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The Dynamic Interplay Between Spacecraft Charging, Space Environment Interactions and Evolving Materials

J.R. Dennison

Materials Physics Group
Physics Department, Utah State University

Acknowledgements

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Ball Aerospace
Orbital

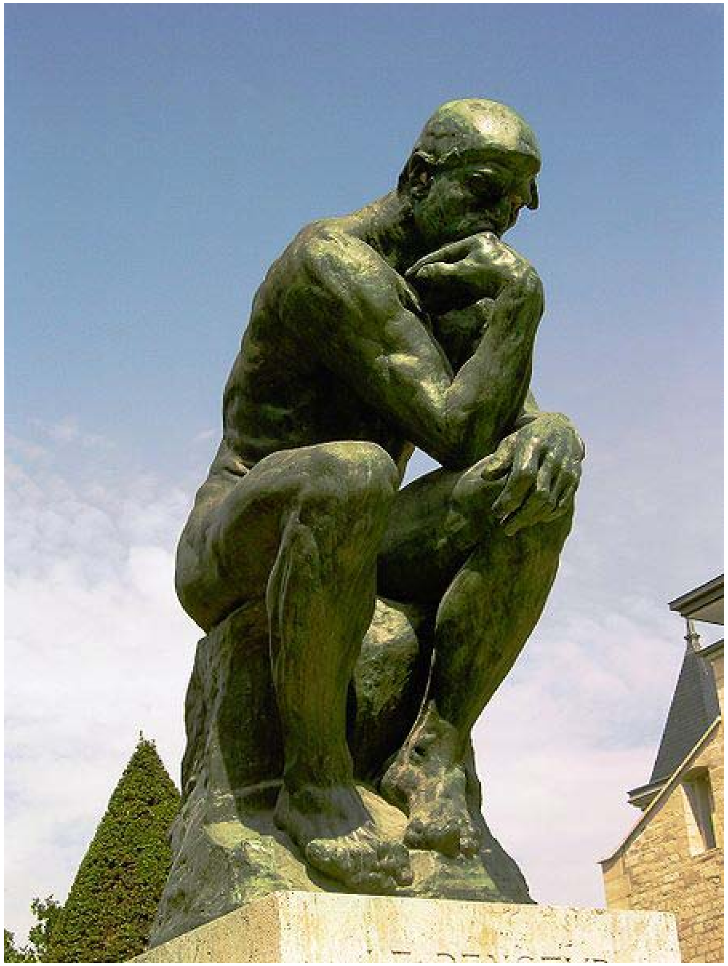
National Research Council

USU Materials Physics Group

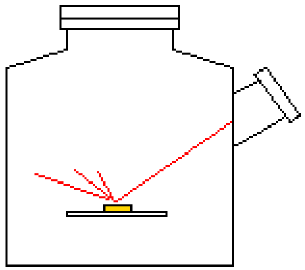
Nothing endures but change.

--Heraclitus of Ephesus
(c. 495 BC)

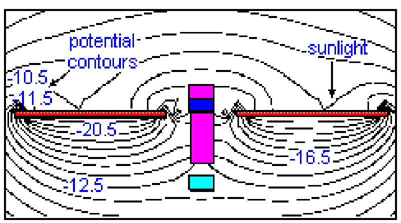
Shit Happens…..

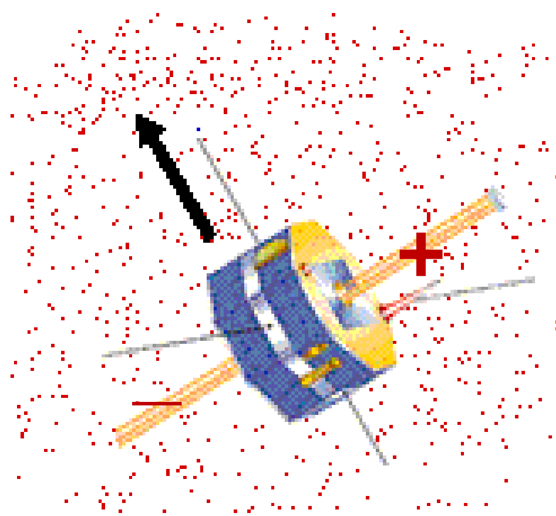


A simplified approach to spacecraft charging modeling…



Materials Properties





m

e^-

I^+

γ

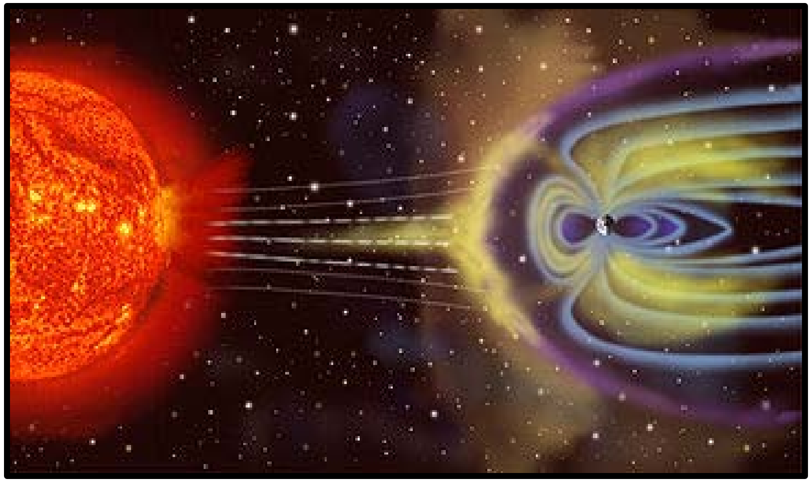
Spacecraft Potential Models

Satellite Moving through Space

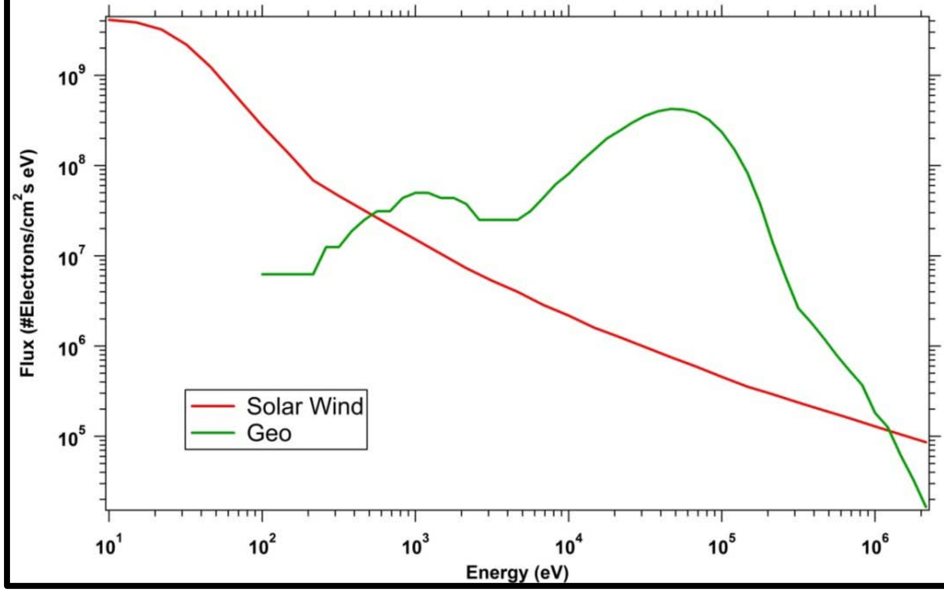
Space Plasma Environment

The Space Environment

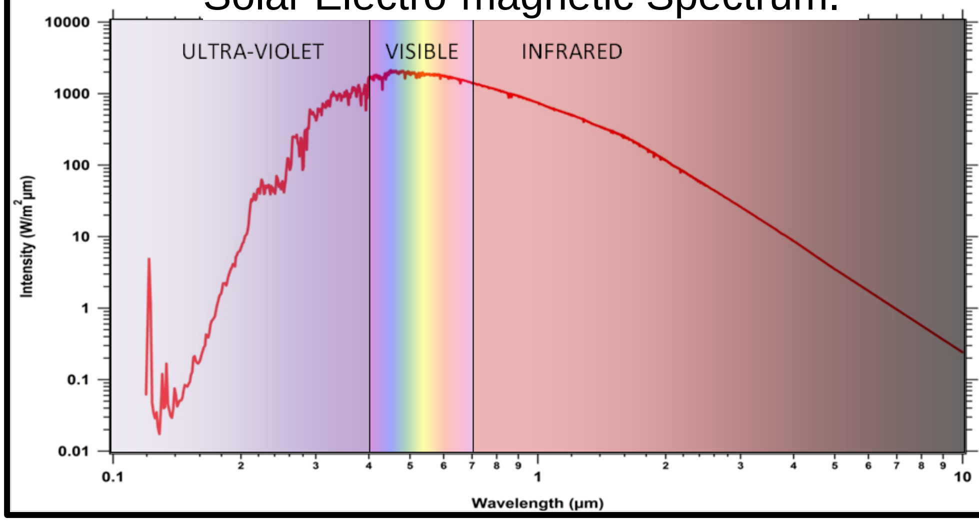
Solar wind and Earth's magneto-sphere structure.



Typical Space Electron Flux Spectra [Larsen].



Solar Electro-magnetic Spectrum.



Incident Fluxes of:

- **Electrons**
- **Ions**
- **Photons**
- **Particles**

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#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 , position, energy, and charge:

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

What do you need to know about the materials properties?

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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**
- **Dielectric Constant**
- **ESD**
- **Range**

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

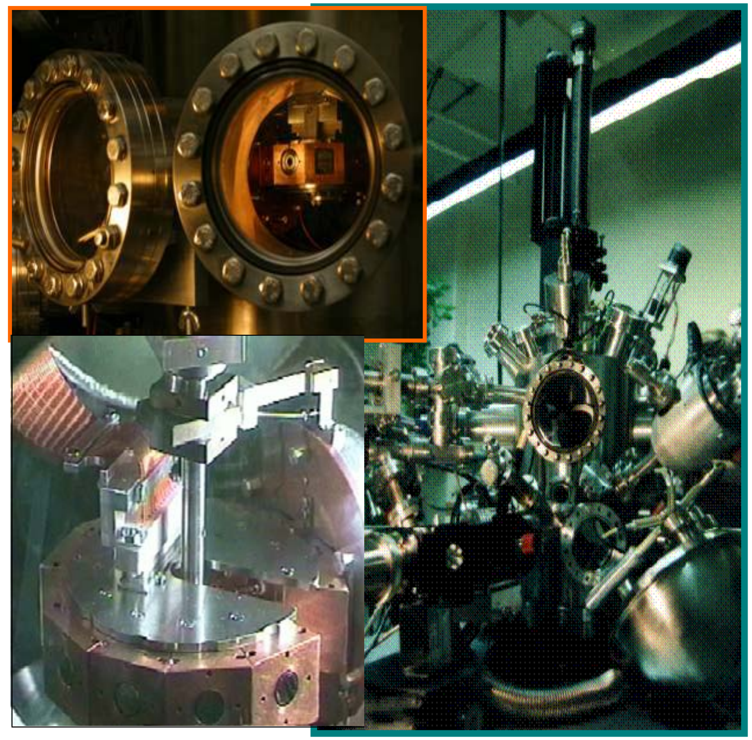
Table 2.1. Parameters for NASCAP Materials Properties

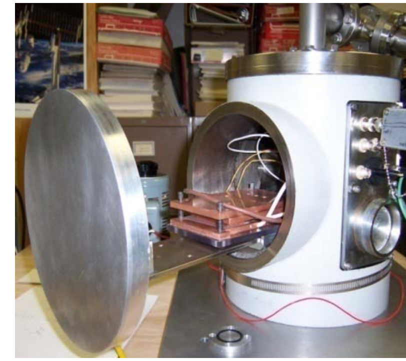
Parameter	Value
[1] Relative dielectric constant; ε_r (Input as 1 for conductors)	1, NA
[2] Dielectric film thickness; d	0 m, NA
[3] Bulk conductivity; σ_o (Input as -1 for conductors)	-1; $(4.26 \pm 0.04) \cdot 10^7$ $ohm^{-1} \cdot m^{-1}$
[4] Effective mean atomic number $<Z_{eff}>$	50.9 ± 0.5
[5] 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 $\delta^H{}_{max}$; $E^H{}_{max}$	(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

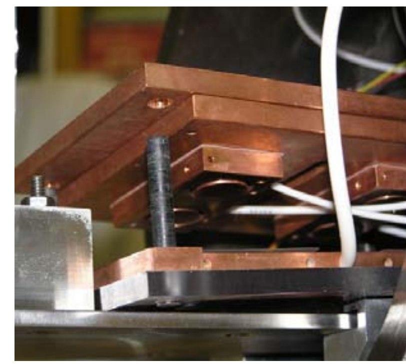
USU Experimental Capabilities

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)







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

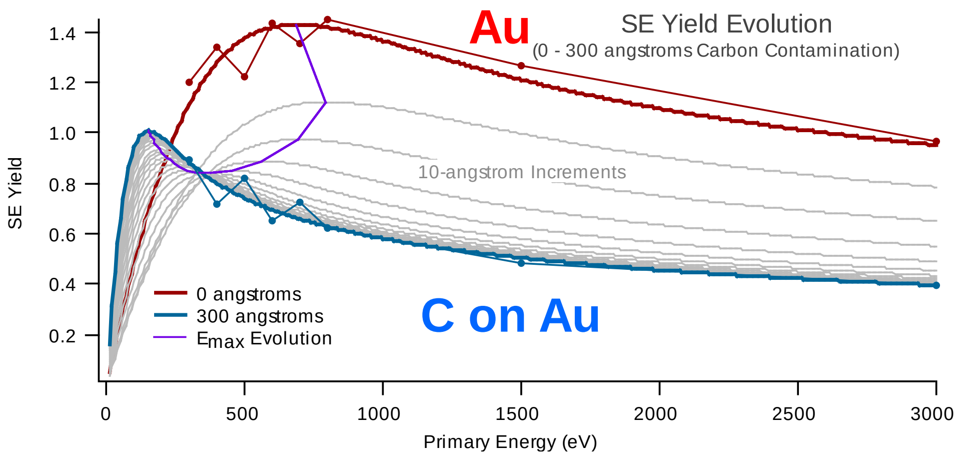
Consider 6 Cases of Dynamical Change in Materials:

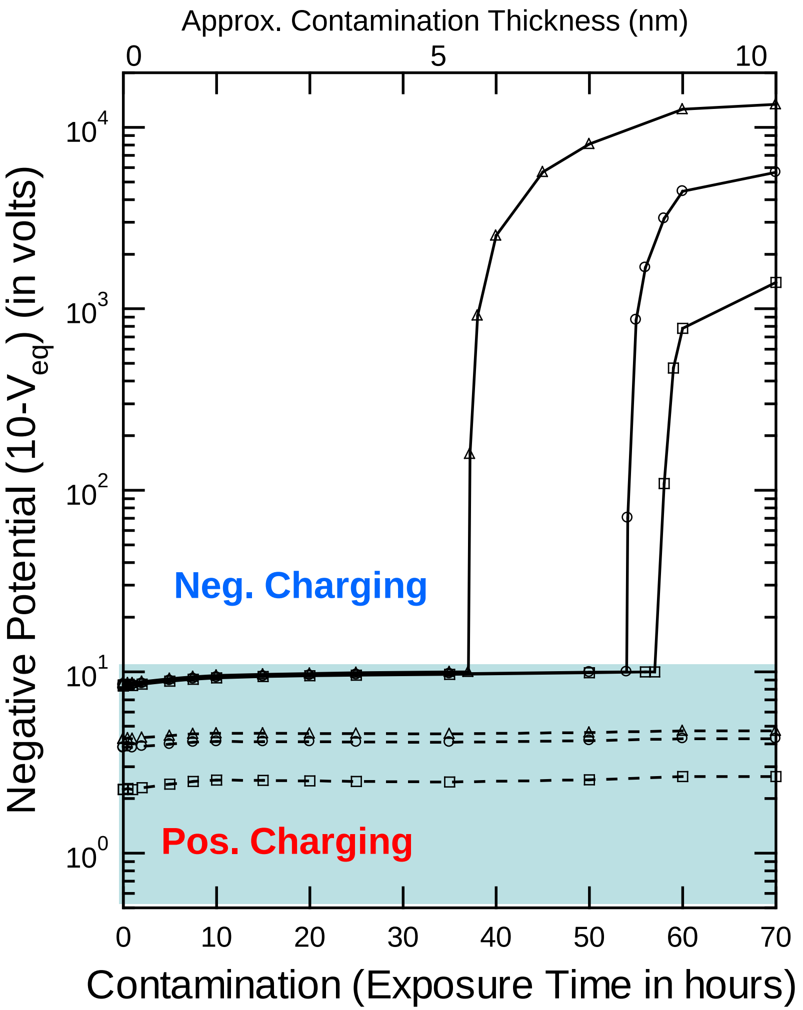
I. Contamination and Oxidation
II. Surface Modification
III. Radiation Effects (and t)
IV. Temperature Effects (and t)
V. Radiation and Temperature Effects
VI. Multilayer/Nanocomposite Effects

Case I: Evolution of Contamination and Oxidation

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

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





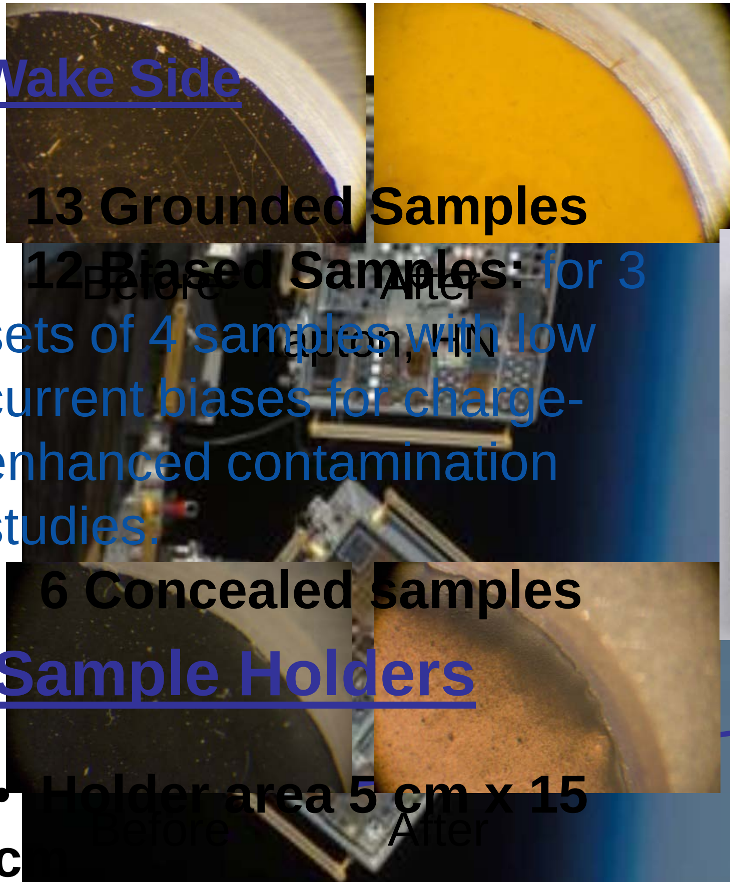
Case I: Evolution of Contamination and Oxidation

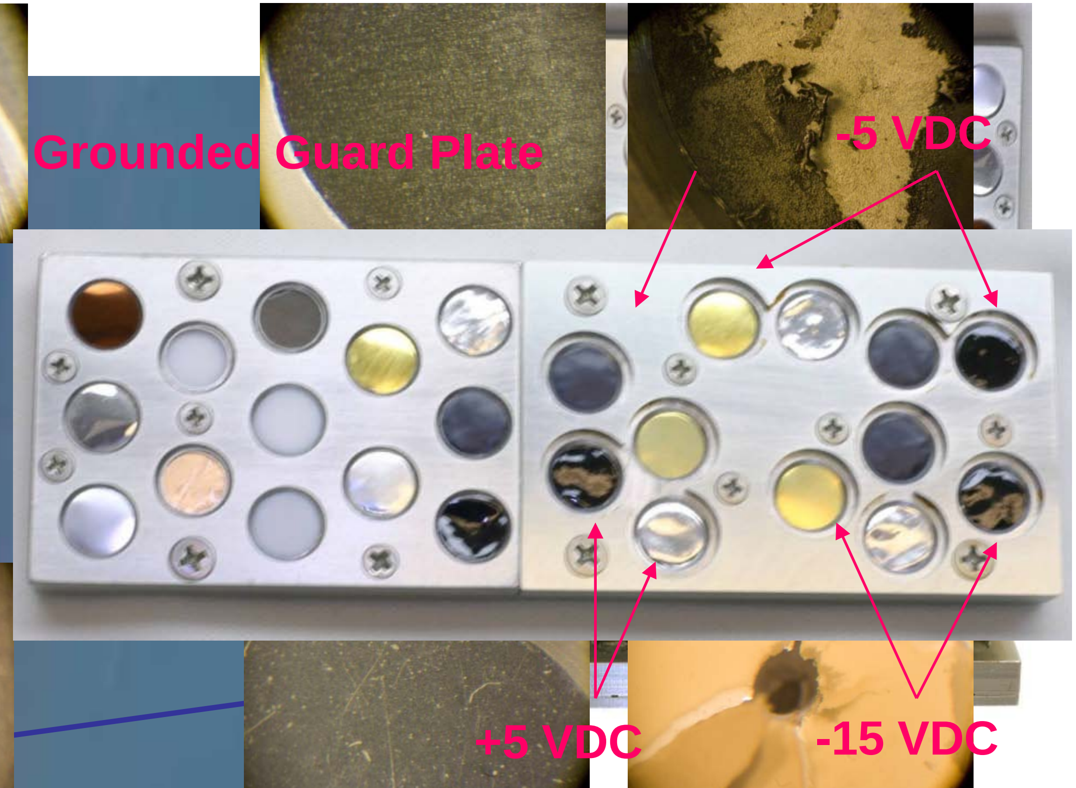
Wake Side

- 13 Grounded Samples
- 12 Biased Samples: for 3 sets of 4 samples with low current biases for charge-enhanced contamination studies.
- 6 Concealed Samples

Sample Holders

- Holder area 5 cm x 15 cm
- 9 mm diameter exposed sample area





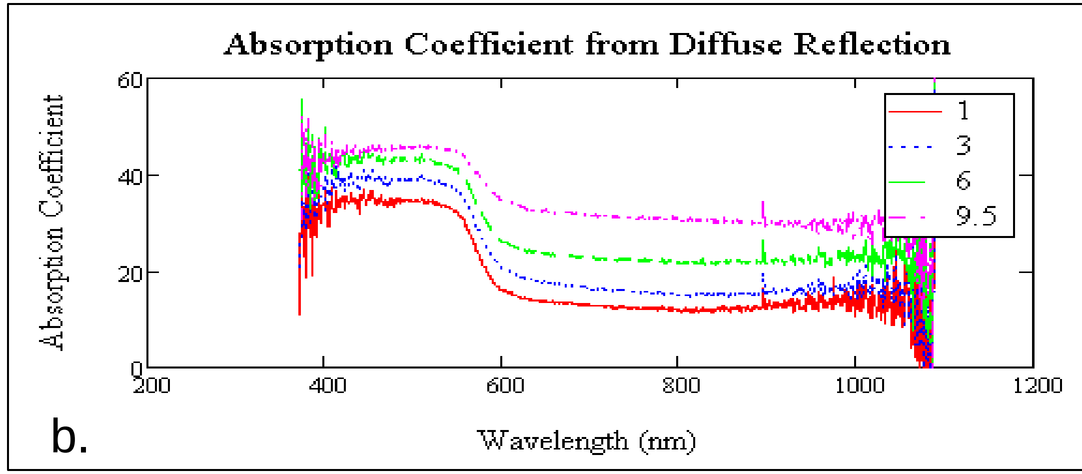
***SUSpECS* on MISSE-6**

Ag coated Mylar with micrometeoroid impact

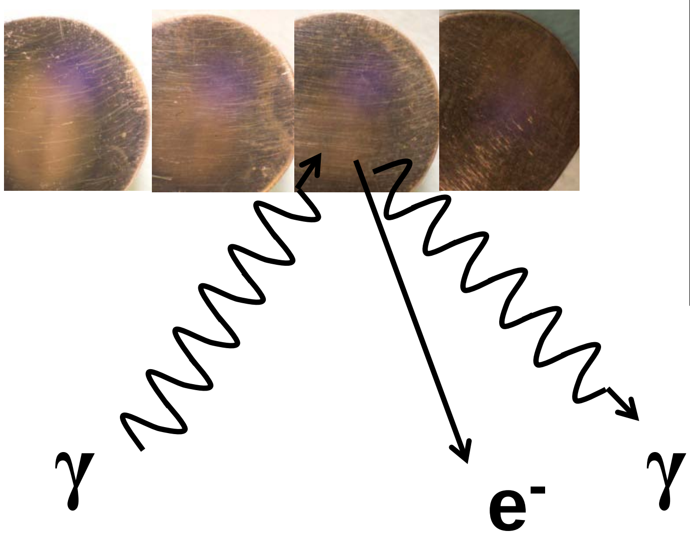
See poster by Dennison, Evans and Prebola

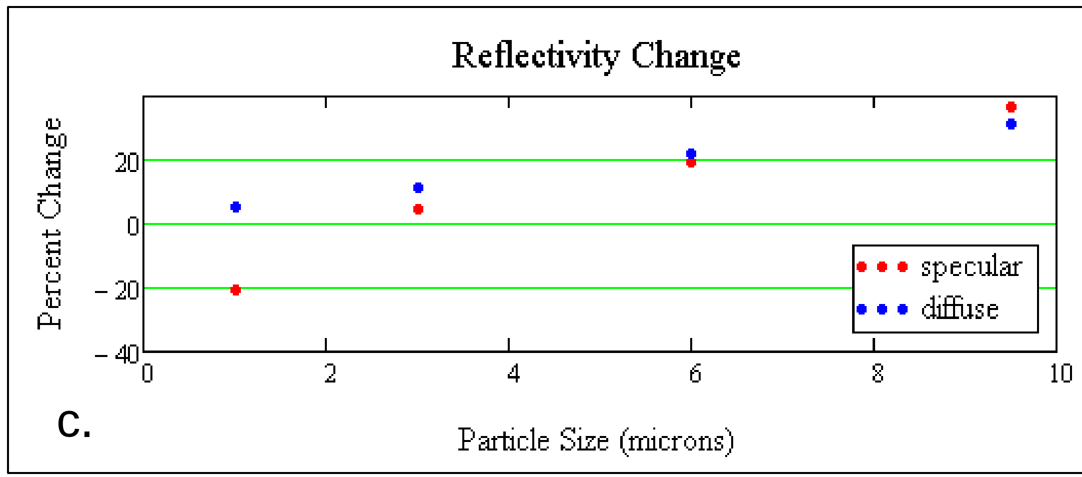
Case II: Surface Modification

Diffuse and Specular Reflectivity changes with surface roughness



Successive stages of roughened Cu





View photon (electron) scattering as a competition for deposited energy and charge:

- **Reflectivity—γ out (Luminescence—γ out)**
- **Photoyield—e out (SE/BSE—e out)**

Cases I and II: Reflectivity as a Feedback Mechanism

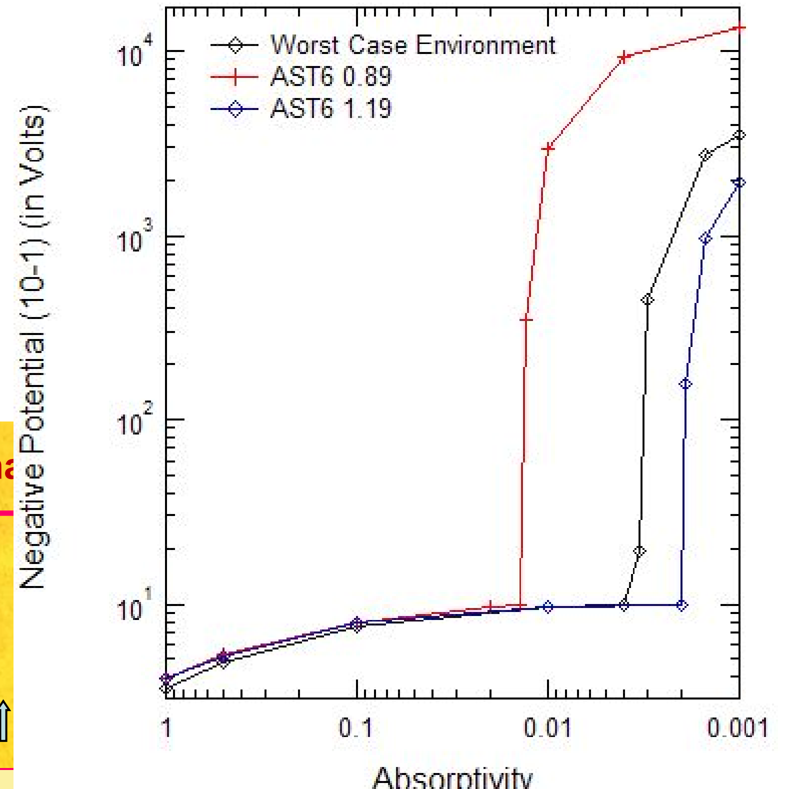
Reflectivity changes with surface roughness and contamination

Reflect→Charging→Contamination

Reflect→Emissivity→Temp→Contamination

Charging→ Reflectivity

Radiation → Reflect→Emissivity→Temp→Contamina



Radiation Damage (Color Change) of Tedlar

B. Mihaljcic in Guild's 11th SCTS Talk

See Lai & Tautz, 2006 & Dennison 2007

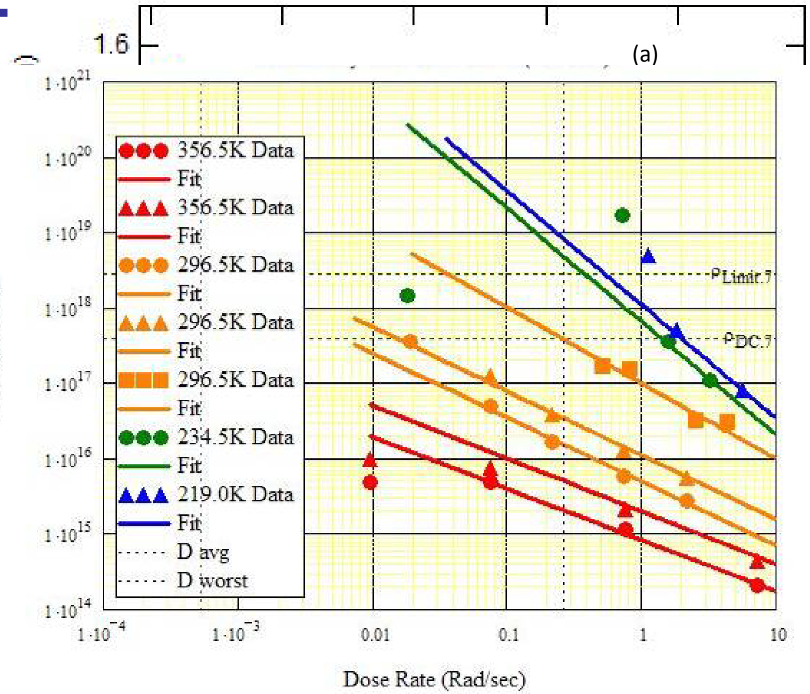
JWST Structure: Charging vs. Ablation

Case III: 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

Examples:

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

Radiation induced Conductivity (RIC)

Mechanical Modification of Electron Transport and Emission Properties

Temperature dependant

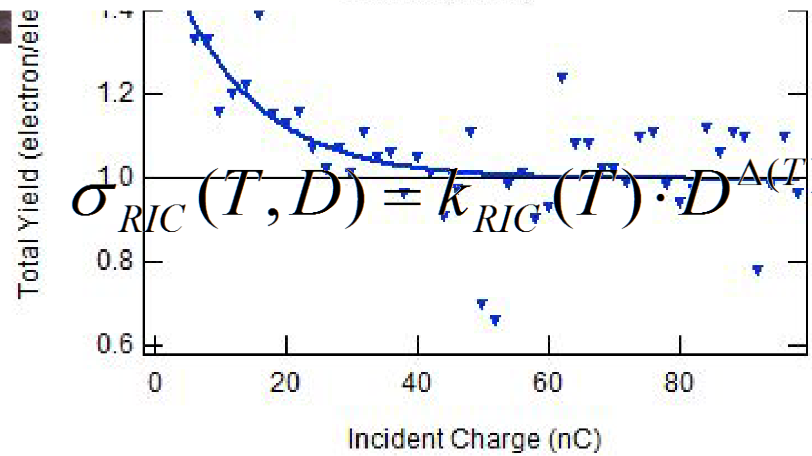
Examples: RBSP, JUNO, JGO/JEO

Caused by bondbreaking and trap creation

(see A Sim posters)

Mechanical and Optical Materials Damage

(see Hoffmann & A Sim posters)



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

Case IV: Temperature Effects

Strong T Dependence for Insulators

<u>Charge Transport</u>

- **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

Case IV: Temperature Effects

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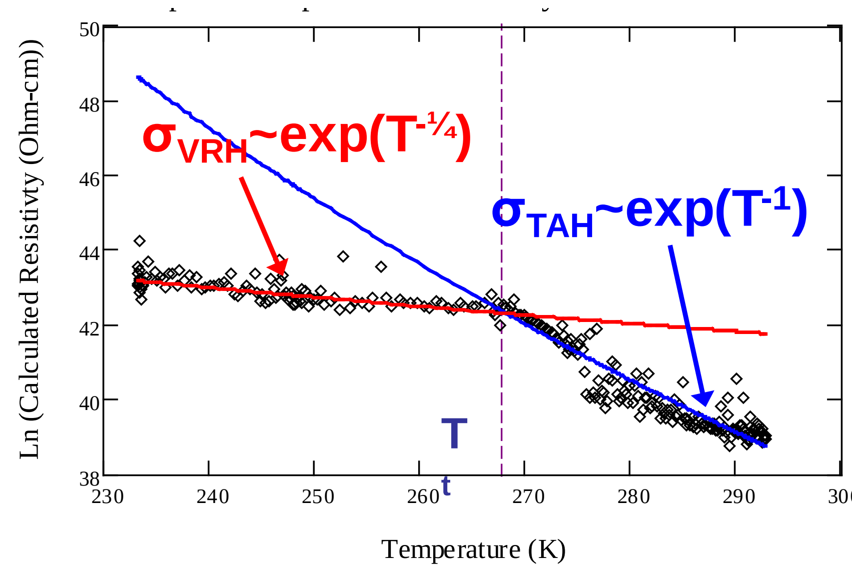
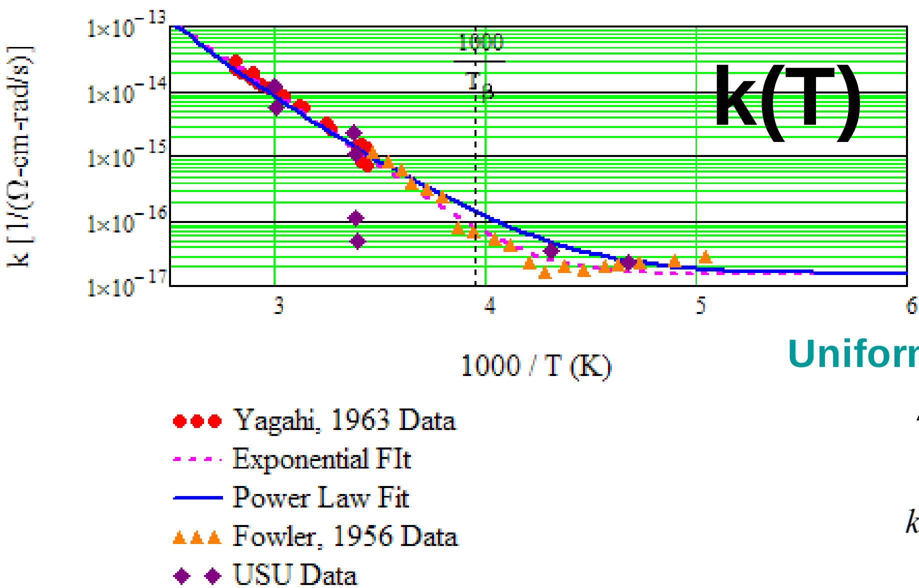
Strong T Dependence for Insulators



Charge Transport

- Conductivity
- RIC
- Dielectric Constant
- ESD



Uniform Trap Density

$$\Delta(T) \to 1$$

$$k(T) \to k_{RICo}$$

Exponential Trap Density

$$\Delta(T) \to {T_c}/{T+T_c}$$

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

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

Case IV: Temperature Effects—JWST

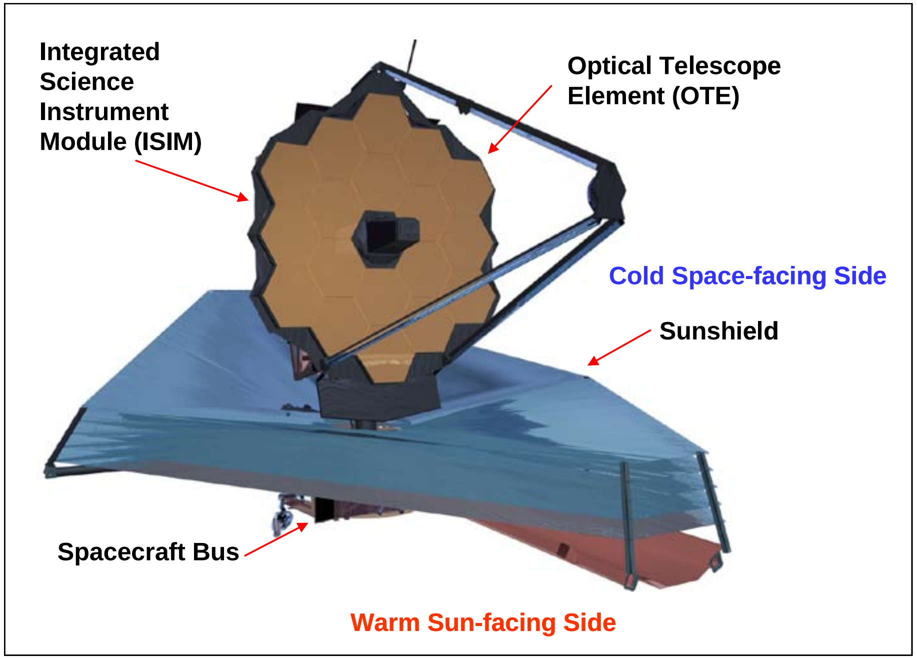
JWST

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 V: Temperature and Dose Effects

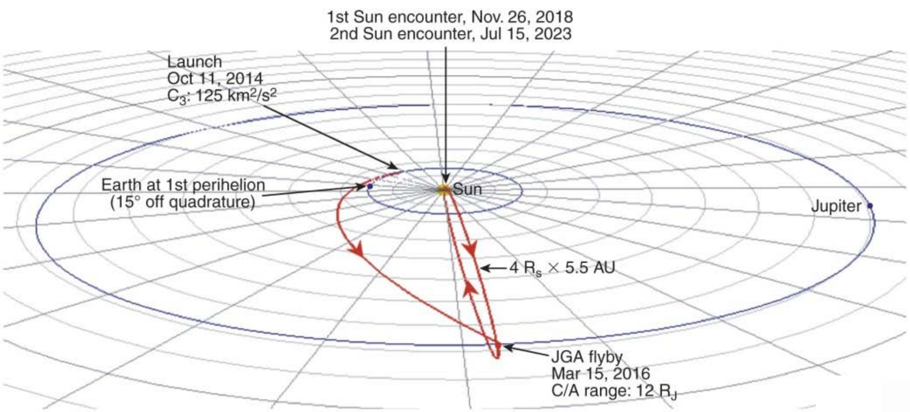


Figure 4-1. Solar Probe mission summary.

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

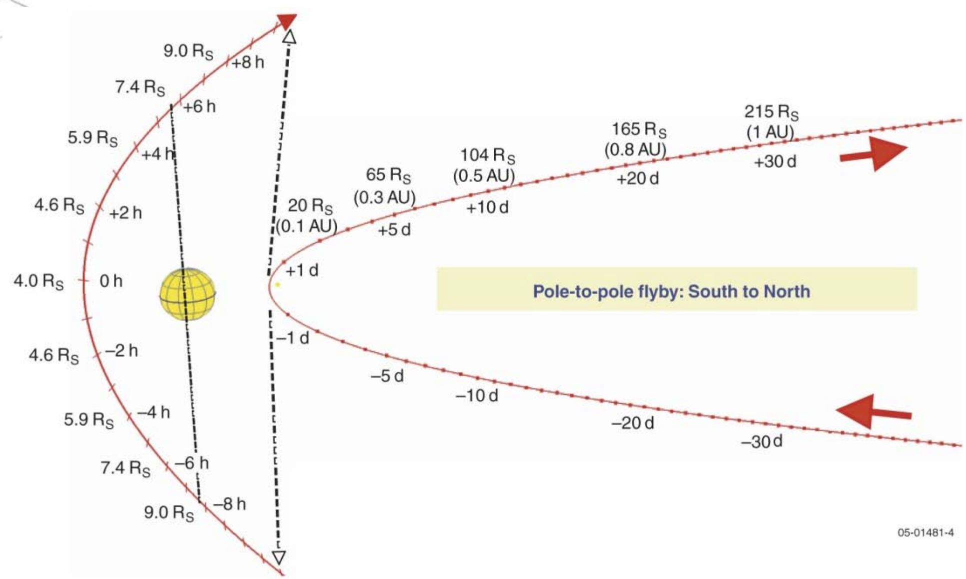
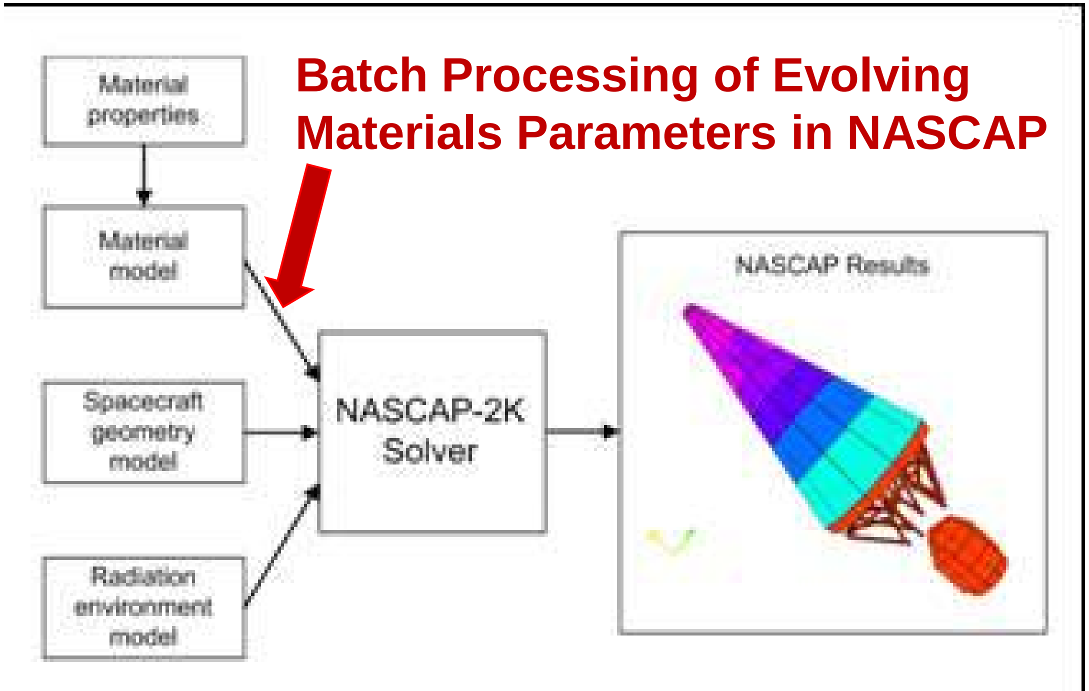


Figure 4-2. Solar encounter trajectory and timeline. Science operations begin at perihelion –-5 days (65 R_s) and continue until perihelion +5 days.

Case V: Temperature and Dose Effects

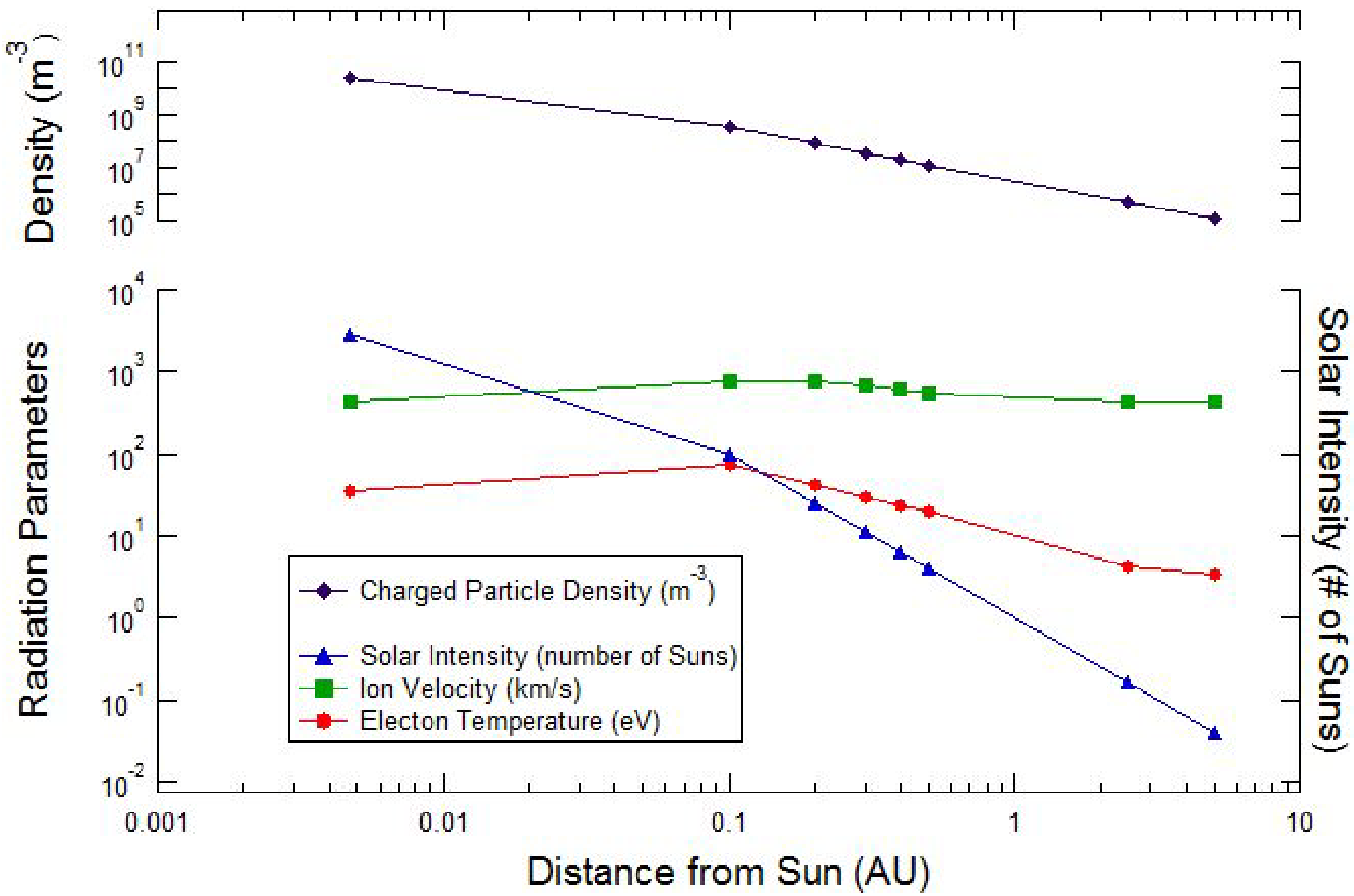
"We anticipate significant thermal and charging issues."

J. Sample



- *Mission design by APL/GSFC*
- *Materials testing by Dennison and Hoffmann*
- *Evolutionary Charging Study by Donegan, Sample, Dennison & Hoffmann*
  (See Donegann et al, JSR 2009)
- *Revised mission design and new charging study*
  (See Donegann 11th SCTC Poster for update)

Case V: Temperature and Dose Effects



Wide Orbital Range

Earth to Jupiter Flyby

Solar Flyby to 4 R_s

WideTemperature Range

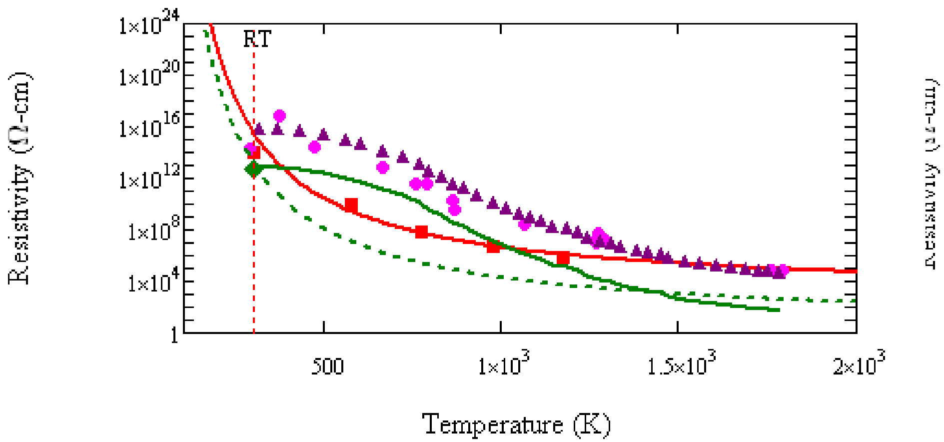
<100 K to >1800 K

Wide Dose Rate Range

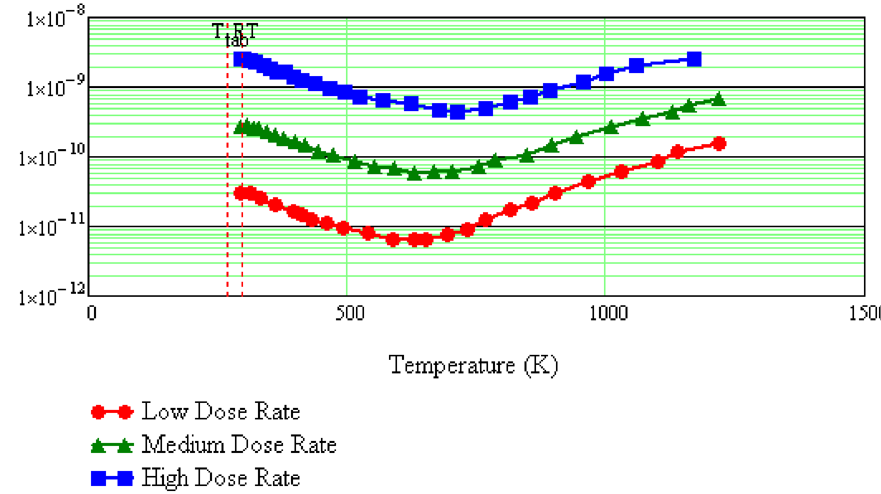
Five orders of magnitude variation!

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

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

Dielectric Constant

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

Electrostatic Breakdown

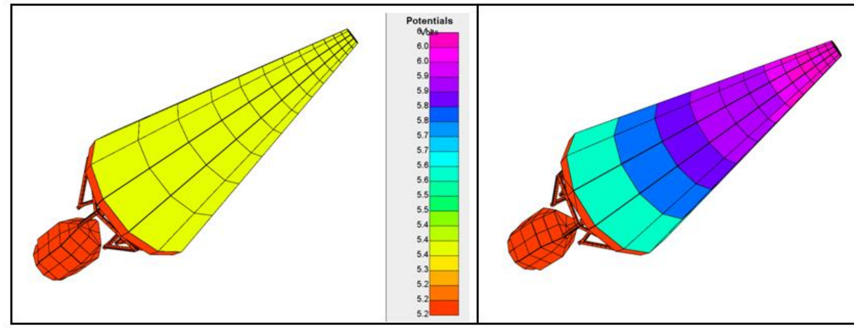
$$E_{ESD}(T) = E_{ESD}^{RT}\, e^{-\alpha_{ESD}(T-298\,K)}$$

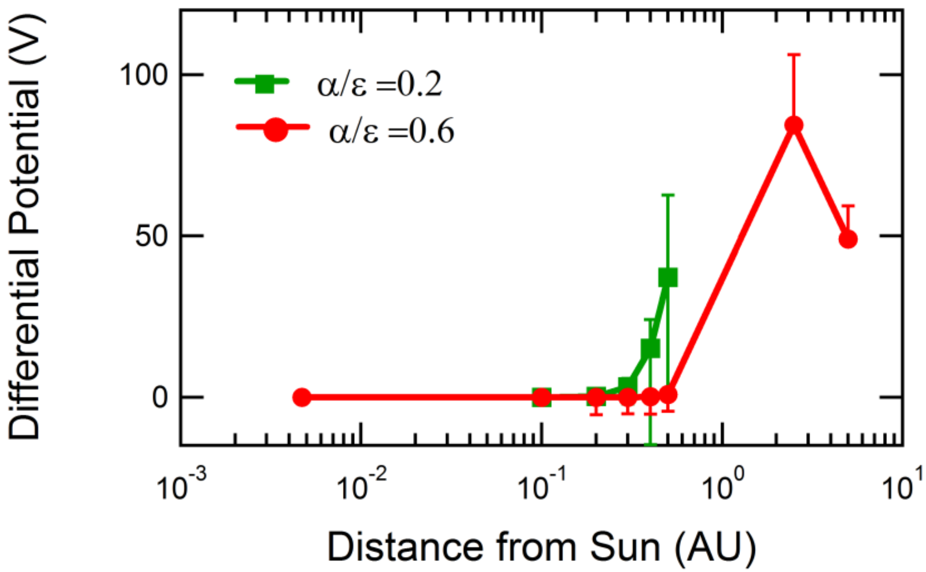
Case V: Temperature and Dose Effects

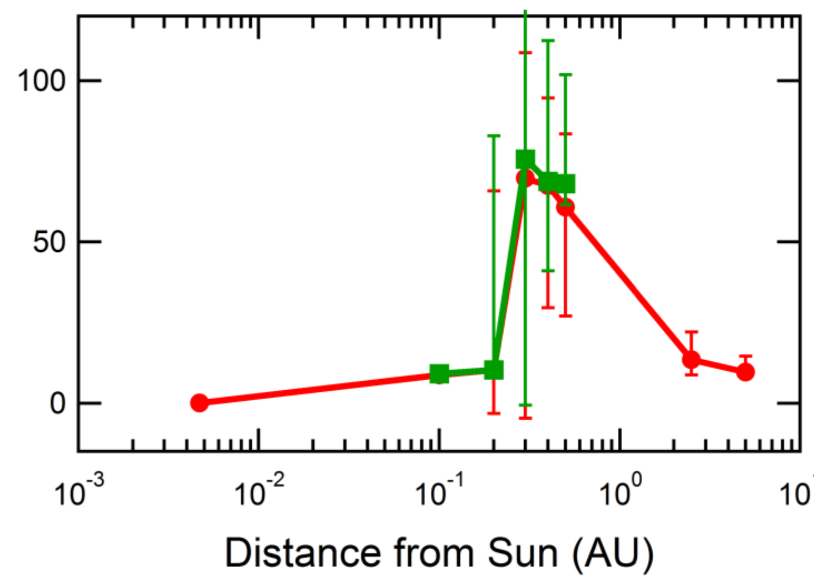
A peak in charging at ~0.3 to 2 AU

"…Curiouser and curiouser…"

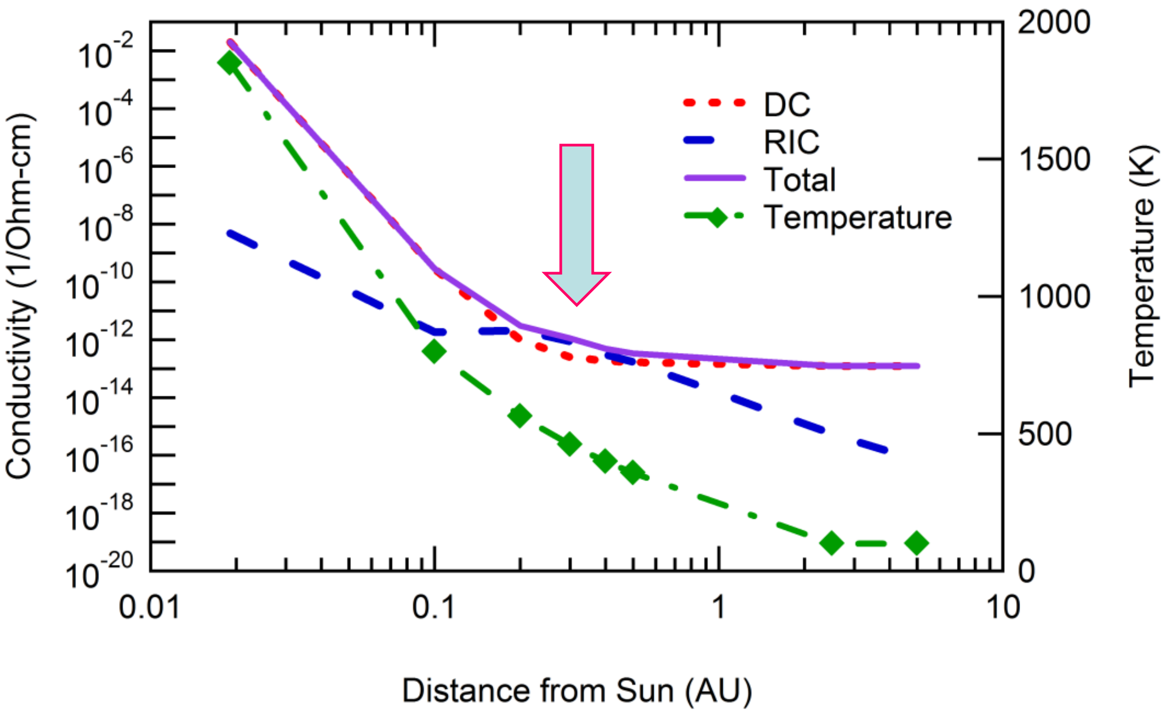
--Alice







Case V: 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 VI: Multilayer/Nanocomposite Effects

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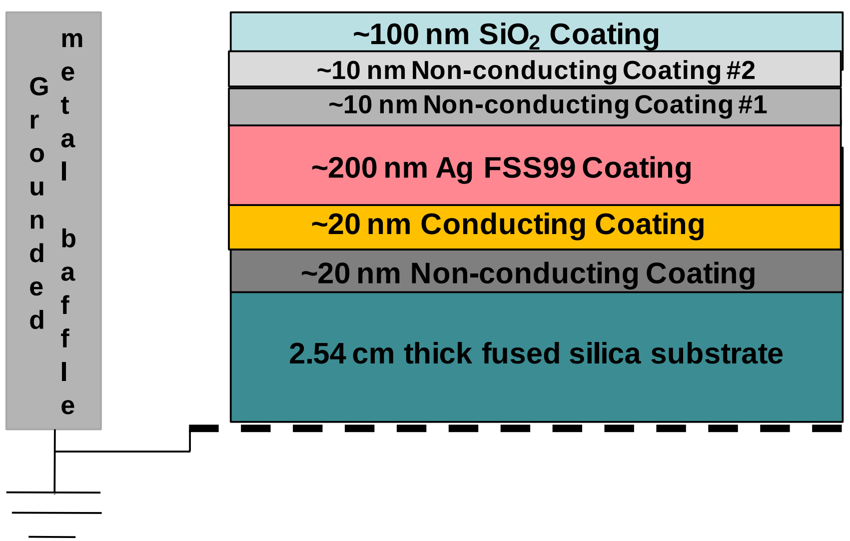
Consider the Effects of Multilayer Materials, Composites, Contamination, or Oxidation

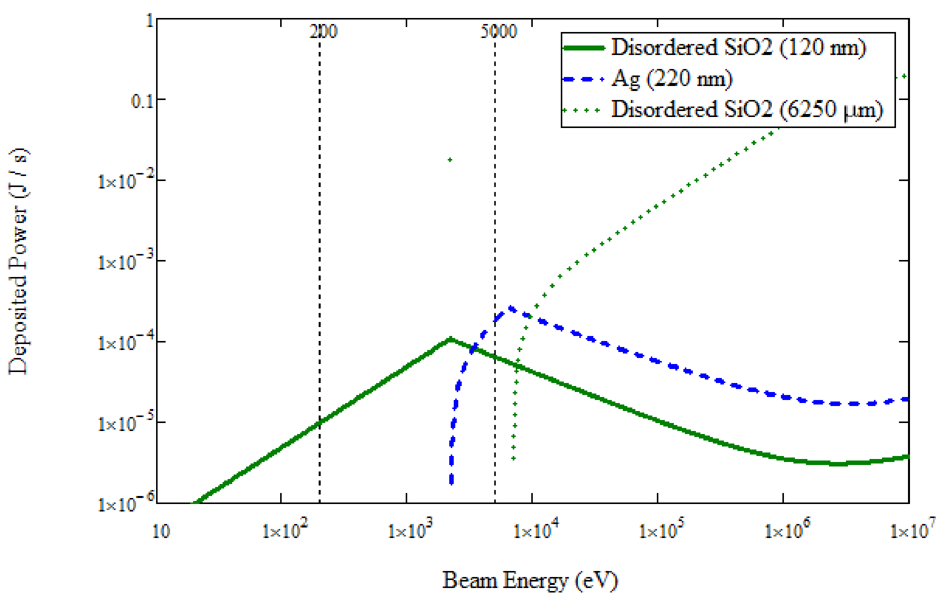
Length Scale
- Nanoscale structure of materials
- Electron penetration depth
- SE escape depth

Time Scales
- Deposition times
- Dissipation times
- Mission duration

Coated Mirror Structure



Power Deposition Graph



Why Does Glow Scale with Flux, Energy and Power?

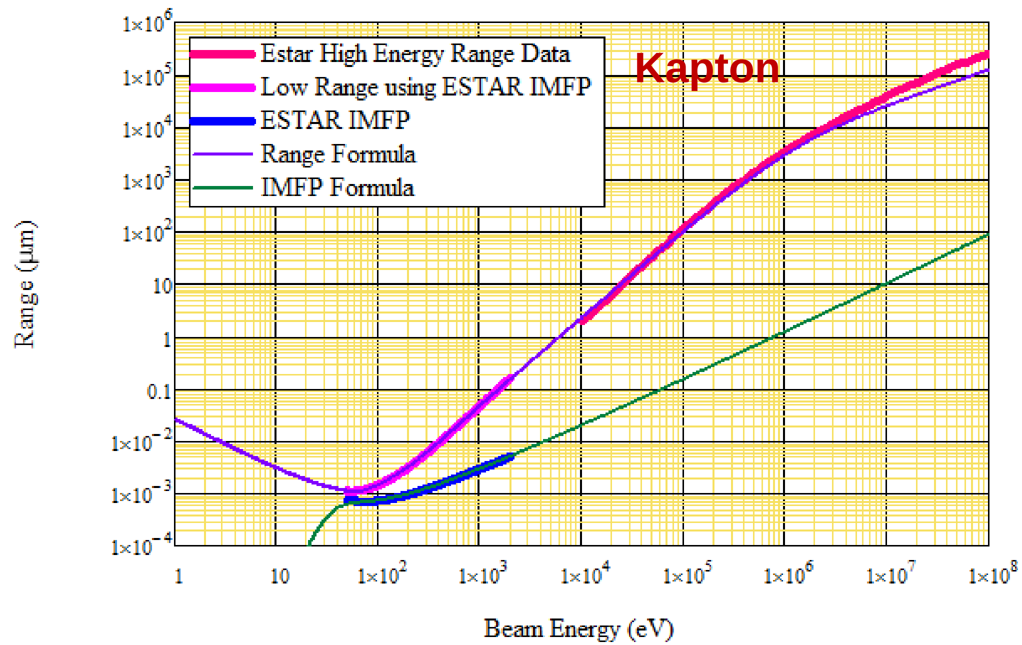
In a simple, but reasonably accurate CSDA, used to model energy loss of electrons traversing solids and their penetration range, the rate of energy loss (dE/dz) is assumed constant.

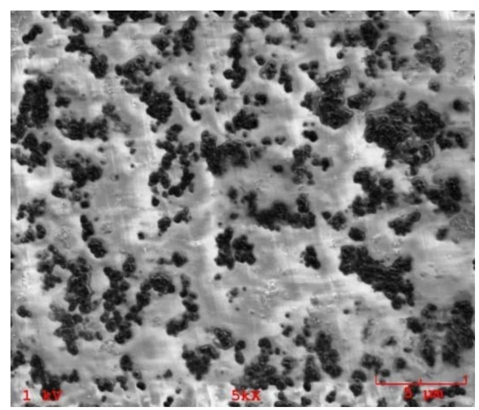
Assuming emission intensity is proportional to energy deposition (dose), emission scales as:

- **Incident e-flux, for non-penetrating radiation**
- **Incident power, for penetrating radiation**

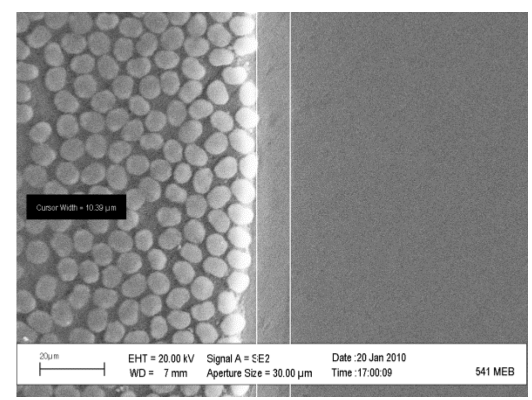
Emission scaling depends on sample geometry and materials properties. May lead to:

- **Power or flux scaling at different incident energies**
- **Energy or flux thresholds and/or cutoffs**
- **Significant emission from high energy e$^-$**
- **Significant emission from back sides or interior surfaces**





10 µm



Diversity of Emission Phenomena in Black Kapton

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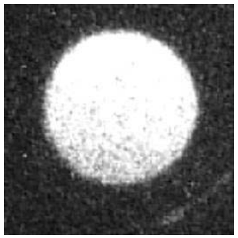
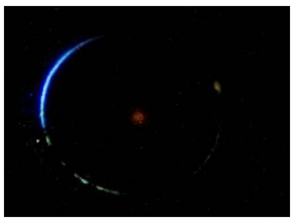
Ball Black Kapton Runs 131 and 131A	22 keV 135 K	110 or 4100 uW/cm^2 5 or 188 nA/cm^2



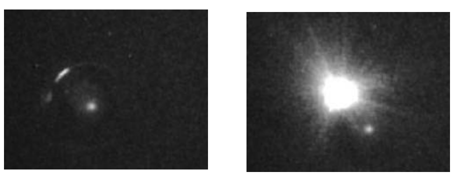
Surface Glow

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

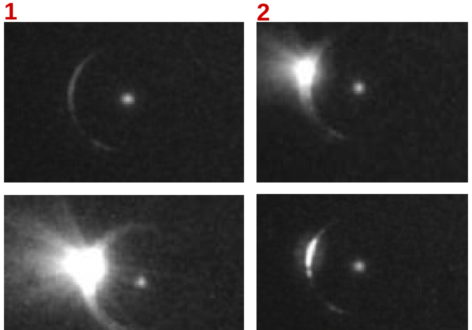


1 2

"Flare"

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

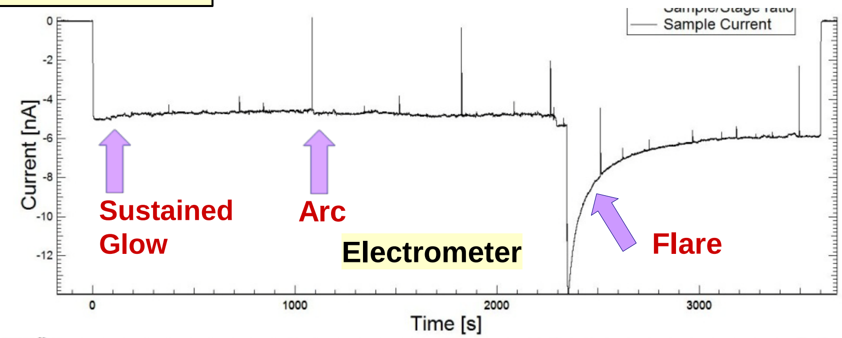
1 2

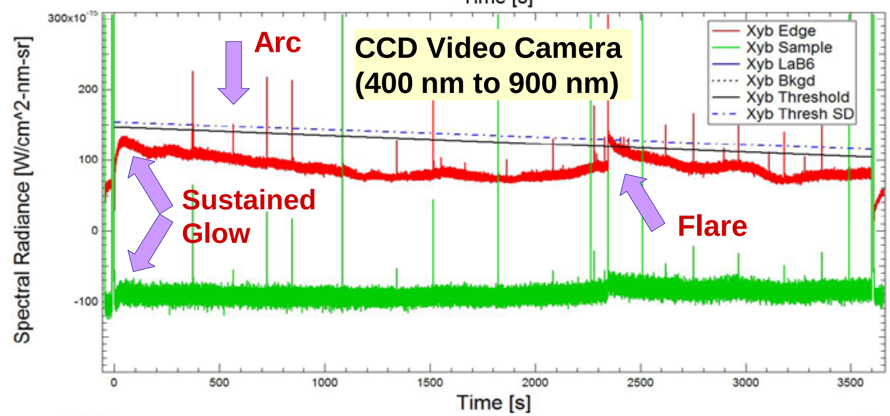


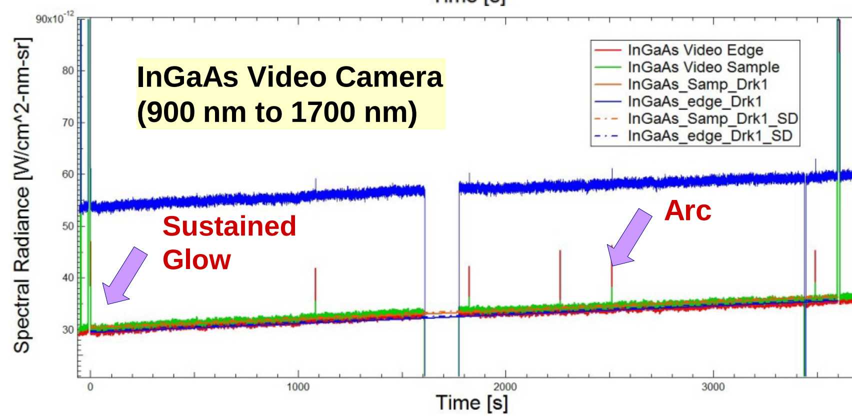
3 4

Arc

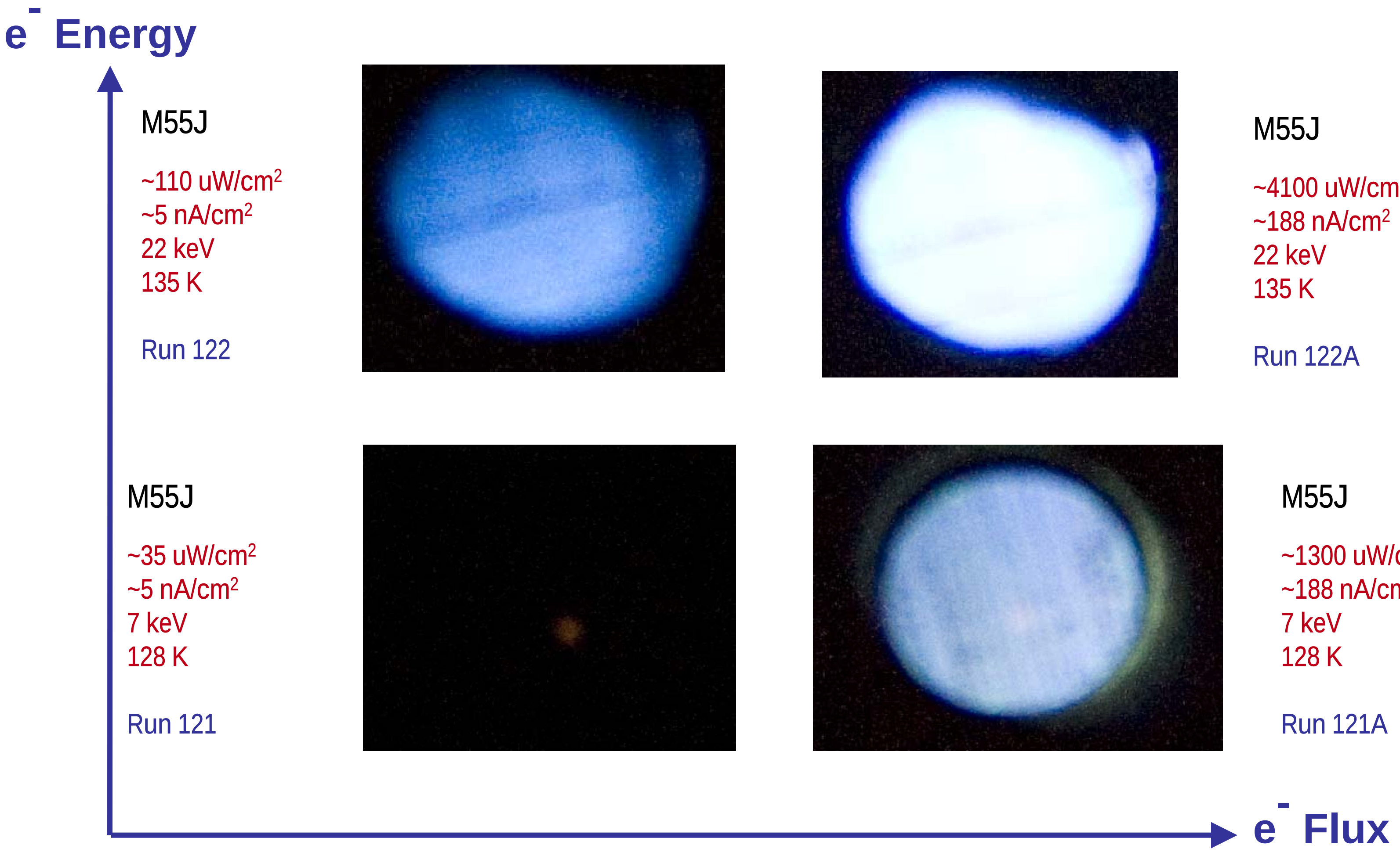
Relatively very high intensity
10-1000X glow intensity
Very rapid <1 us to 1 s







Glow Increases with Increasing Flux, Energy and Power

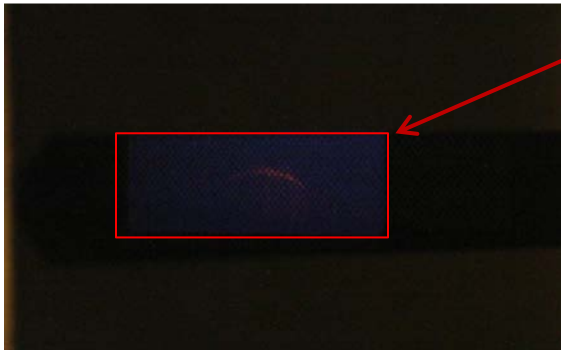


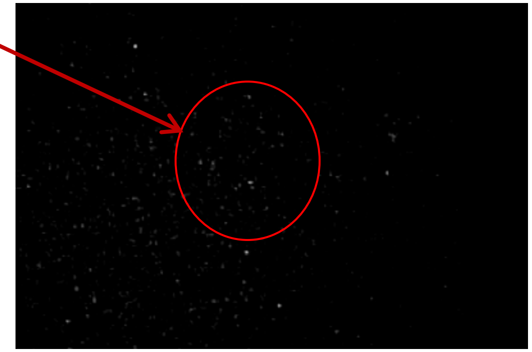
- **Surface Glow, Edge Glow, and Arcing Frequency are all found to increase with increasing incident electron flux and energy.**
- **Insufficient data for trends to establish functional dependence and possible thresholds or cut-offs**

Emission Increases with Decreasing Temperature

Sample Area

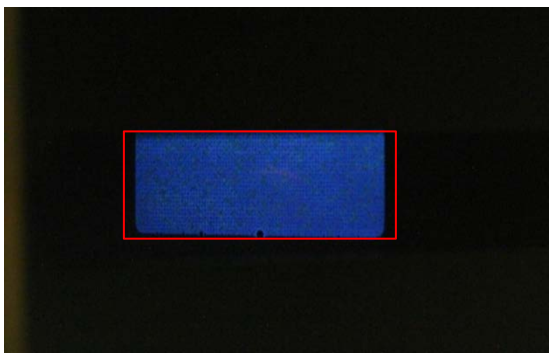
Surface Glow
296 K

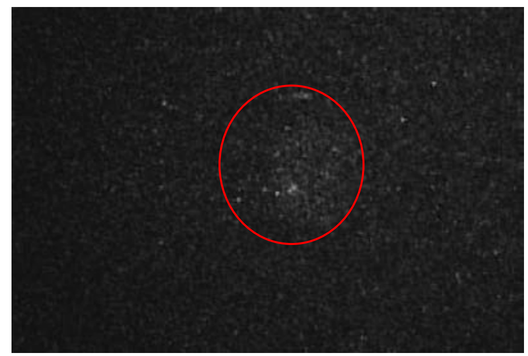




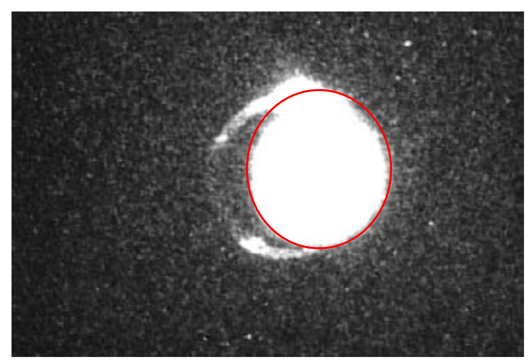
Surface Glow
294 K

Surface Glow
90 K





Surface Glow
130 K



"Flare"
130 K

T300 Glow seen at MSFC

Flux density =1 nA/cm^2
Energy=22 keV
Power 22 uW/cm^2
Temp = 296 K and 90 K

$I_{90}/I_{296} \sim 4$

Similar behavior seen for M55J and Black Kapton

M55J Glow seen at USU

Flux density =5 nA/cm^2
Energy=22 keV
Power 110 uW/cm^2
Temp = 294 K and 130 K

Model for Luminescence Intensity in Fused Silica

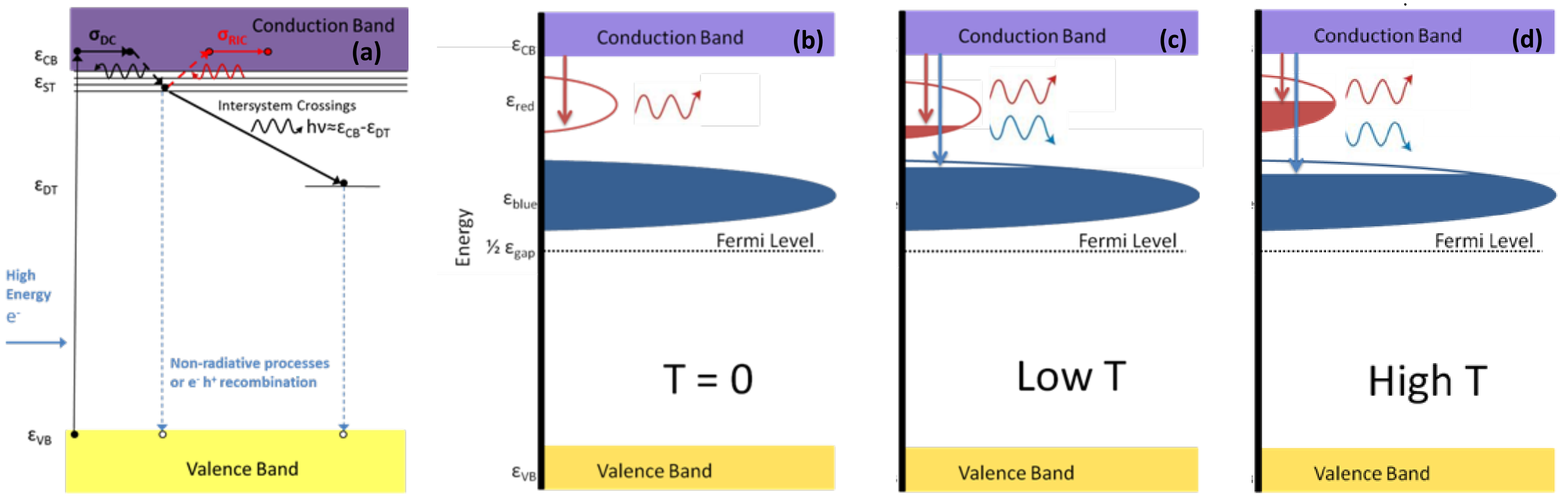


Fig. 2. Qualitative two-band model of occupied densities of state (DOS) as a function of temperature during cathodoluminescence. **(a)** Modified Joblonski diagram for electron-induced phosphorescence. Shown are the extended state valence (VB) and conduction (CB) bands, shallow trap (ST) states at ε_{ST} within ~k_BT below the CB edge, and two deep trap (DT) distributions centered at ε_{DT}=ε_{red} and ε_{DT}=ε_{blue}. Energy depths are exaggerated for clarity. **(b)** At *T*≈0 K, the deeper DT band is filled, so that there is no blue photon emission if ε_{blue}<ε_{eff}. **(c)** At low *T*, electrons in deeper DT band are thermally excited to create a partially filled upper DT band (decreasing the available DOS for red photon emission) and a partially empty lower DT band (increasing the available DOS for blue photon emission) **(d)** At higher *T*, enhanced thermal excitations further decrease red photon emission and increase blue photon emission. Radiation induced

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

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

$$\dot{D}(J_b,E_b) = \frac{E_b\, J_b[1-\eta(E_b)]}{q_e \rho_m} \times \begin{cases} [1/L] & ;\ R(E_b) < L \\ [1/R(E_b)] & ;\ R(E_b) > L \end{cases} \quad (2)$$

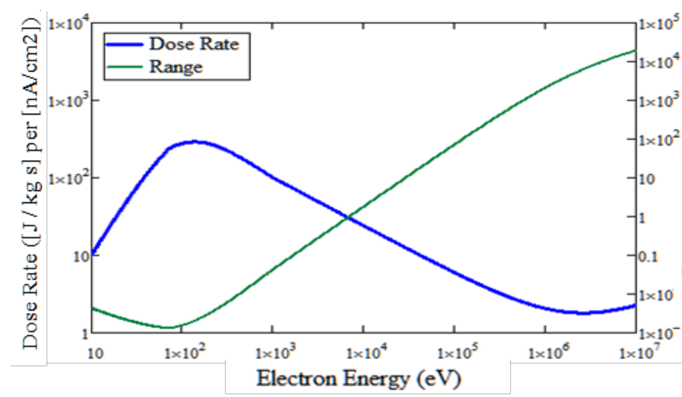


Fig. 3.Range and dose rate of disordered SiO_2 as a function of incident energy using calculation methods and the continuous slow-down approximation described in [5].

Measured Cathodoluminescence Intensity in Fused Silica

UtahState University MATERIALS PHYSICS GROUP

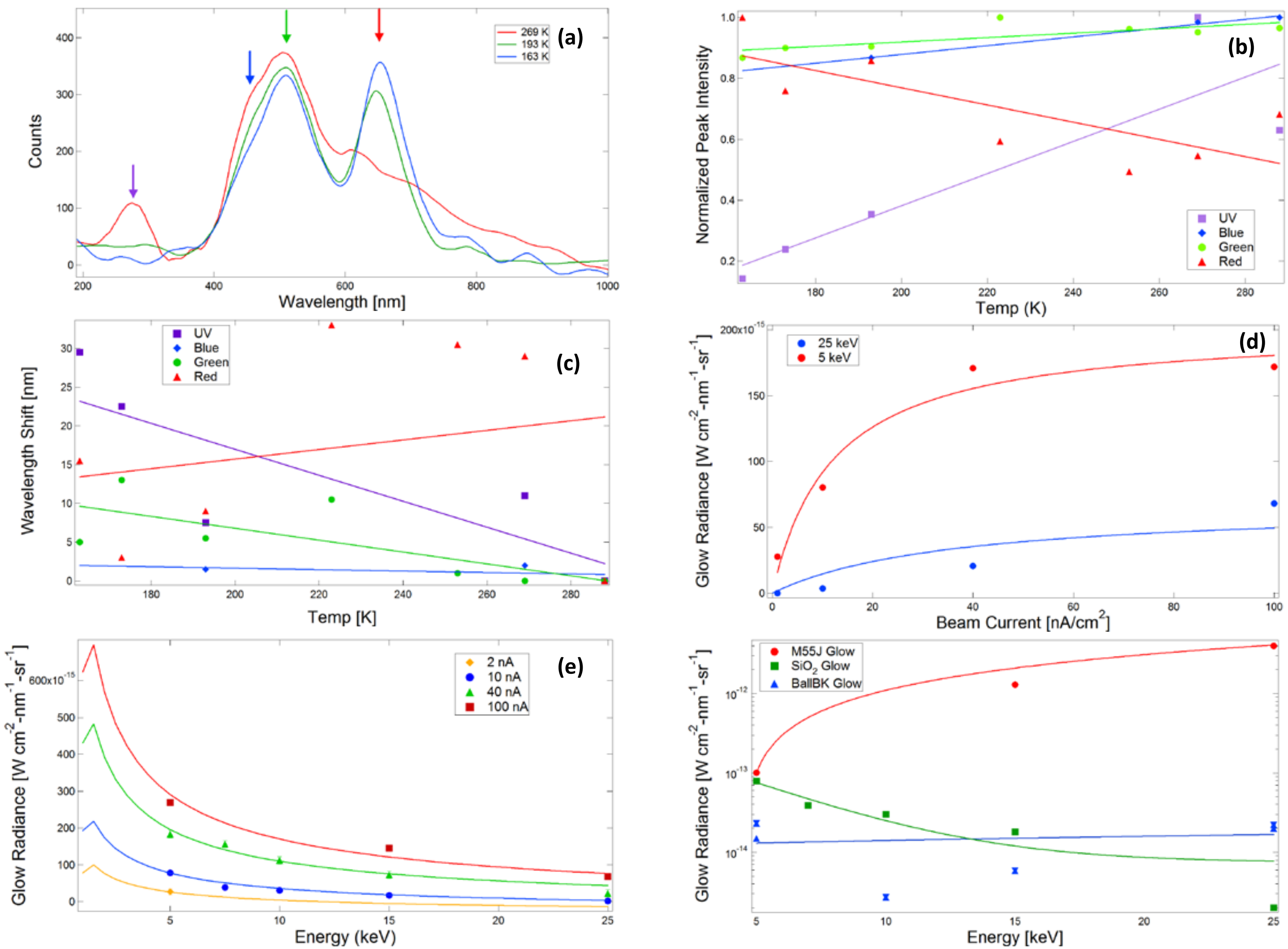
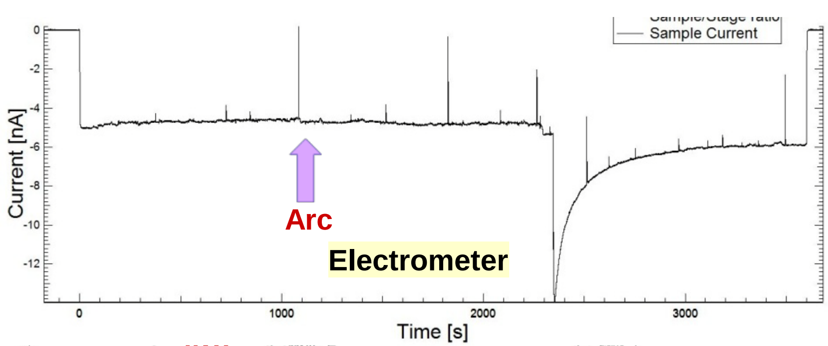
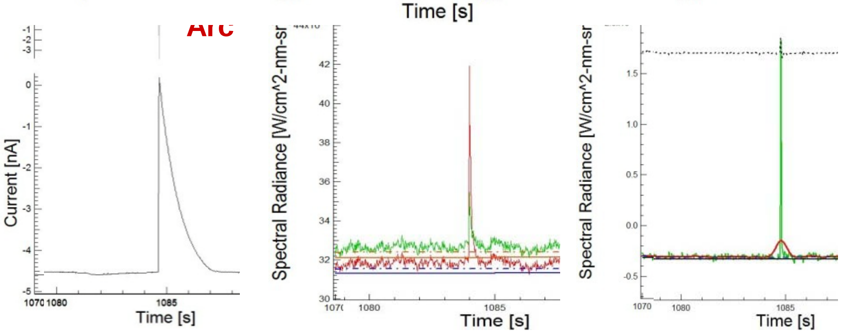


Fig. 1. Optical measurements of luminescent thin film disordered SiO_2 samples. **(a)** Three luminescence UV/VIS spectra at decreasing sample temperature. Four peaks are identified: red (~645 nm), green (~500 nm), blue (~455 nm) and UV (275 nm). **(b)** Peak amplitudes as a function of sample temperature, with baseline subtracted and normalized to maximum amplitudes. **(c)** Peak wavelength shift as a function of sample temperature. **(d)** Total luminescent radiance versus beam current at fixed incident energy fit by (1). **(e)** Total luminescent radiance versus beam energy at fixed incident flux fit by (1). **(f)** Total luminescent radiance versus beam energy at fixed 10 nA/cm^2 incident flux for epoxy-resin M55J carbon composite (red; linear fit), SiO_2 coated mirror (green; fit with (1)), and

Arcs Observed in Black Kapton and M55J

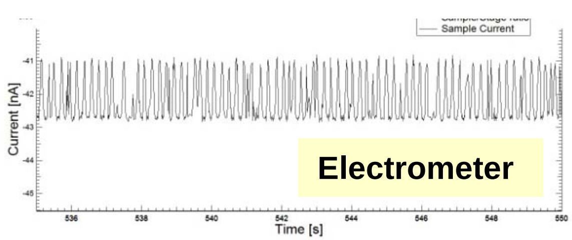
Ball Black Kapton	22 keV	110 or 4100 uW/cm^2
Runs 131 and 131A	135 K	5 or 188 nA/cm^2





Electrometer InGaAs Video CCD Video

Rapid Arcing at 4 mW/cm^2 ~20000 ars/hr

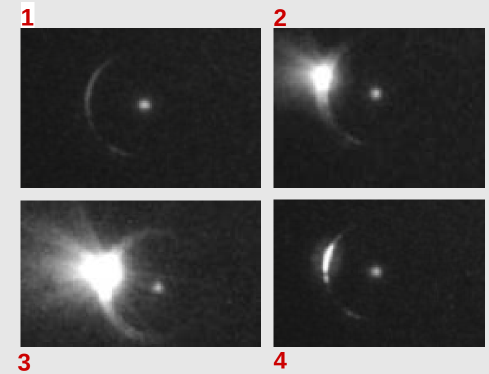


Arc Characteristics

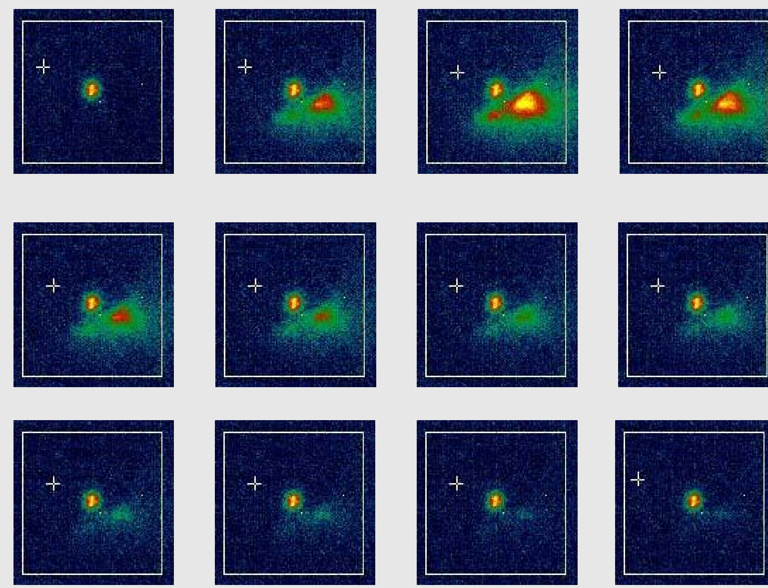
Arc duration:
~0.2 to 0.8 s in electrometers and video cameras

Arc Freq. at 110 μW/cm^2 :
~10 arcs/hr for Black Kapton
~30 arcs/hr for M55J

Arc Intensity:
~ 10X to1000X glow amplitude
~5% to 20% of glow power



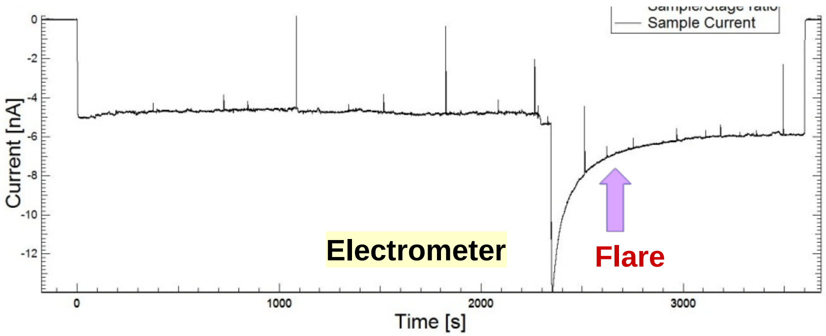
CCD camera (400nm-900nm)

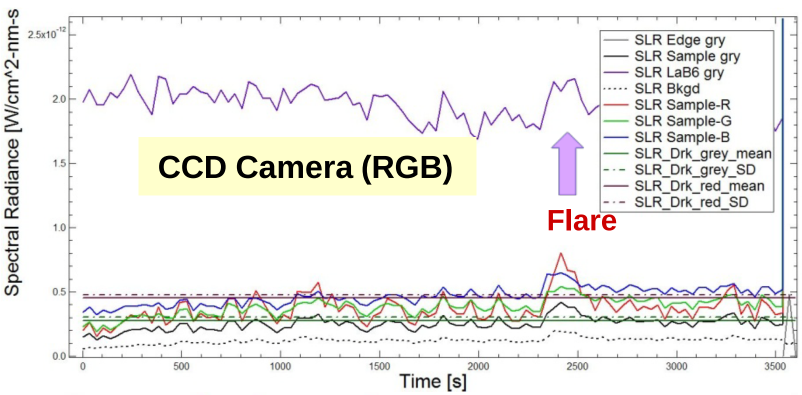


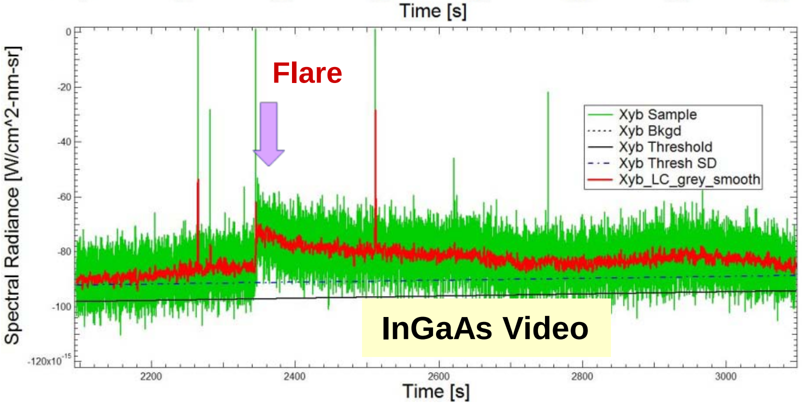
Consecutive frames of discharge event (60 frames/sec)

InGaAs camera (900nm-1700nm)

“Flares” Observed in Black Kapton







Ball Black Kapton

Runs 131

110 uW/cm^2

5 nA/cm^2

22 keV

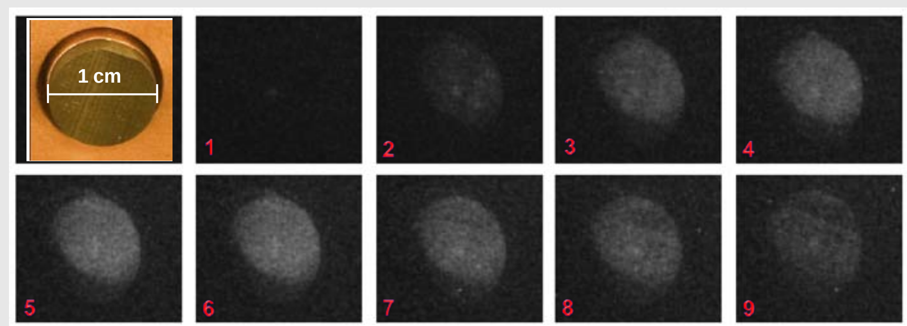
135 K

“Flare” Characteristics

“Flare” duration:
Abrupt onset
~2-10 min exp. decay time in electrometers and video cameras

“Flare” Freq.uency:
0-2 flares/hr

“Flare” Intensity:
~ 2X to20X glow amplitude
~5% to 20% of glow power



CCD camera (400nm-900nm)

M55J

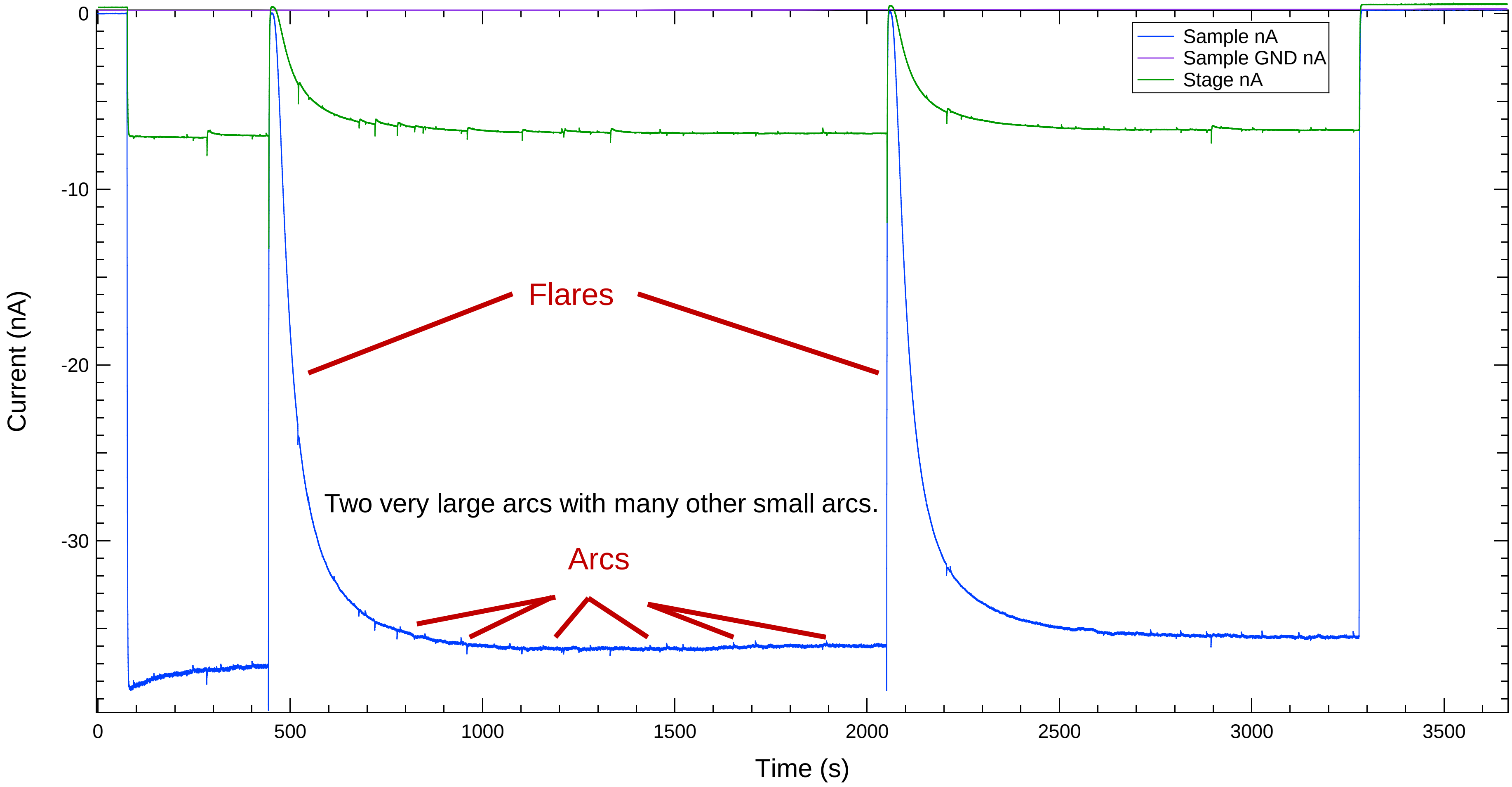
5 nA/cm^2

22 keV

135 K

Details of Electrometer "Flare" Signature

Electrometer Data



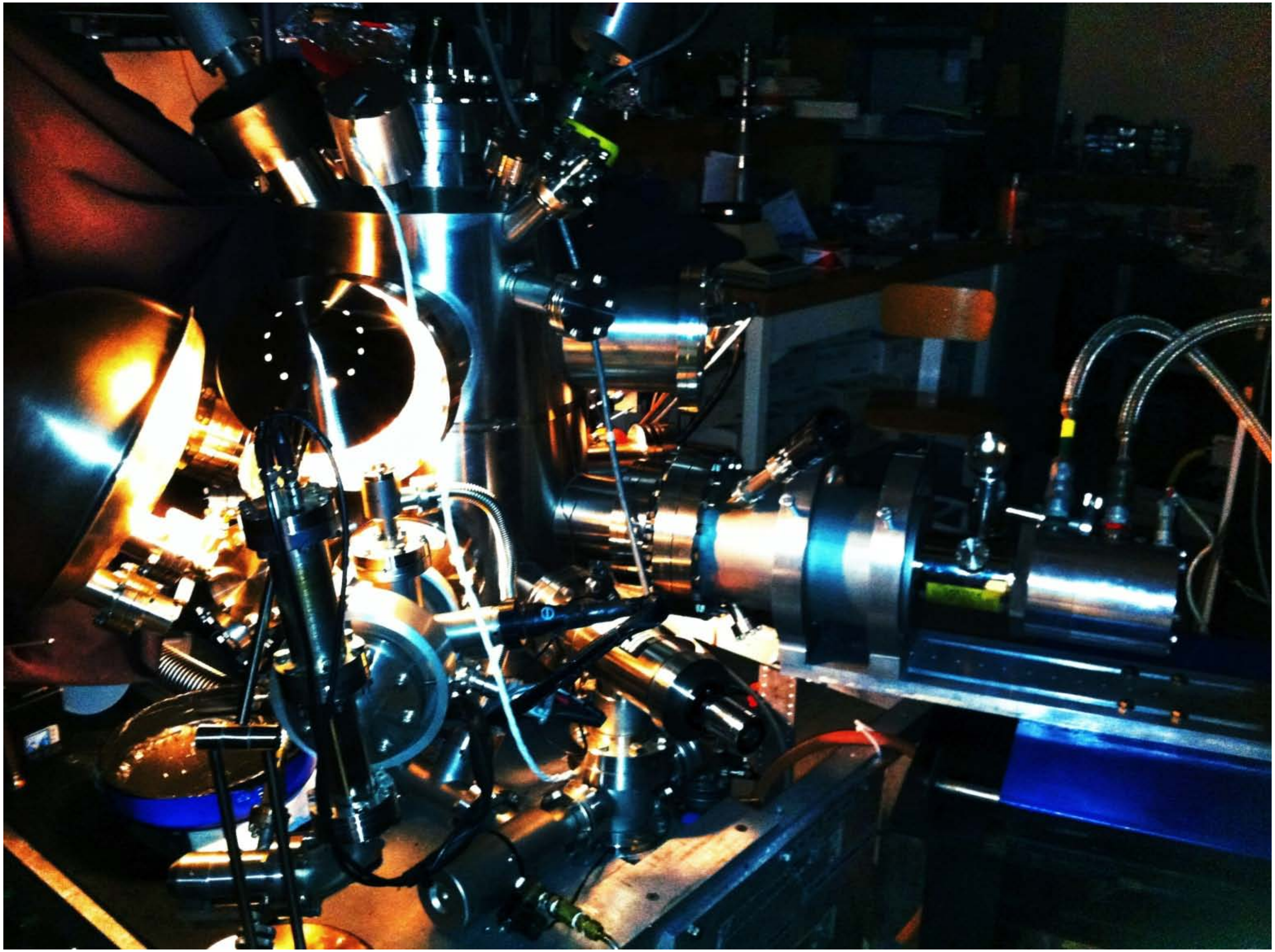
High Conductivity
C-loaded Kapton
25keV 38nA ~1 hr

Total Beam Time: 3204 s
# of Arcs: >50

Conclusions

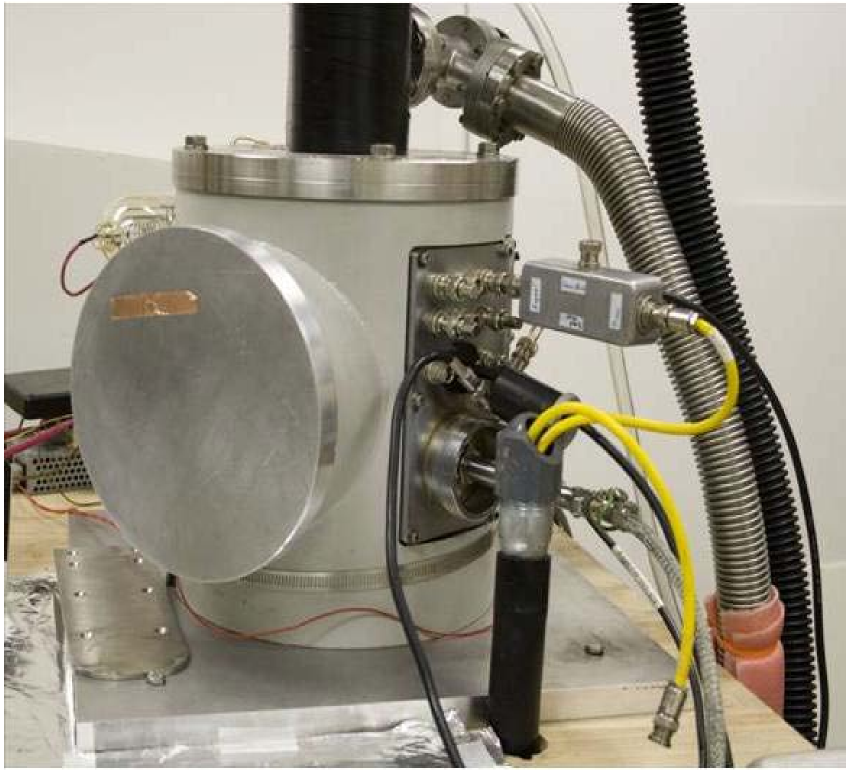
- Complex satellites require:
  - Complex materials configurations
  - More power
  - Smaller, more sensitive devices
  - More demanding environments
- There are numerous clear examples where **accurate dynamic charging models** require **accurate dynamic materials properties**
- It is not sufficient to use static (BOL or EOL) materials properties
- Enivronment/Materials Modification feedback mechanisms can cause many new problems
- Use available modeling tools with broader materials knowledgebase and a conscious awareness of the dynamic nature of materials to foresee and mitigate potential spacecraft charging problems

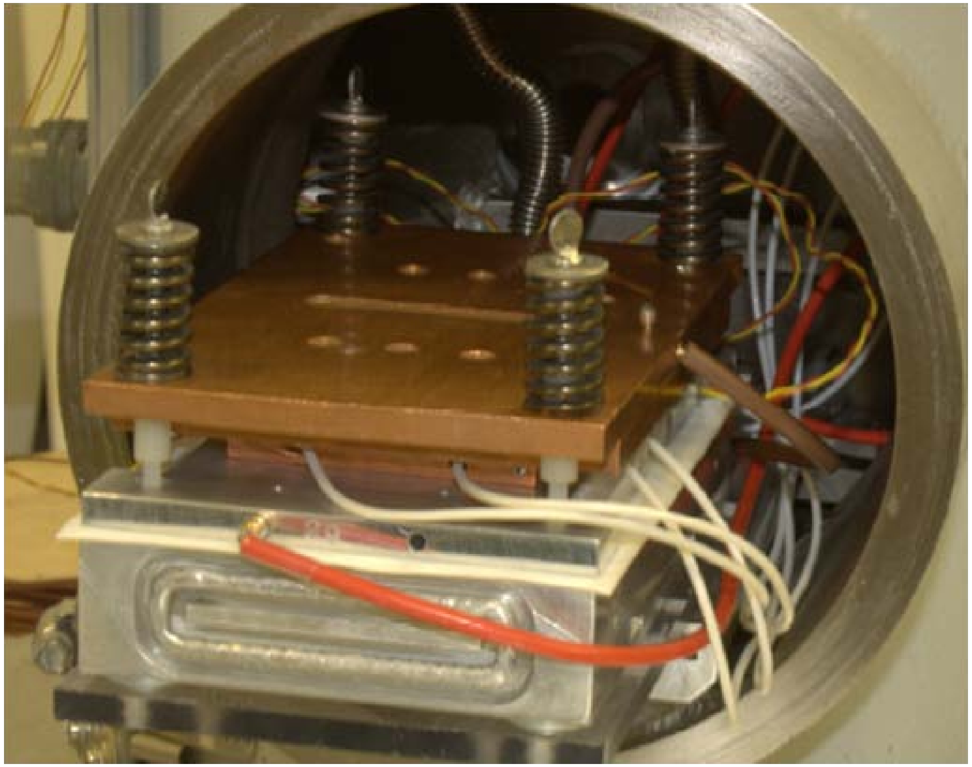
End with a Bang



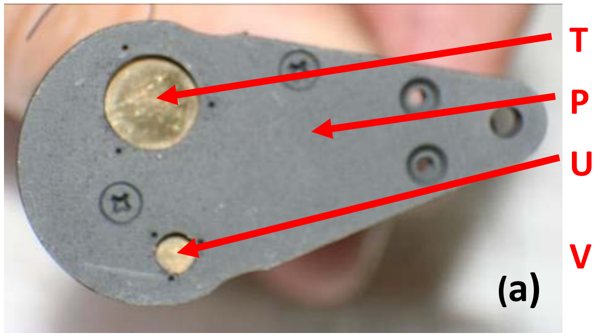
Supplemental Slides

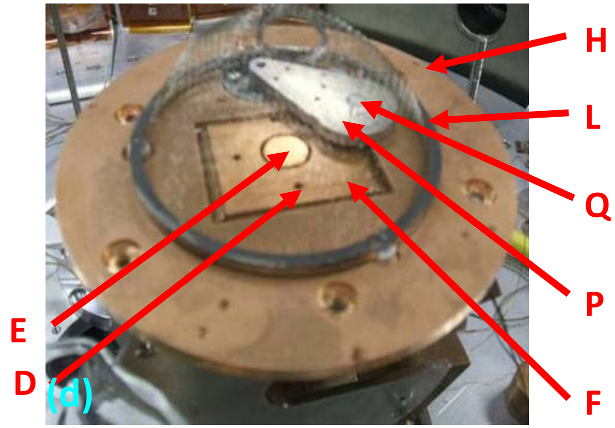
Extremely Low Conductivity

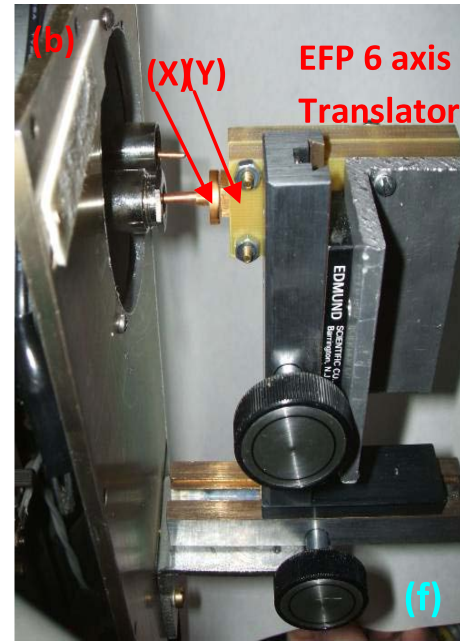


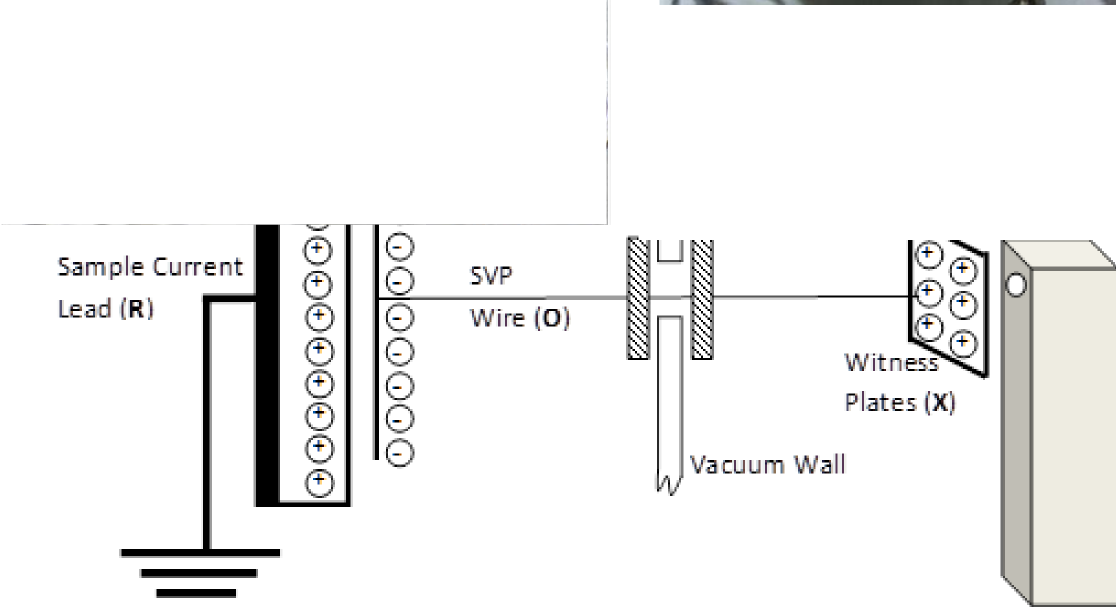


Surface Voltage









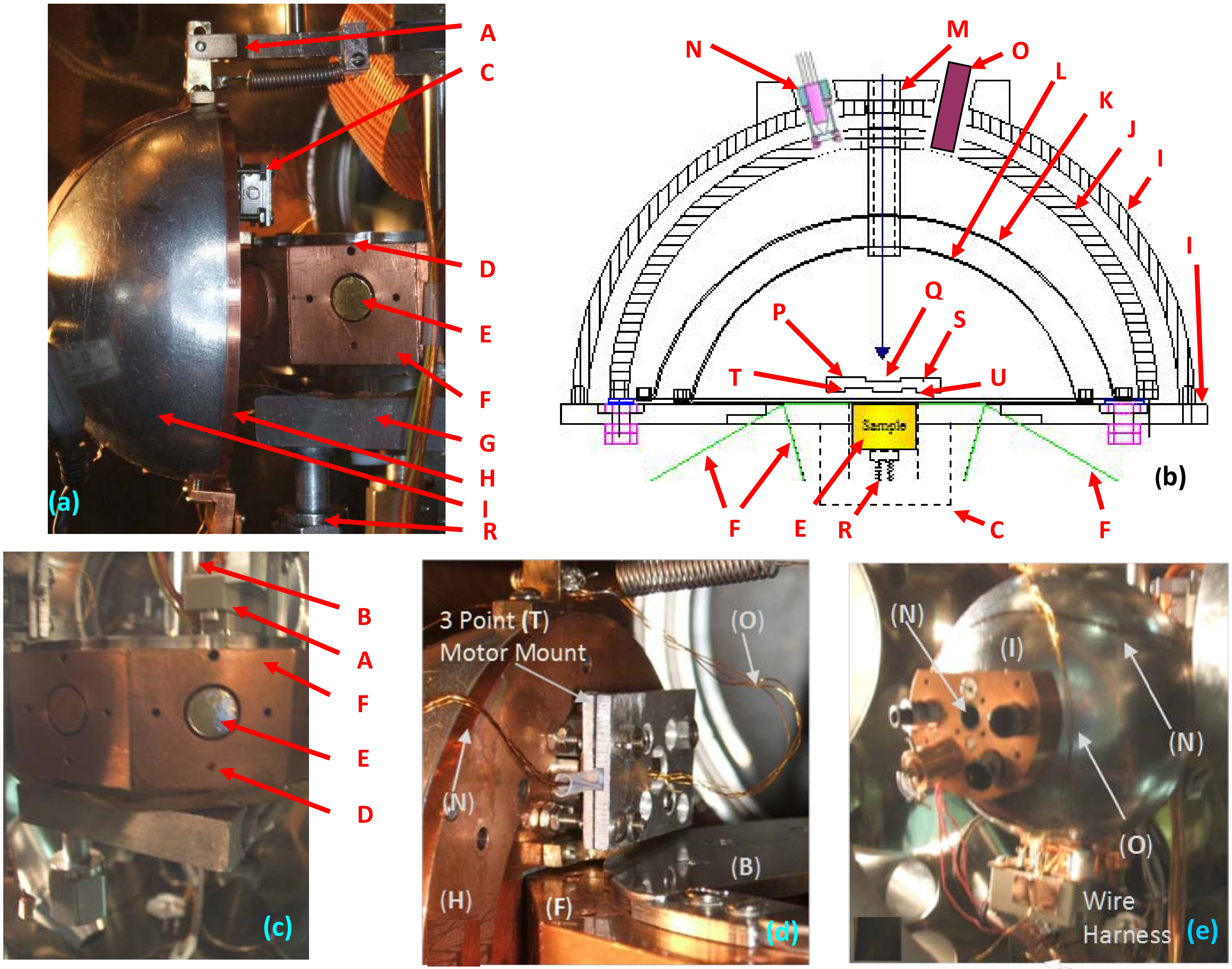
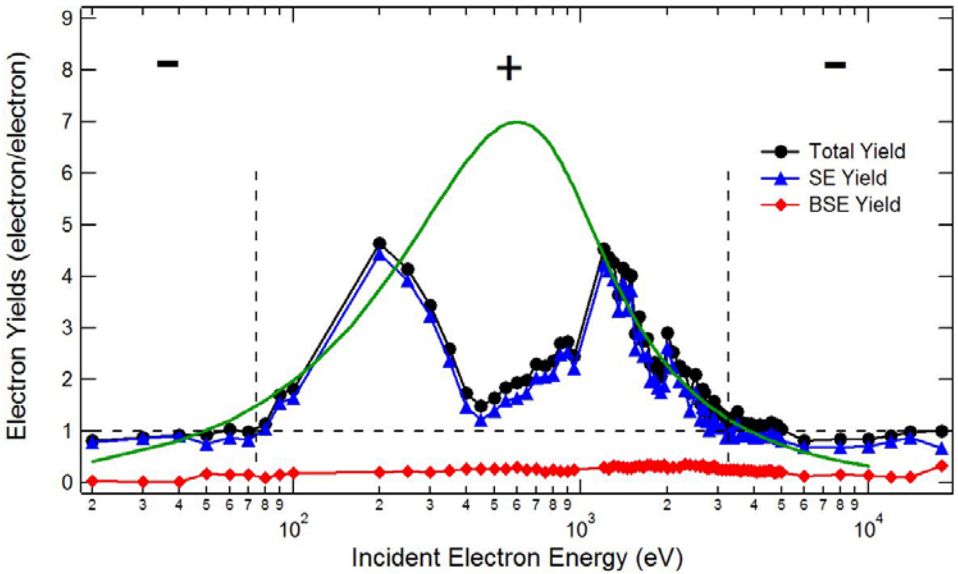
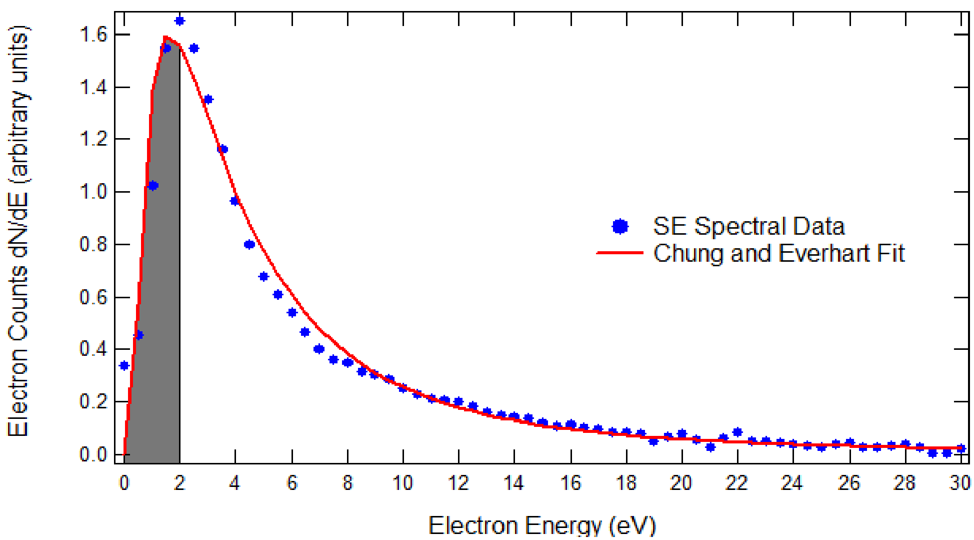


Fig. 2. **Hemispherical Grid Retarding Field Analyzer (HGRFA).** ***(a) Photograph of sample stage and HGRFA detector (side view). (b) Cross section of HGRFA. (c) Photograph of sample stage showing sample and cooling reservoir. (d) Side view of the mounting of the stepper motor. (e) Isometeric view of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

Low Charge Capabilities





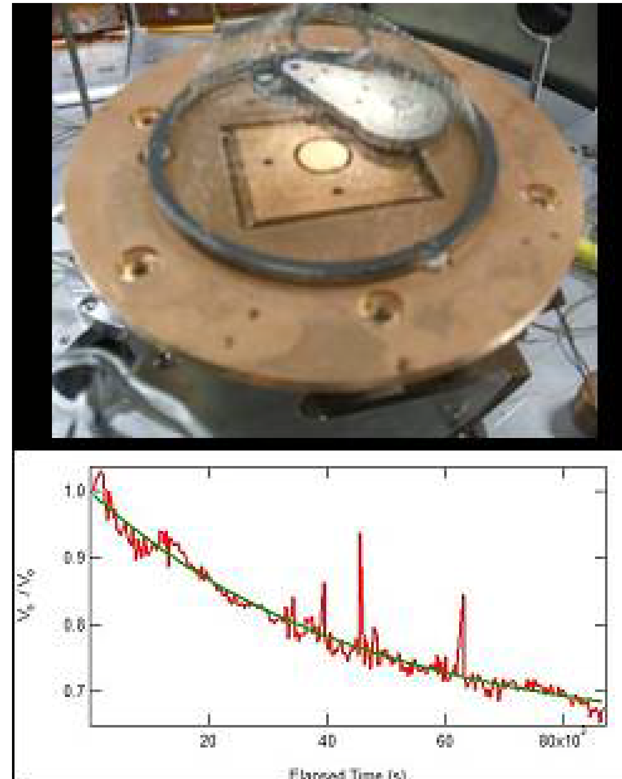
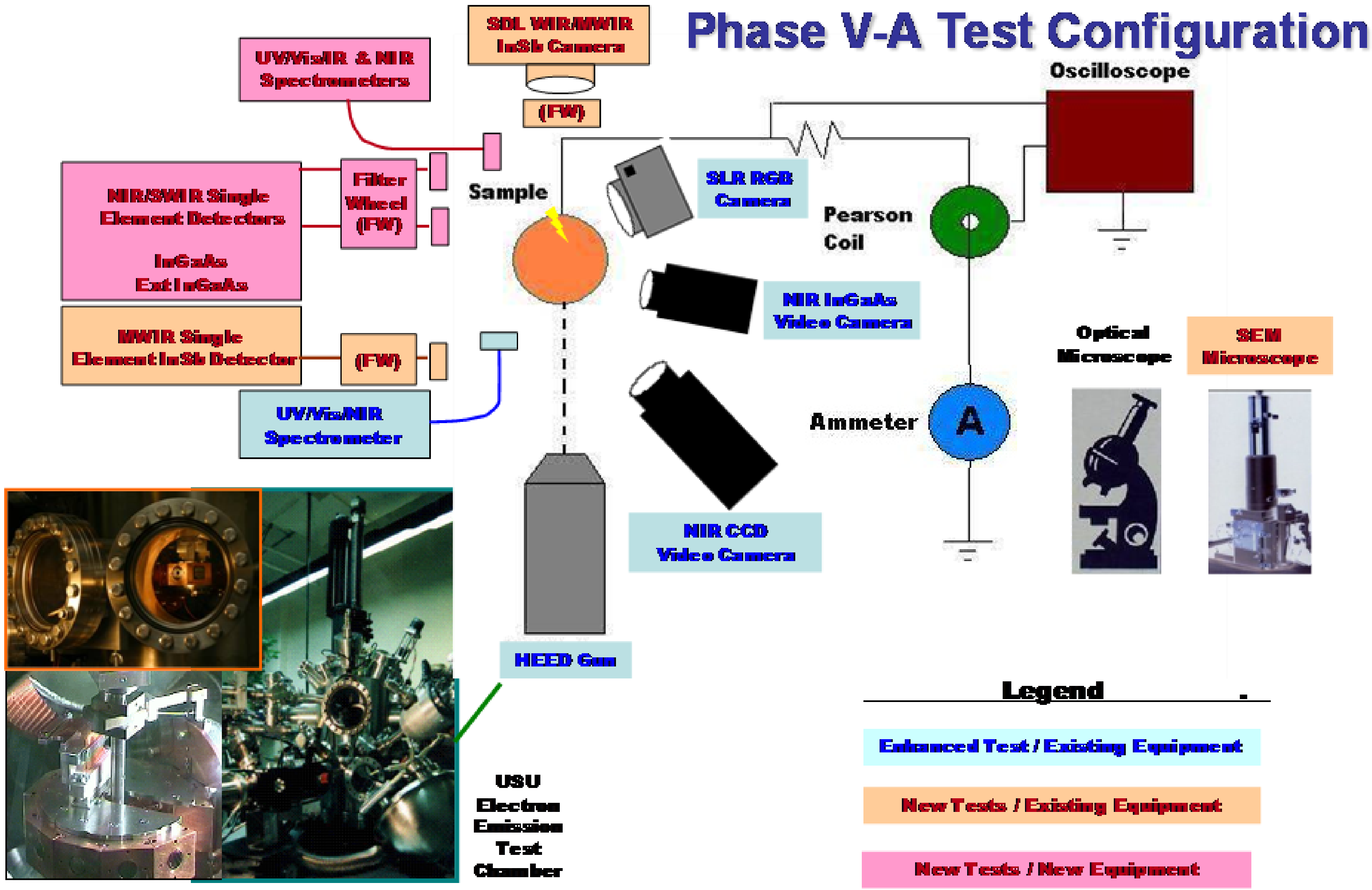


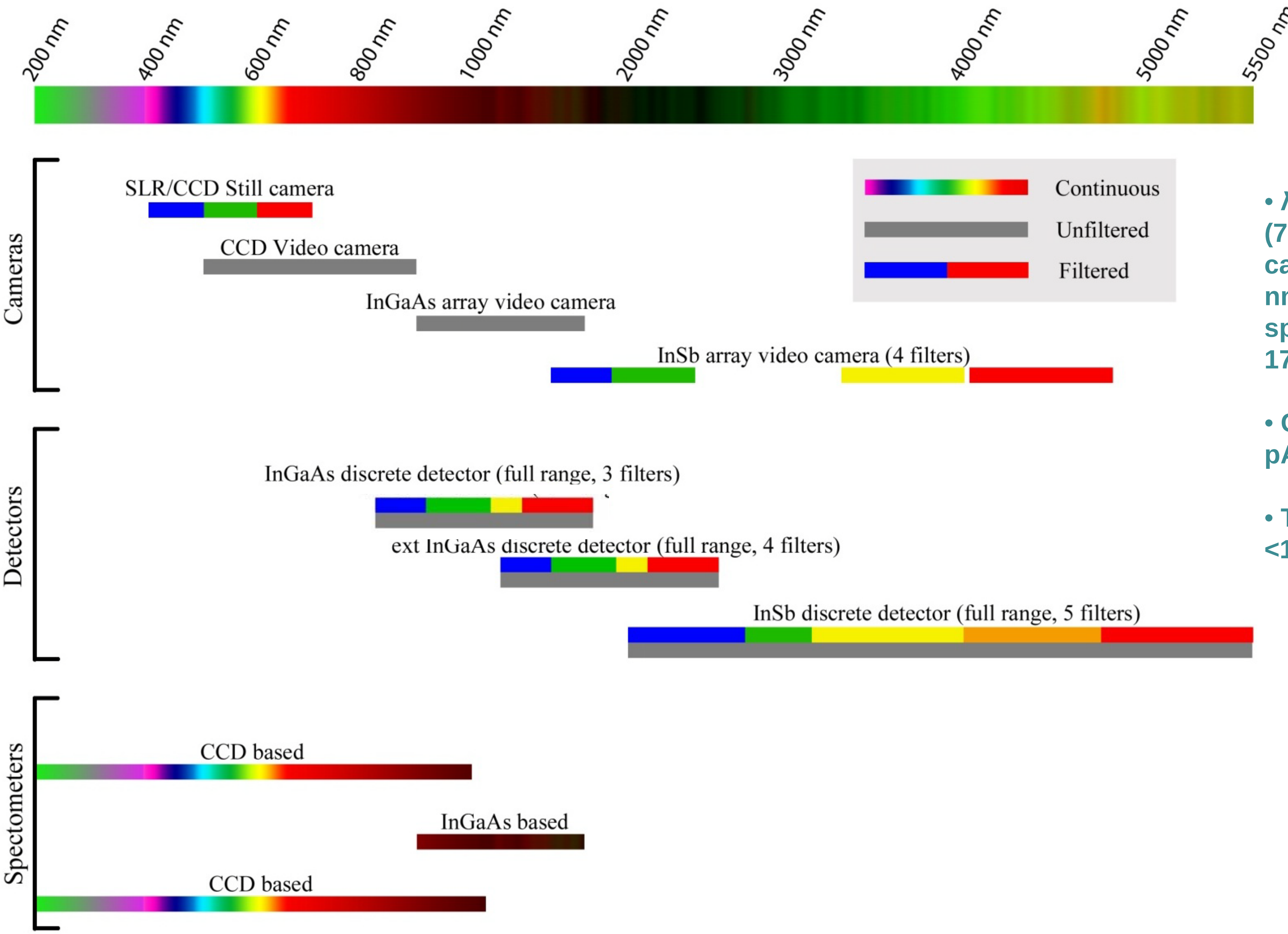
Figure 5. (top) Interior of Hemispherical grid retarding field analyzer detector showing sample and "flipper" to measure surface voltages with electrostatic field transfer probe. **(bottom)** Surface voltage decay curve for Kapton E sample after electron beam

Luminescence/Arc/Flare Test Configuration



Sample cooled with l-N_2 to 100-135 K.
Chamber walls at ambient.

Luminescence/Arc/Flare Test Configuration



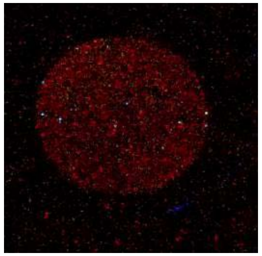
- λ range: detectors (700-5500 nm), cameras (400-5000 nm), and spectrometers (200-1700 nm)
- Current range: (0.1 pA to 1 mA)
- Temporal range: $<10^{-9}$ s to $>10^{4}$ s

Comparison of Luminescence Images

Sustained Glow

Kapton XC

500 nA/cm^2
22 keV
150 K



M55J

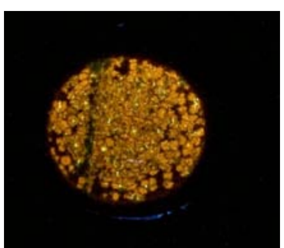
1 nA/cm^2
22 keV
100 K

IEC Shell Face Epoxy Resin with Carbon Veil

1 nA/cm^2
22 keV
100 K

Kapton E

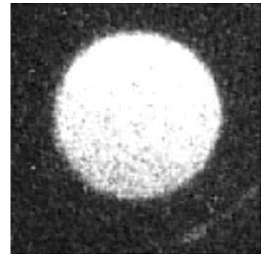
500 nA/cm^2
22 keV
150 K



"Flare"

Kapton XC

50 nA/cm^2
22 keV
150 K



M55J

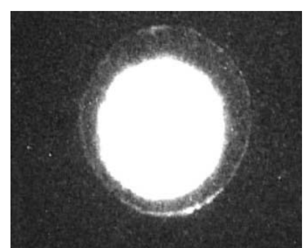
1 nA/cm^2
22 keV
100 K

IEC Shell Face Epoxy Resin with Carbon Veil

1 nA/cm^2
22 keV
100 K

Kapton E

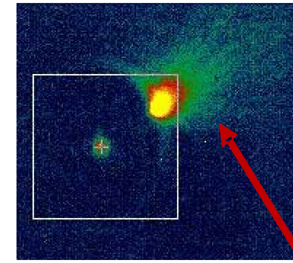
5 uA/cm^2
22 keV
150 K



Arcs

Kapton XC

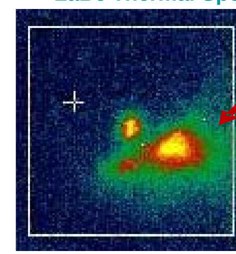
5 nA/cm^2
22 keV
1350 K



LaB6 Thermal Spot

M55J

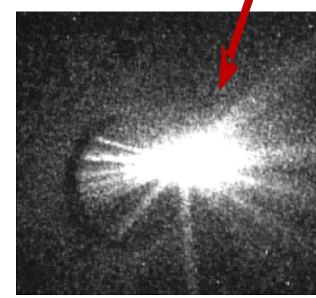
5 nA/cm^2
22 keV
135 K



Arc

IEC Shell Face Epoxy Resin with Carbon Veil

5 nA/cm^2
22 keV
100 K



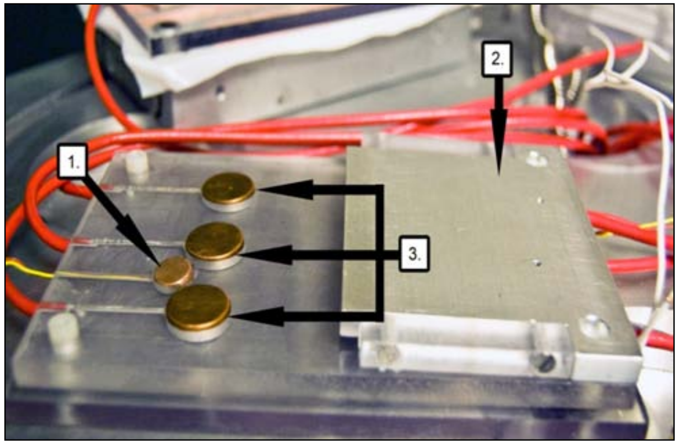
1 cm Dia test samples

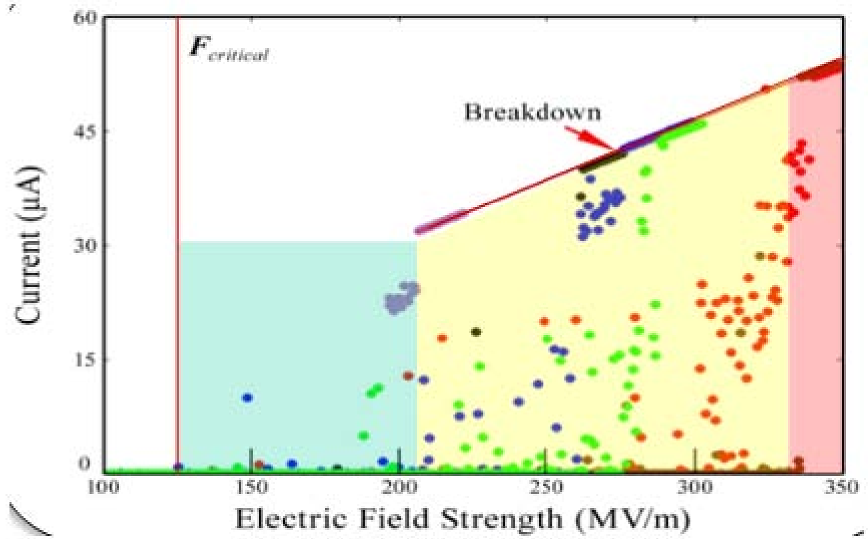
30 s Exposure SLR Camera (400nm-640nm)

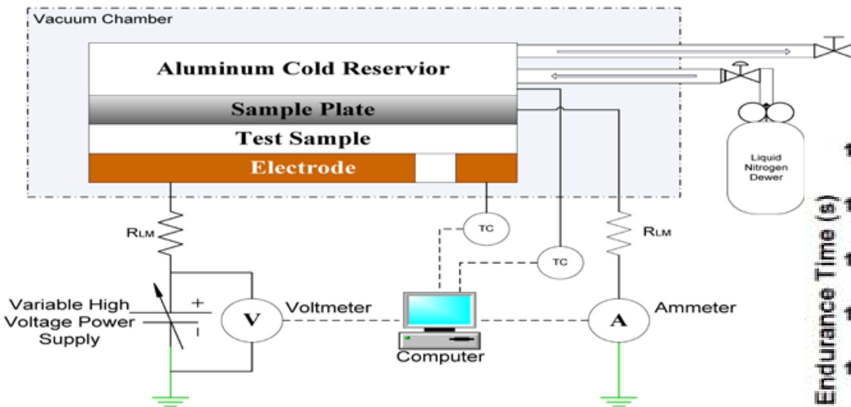
33 ms Exposure CCD Video Camera (500nm-900nm)

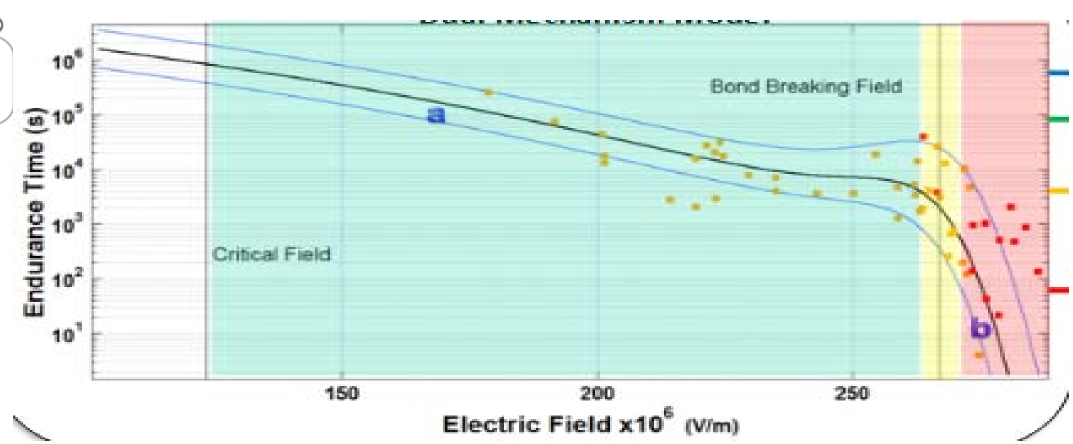
17 ms Exposure InGaAs Video Camera (900nm-1700nm)

Electrostatic Breakdown

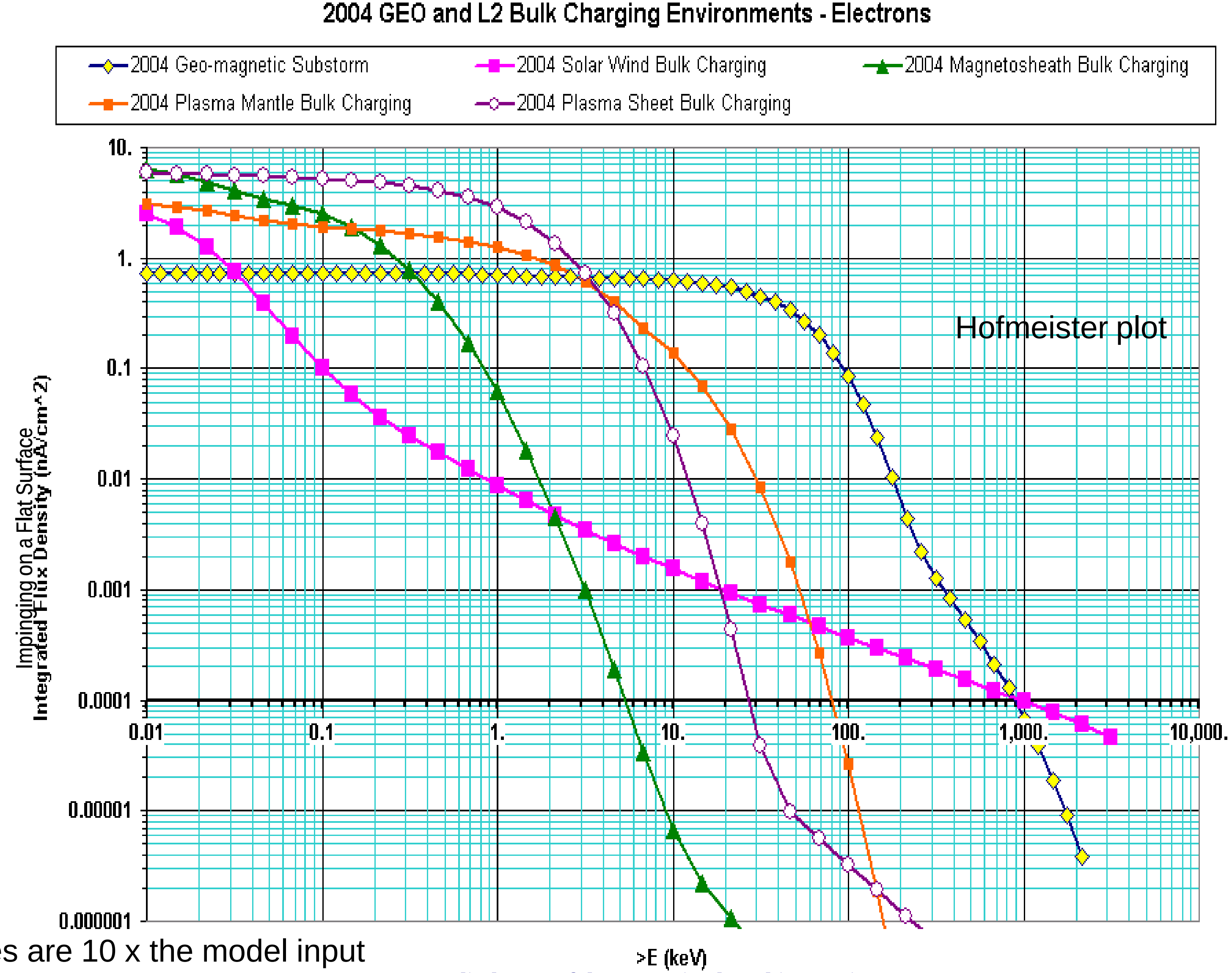








EV Spec worst case (Minow)



These values are 10 x the model input values, adjusted in the model per recent Geotail and WIND data

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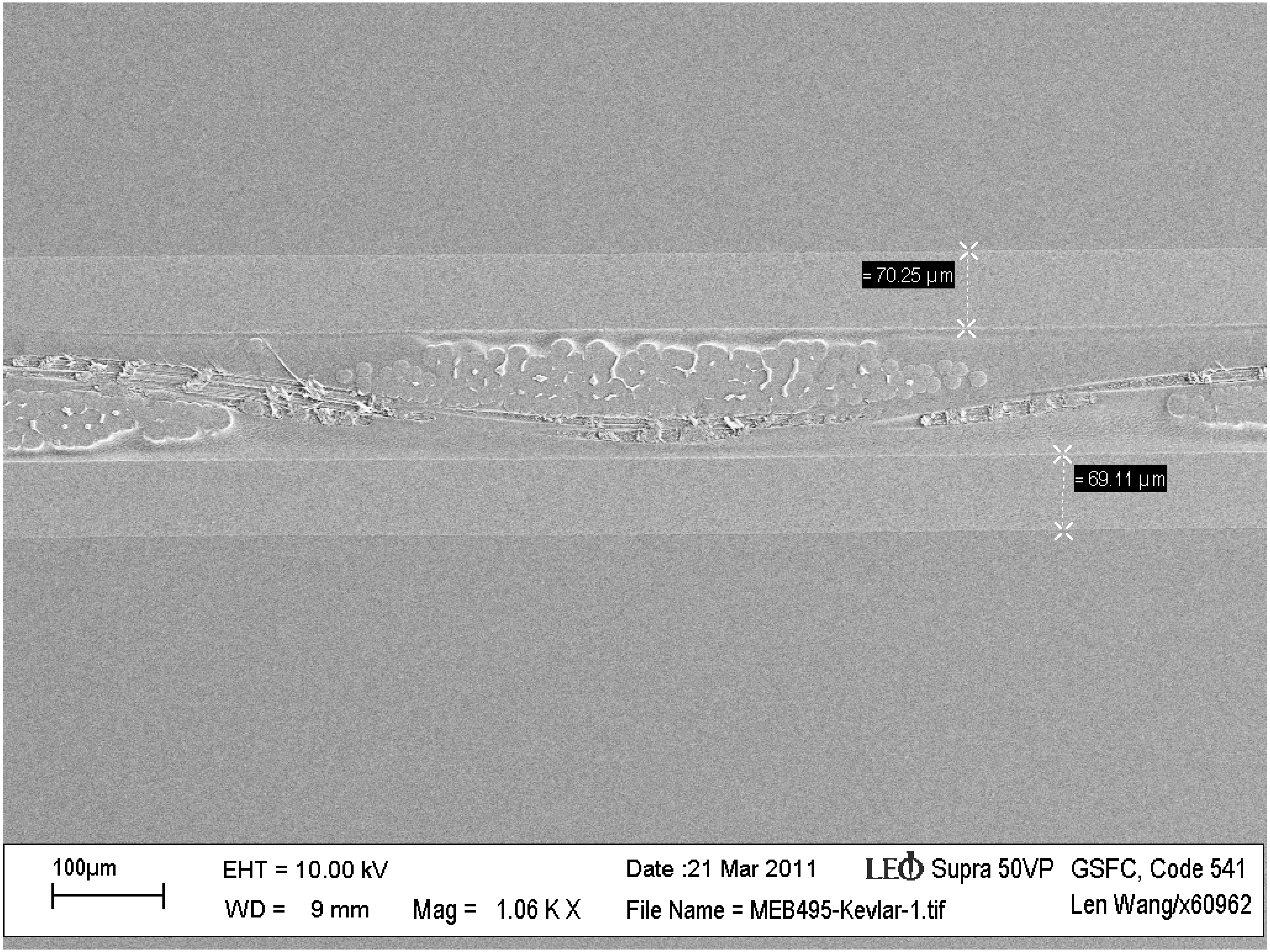
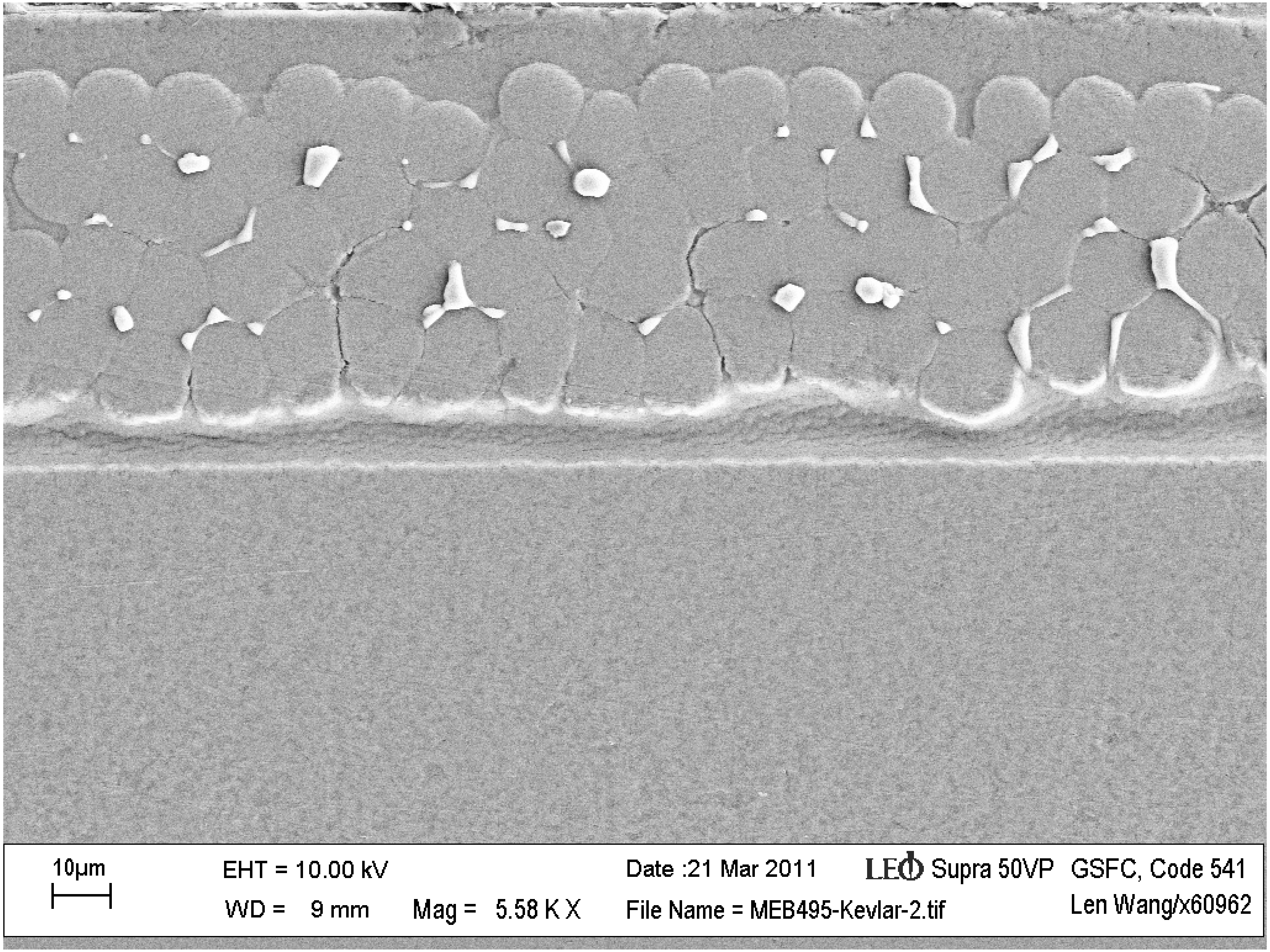
Ball Kapton/Kevlar Composite—SEM Inspection (GSFC)



Sample 275XC/Kevlar/275XC cross section view

Ball Kapton/Kevlar Composite—SEM Inspection (GSFC)



Sample 275XC/Kevlar/275XC cross section view