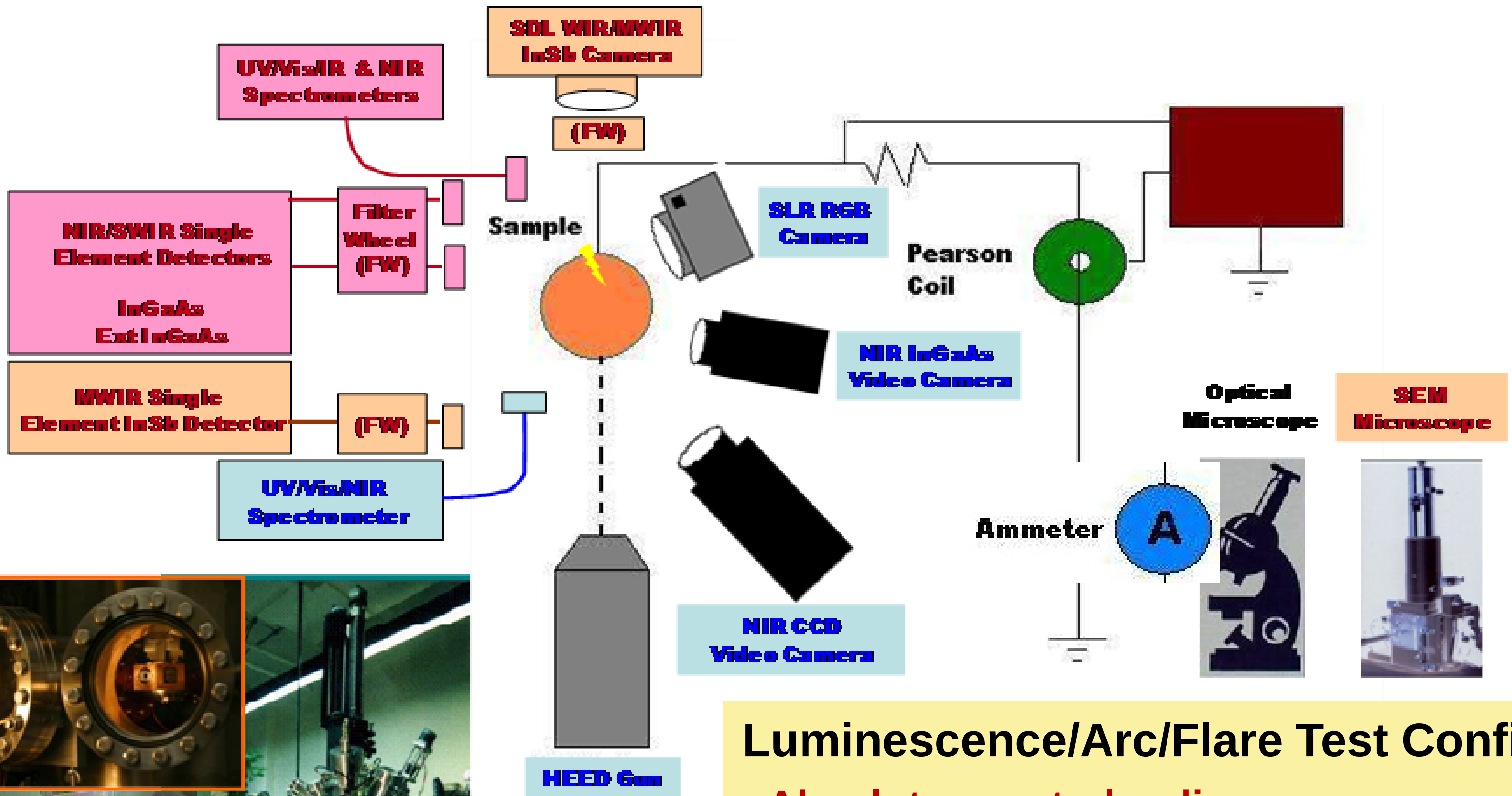


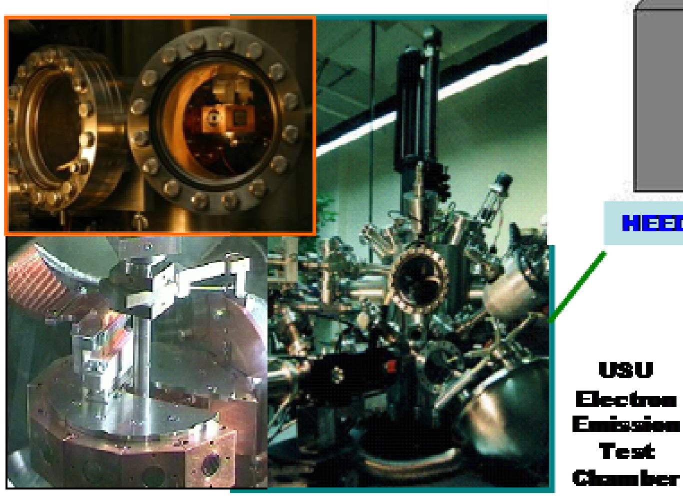
Faraday Cup Z Translation Stage

USU Closed Cycle He Cryostat



Photon Emission Measurements

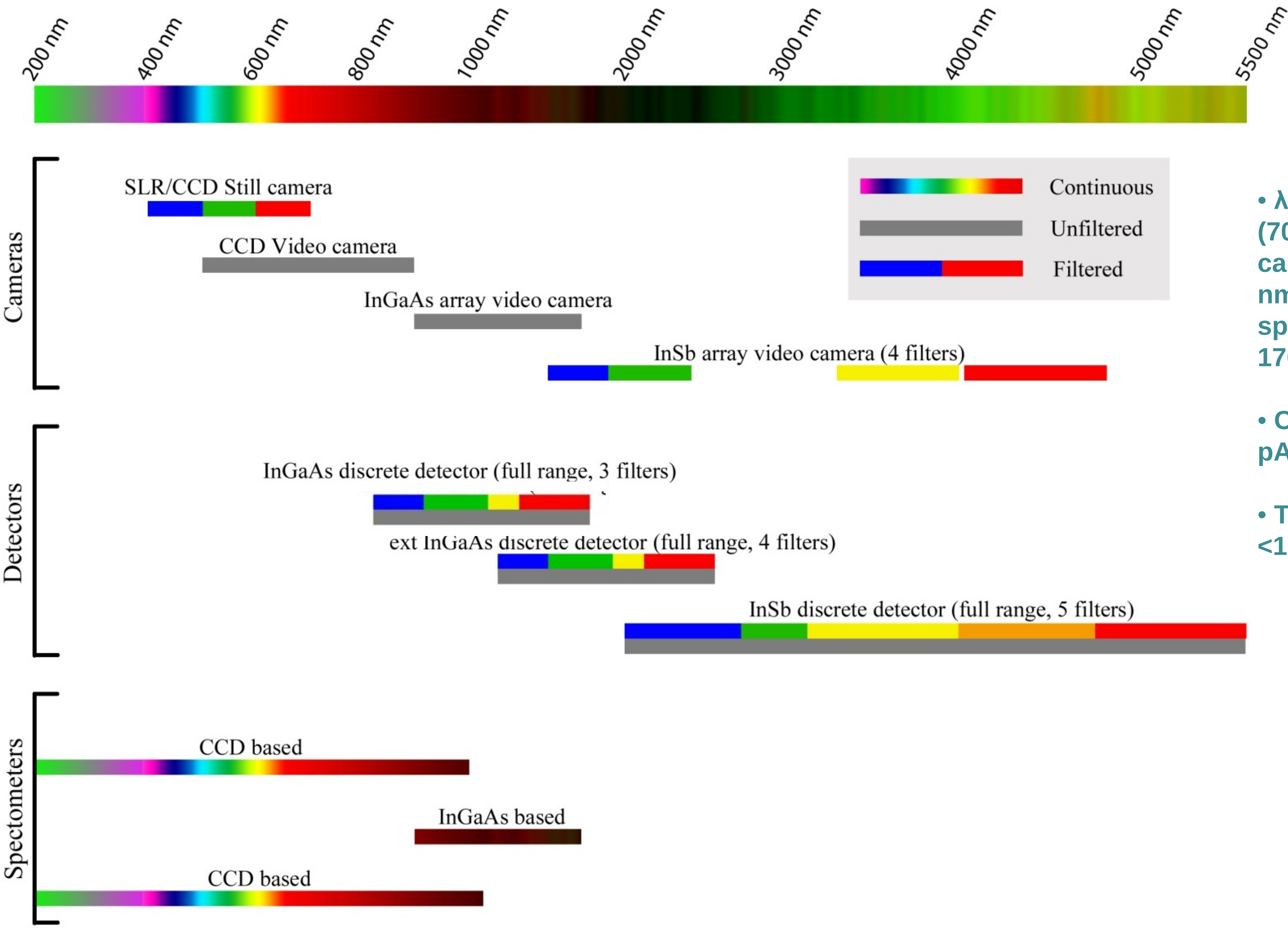




Luminescence/Arc/Flare Test Configuration

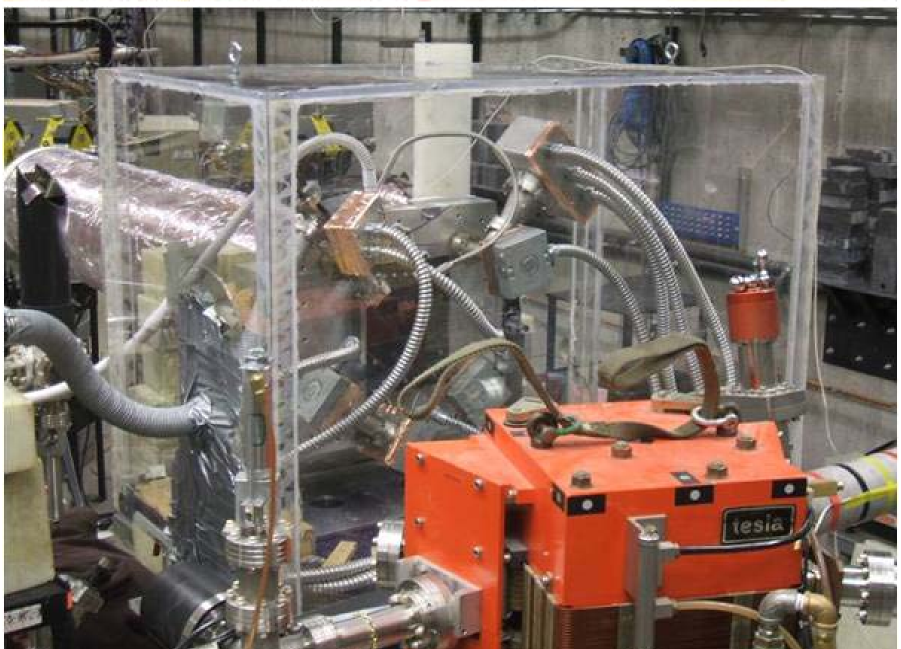
- Absolute spectral radiance
- ~200 nm to ~5000 nm
- 4 cameras (CCD, iiCCD, InGaAs, InSb)
- Discreet detectors filters
- 2 Spectrometers (~200 nm to ~1900 nm)
- e^- at ~1 pA/cm^2 to ~10uA/cm^2 & ~20 eV to 30 keV
- 35 K< T< 350 K
- Multiple sample configurations to ~10x10cm

Luminescence/Arc/Flare Test Configuration

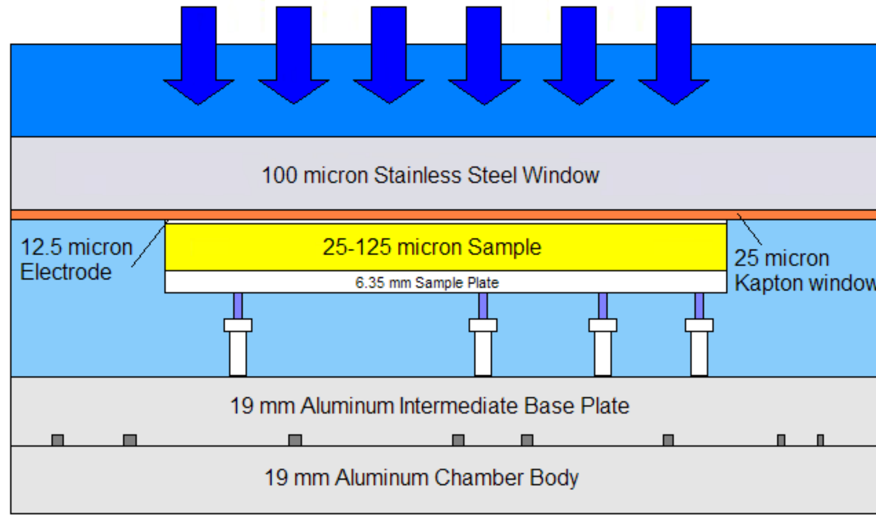


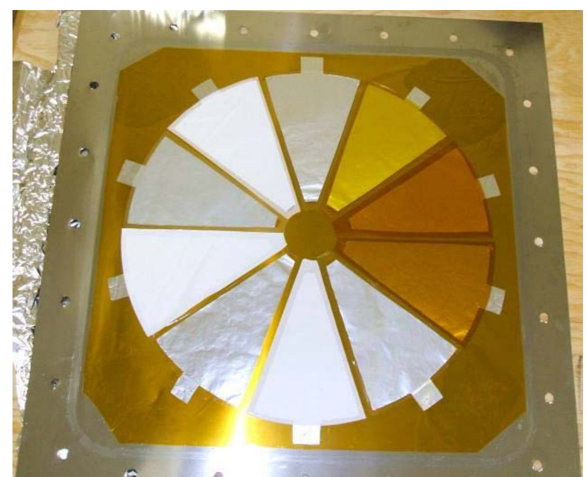
- λ range: detectors (700-5500 nm), cameras (400-5000 nm), and spectrometers (200-1700 nm)
- Current range: (0.1 pA to 1 mA)
- Temporal range: $<10^{-9}$ s to $>10^{4}$ s

Radiation Induced Conductivity

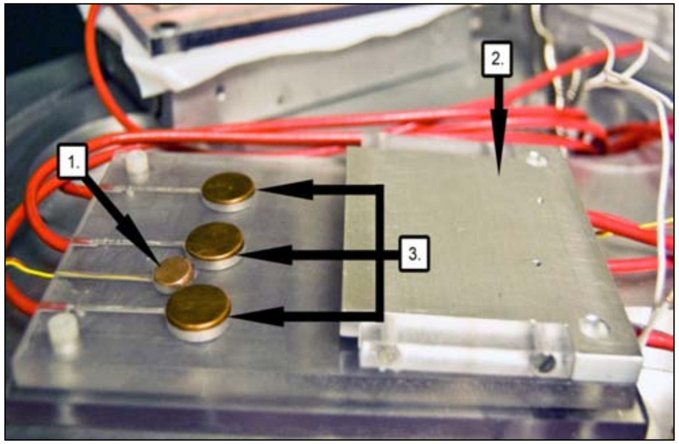


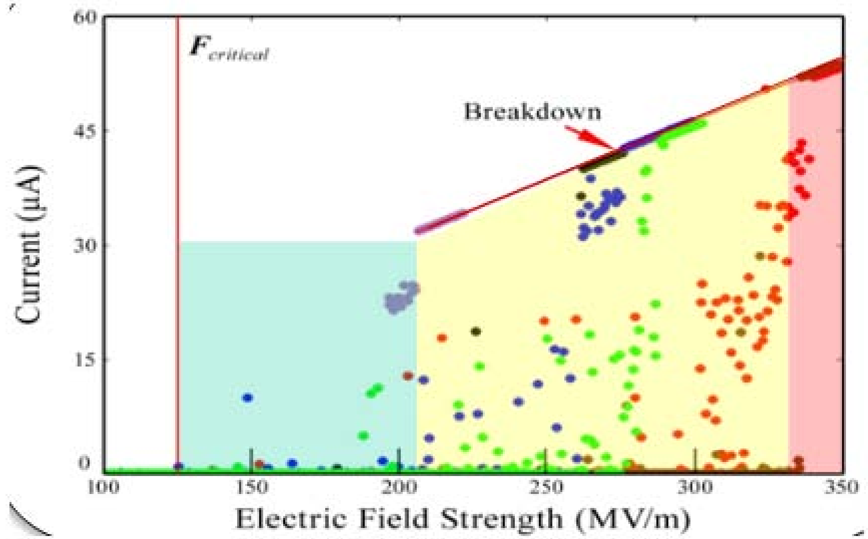
~4 MeV Pulsed Electrons

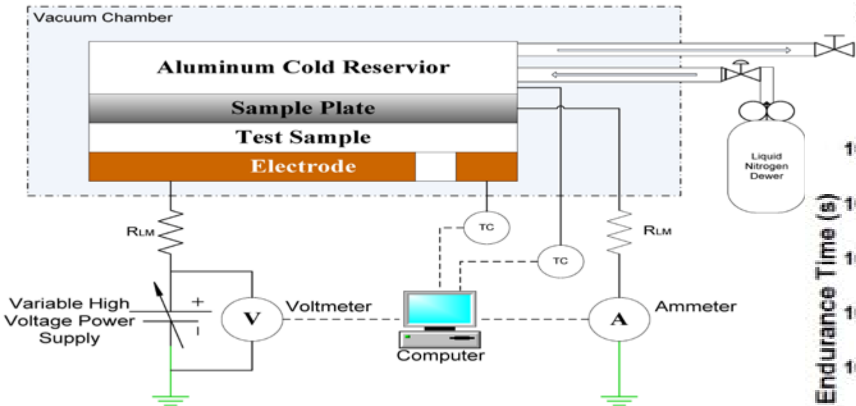


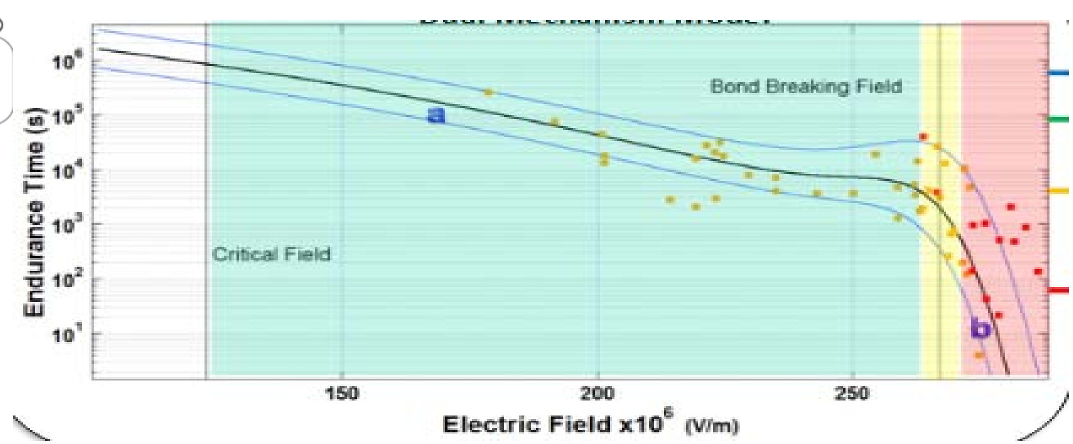


Electrostatic Breakdown

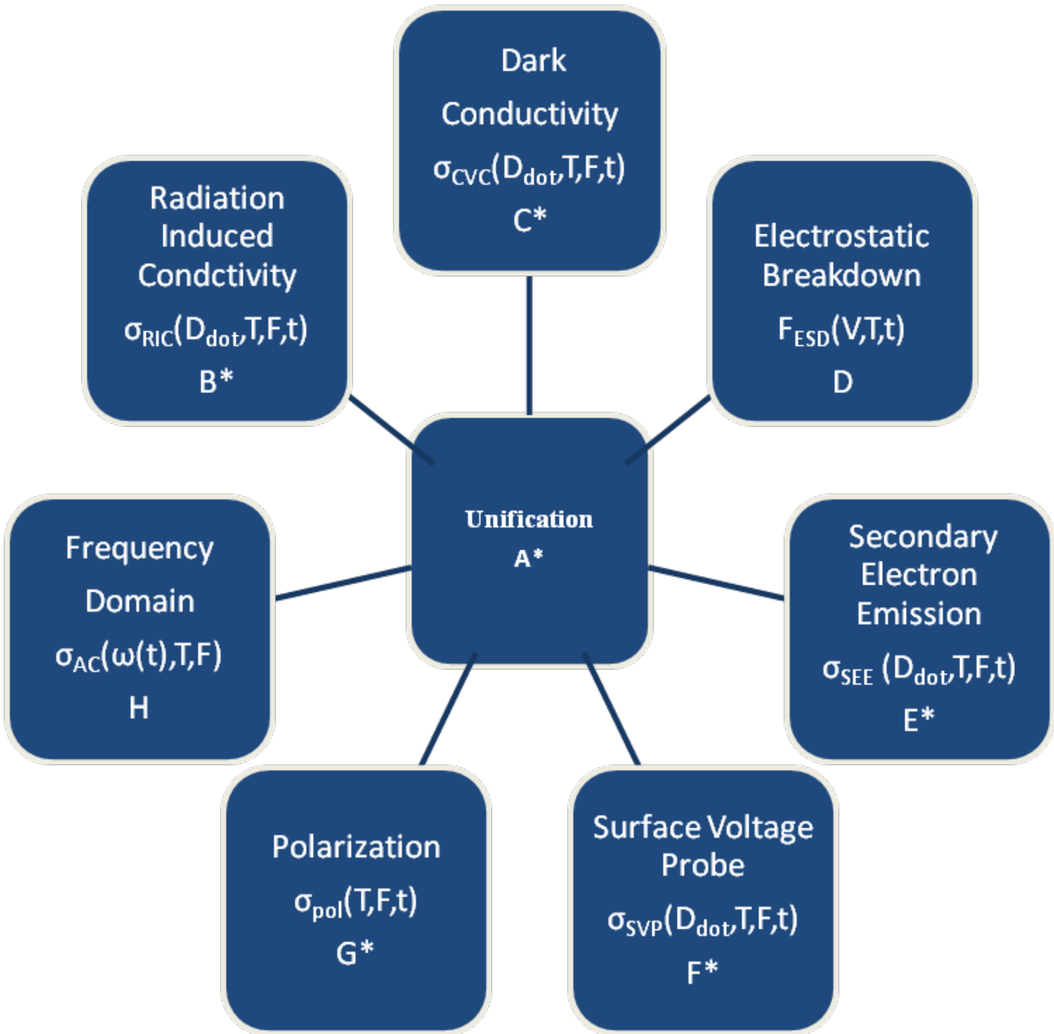








Just a drop in the bucket…



<u>Complete set of dynamic transport equations</u>

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

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

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

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

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

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

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

<u>A quantum mechanical model</u> of the spatial and energy distribution of the electron states