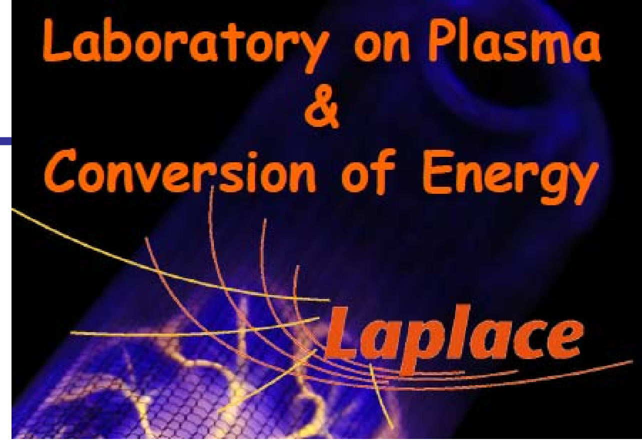
Summer 6-19-2013

# An Overview of the Materials Physics Group And Potential Collaborations with LAPLACE

JR Dennison
*Utah State University*

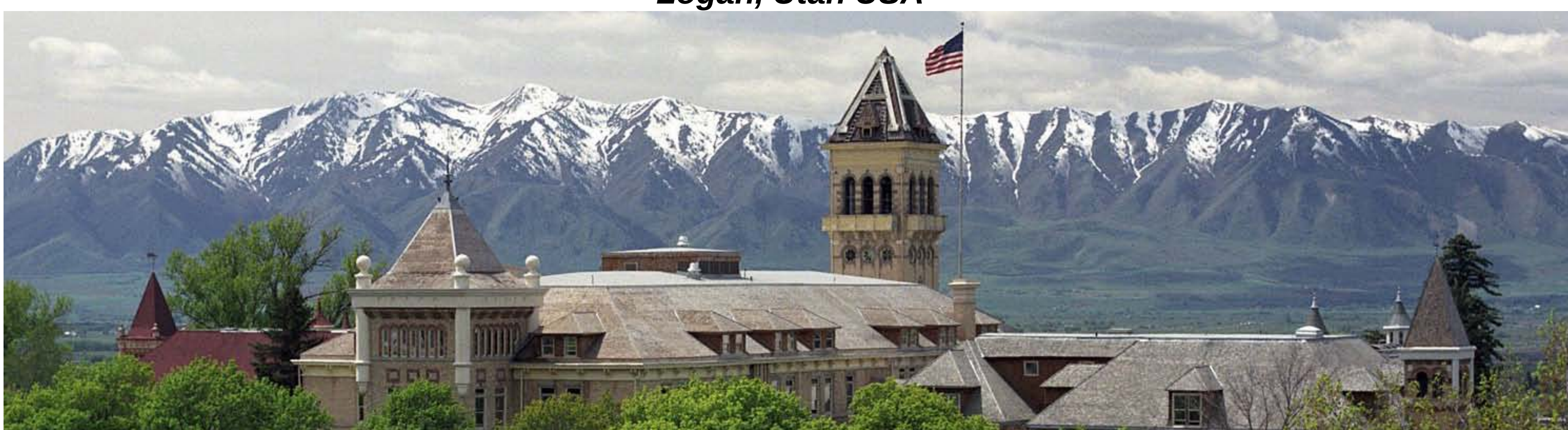



UtahState University
MATERIALS PHYSICS GROUP

*Toulouse, France*
*19 June, 2013*

# *An Overview of the Materials Physics Group And Potential Collaborations with LAPLACE*

**J.R. Dennison**
*Materials Physics Group*
*Physics Department, Utah State University*
*Logan, Utah USA*

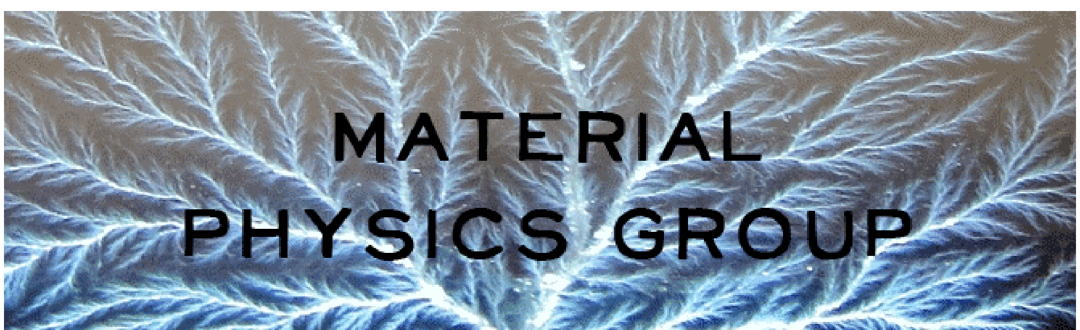


# Utah State University

## USU Materials Physics Group

***Utah State University***

***Logan, Utah, USA***



# Acknowledgements

## Support & Collaborations

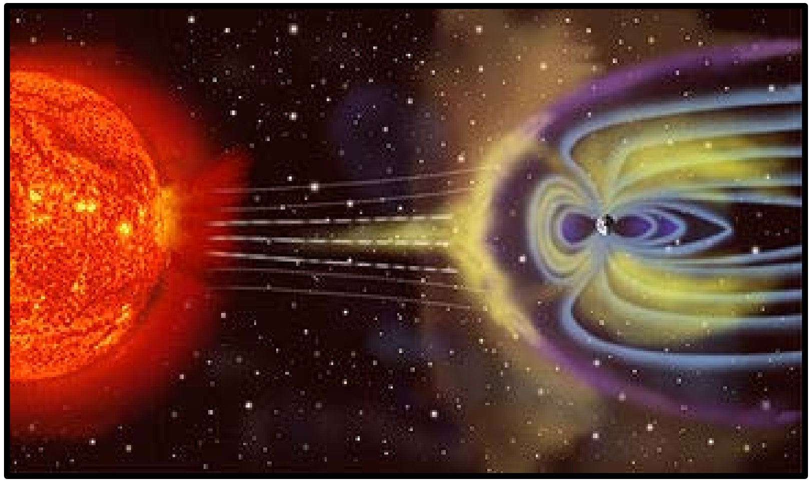
*NASA SEE Program*
*JWST (GSFC/MSFC)*
*SPM (JHU/APL)*
*RBSP (JHU/APL)*
*Solar Sails (JPL)*
*AFRL*
*Boeing*
*Ball Aerospace*
*Orbital*

*National Research Council*

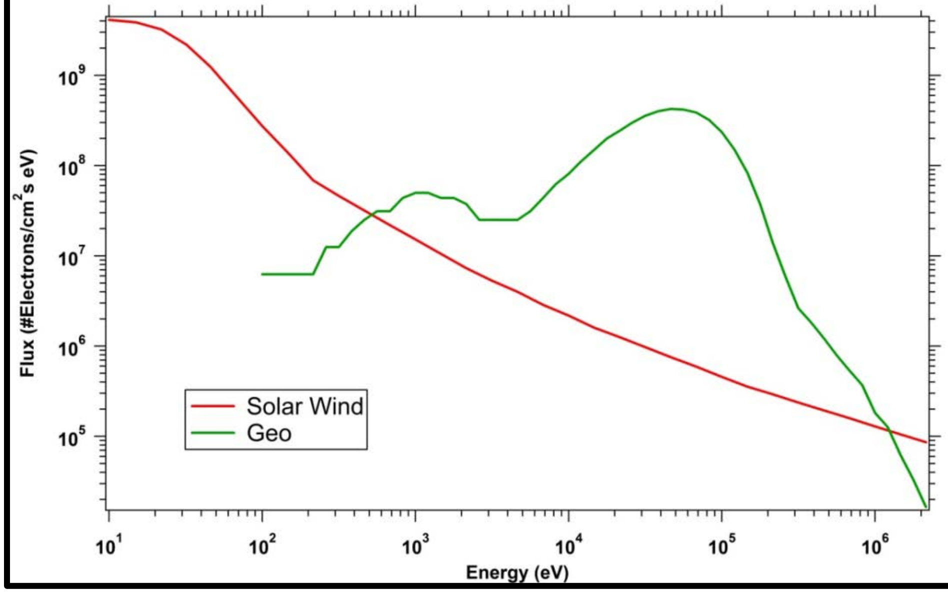
USU Materials Physics Group

# The Space Environment

Solar wind and Earth's magneto-sphere structure.



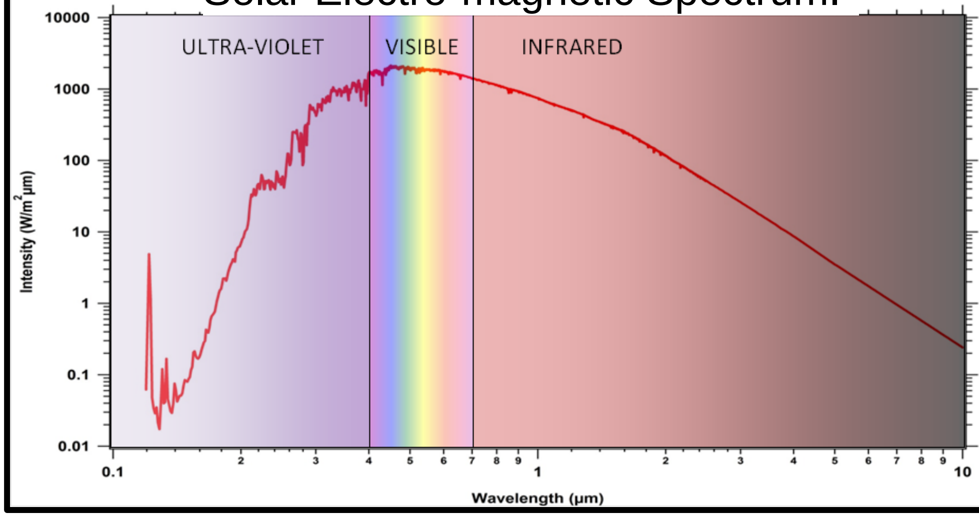
Typical Space Electron Flux Spectra [Larsen].



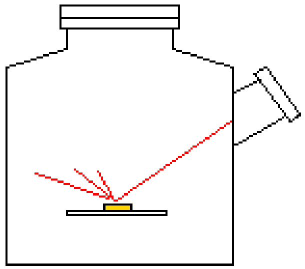

## Incident Fluxes of:

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

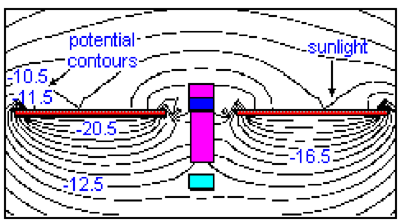
Solar Electro-magnetic Spectrum.

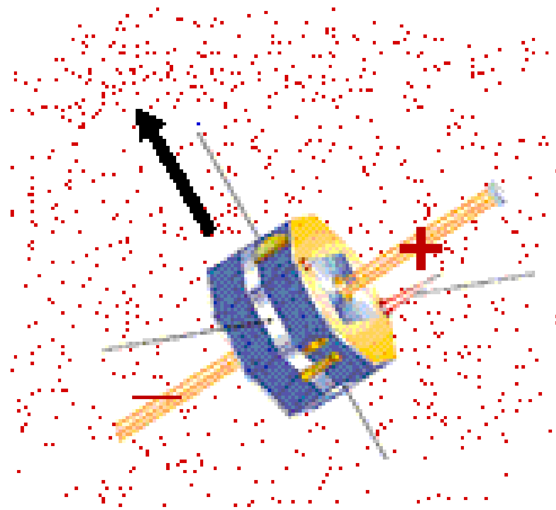


# A simplified approach to spacecraft charging modeling…



**Materials Properties**



m

$e^-$

$I^+$

$\gamma$

**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**

# Focus of the Materials Physics Group

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

- ➢ Time (Aging), t
- ➢ Position (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(z,t)
  - Charge Rate (Current), Ǒ
  - 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,z,Q,D,Ď)

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

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

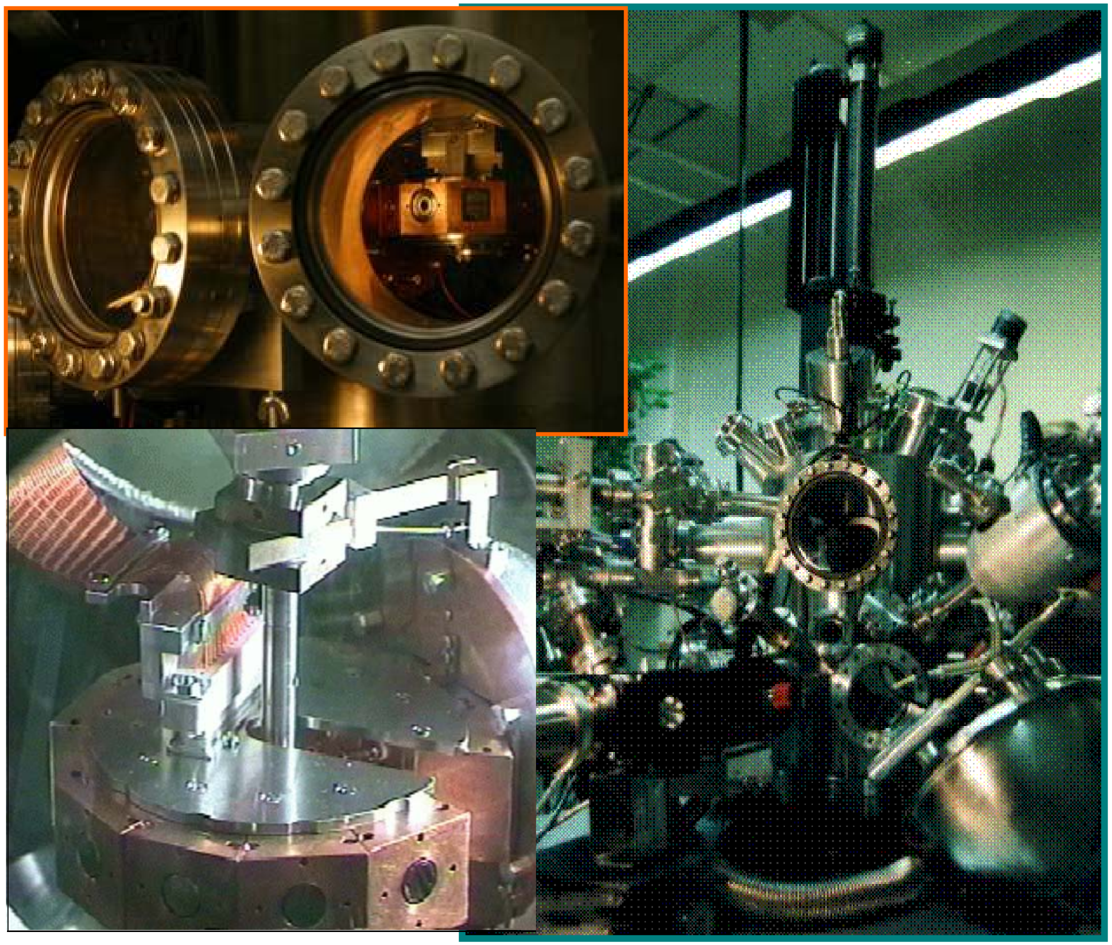
## Materials Physics Group Measurement Capabilities

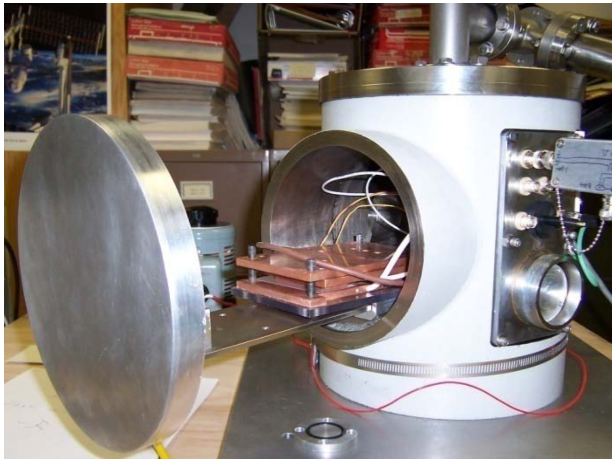
**Electron Emission**
**Ion Yield**

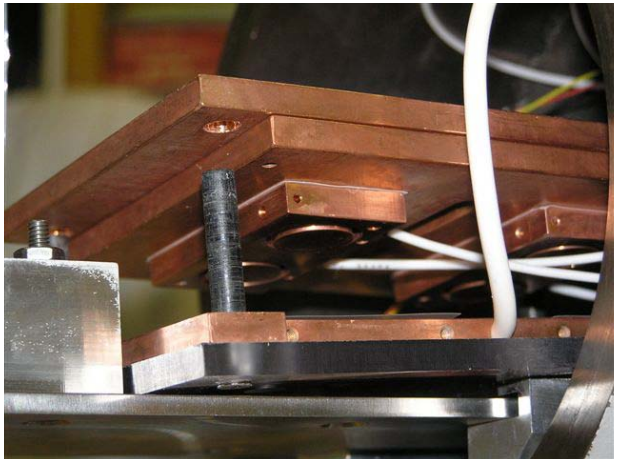
**Photoyield**
**Luminescence**

**Conductivity**
**Electrostatic Discharge**

**Radiation Induced Cond.**
**Radiation Damage**





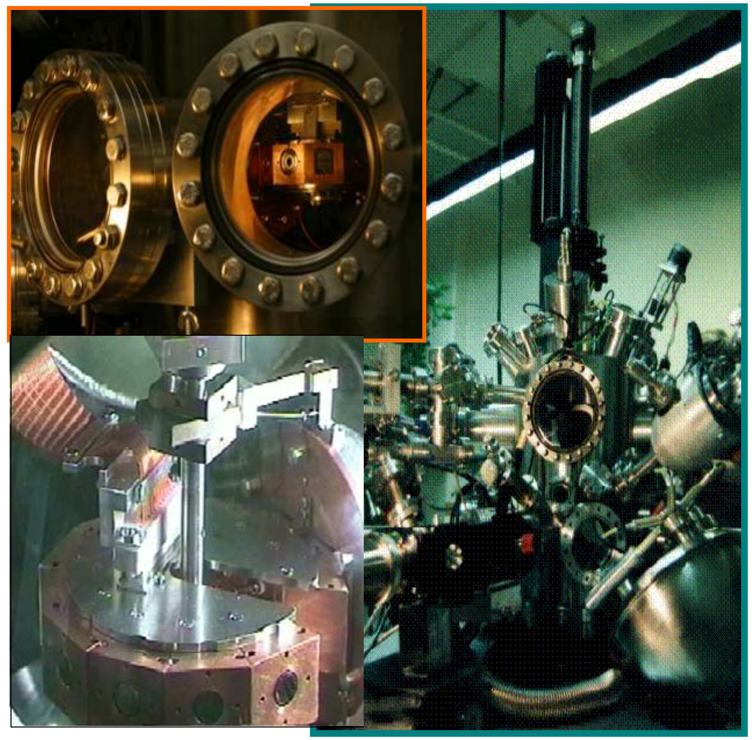


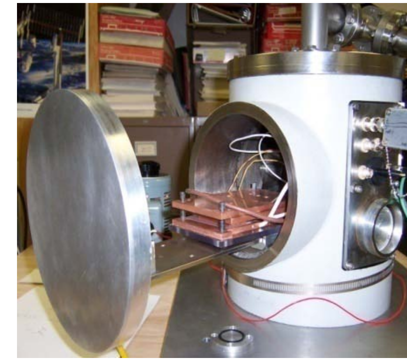
**Dependence on: Press., Temp., Charge, E-field, Dose, Dose Rate**

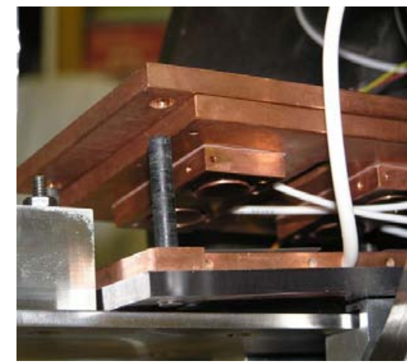
# USU Experimental Capabilities

## <u>Absolute Yields</u>

- 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)

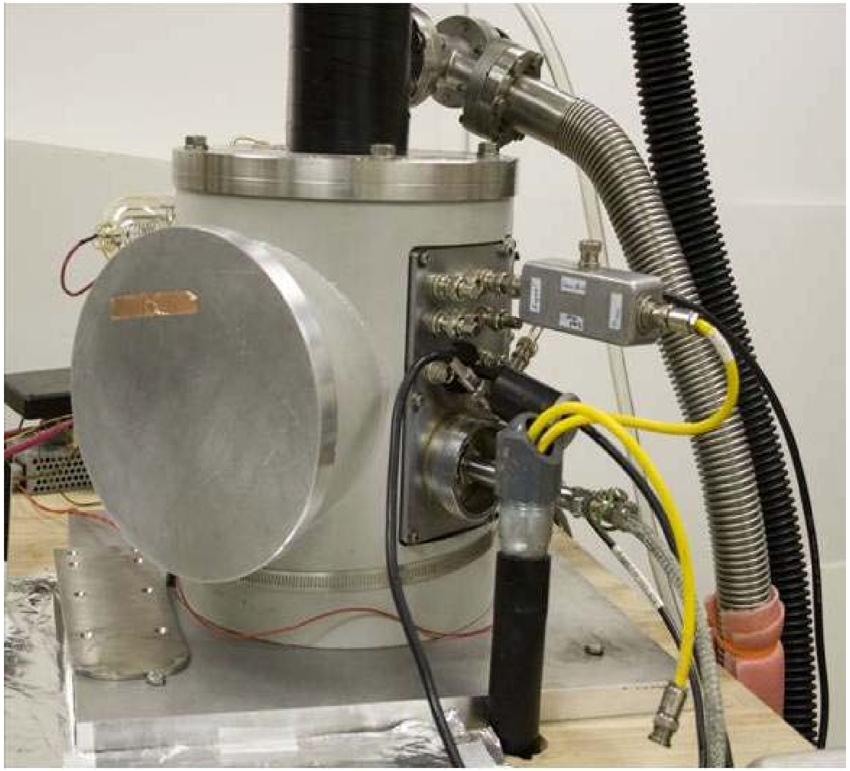


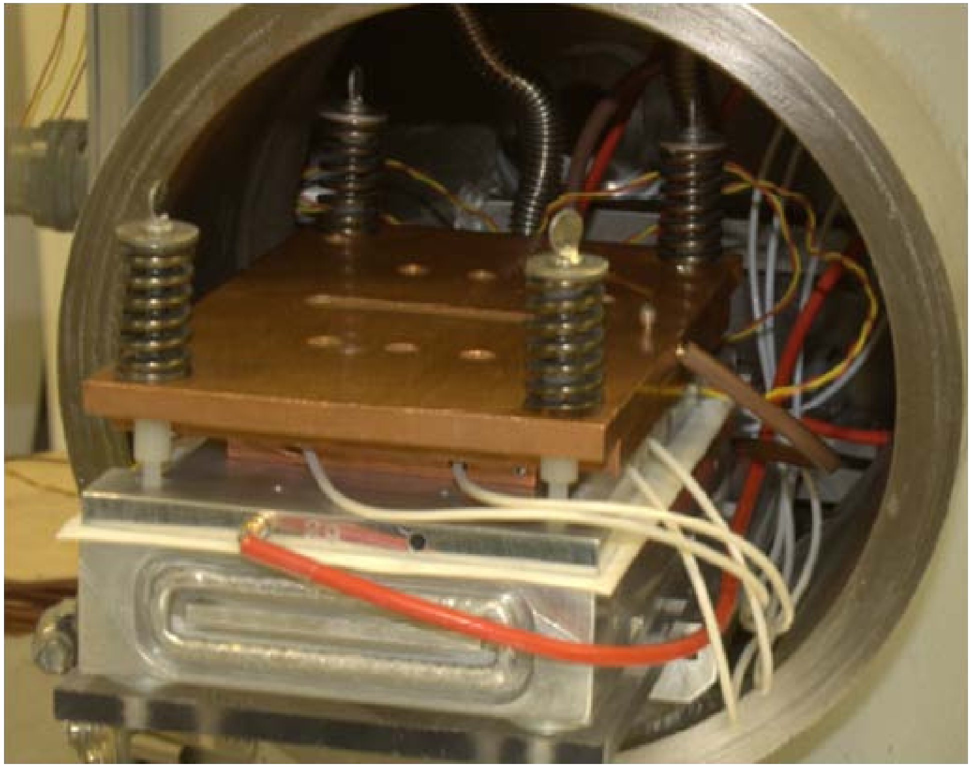




- Conductivity (<$10^{-22}$ $[\text{ohm-cm}]^{-1}$)
- Surface Charge (<1 V to >15 kV)
- ESD (low T, long duration)
- Radiation Induced Conductivity (RIC)
- Evolution of internal charge distributions (EA)
- Multilayers, contamination, surface modification
- Radiation damage
- Modeling
- Sample Characterization

# Extremely Low Conductivity





# Absolute Electron Yields



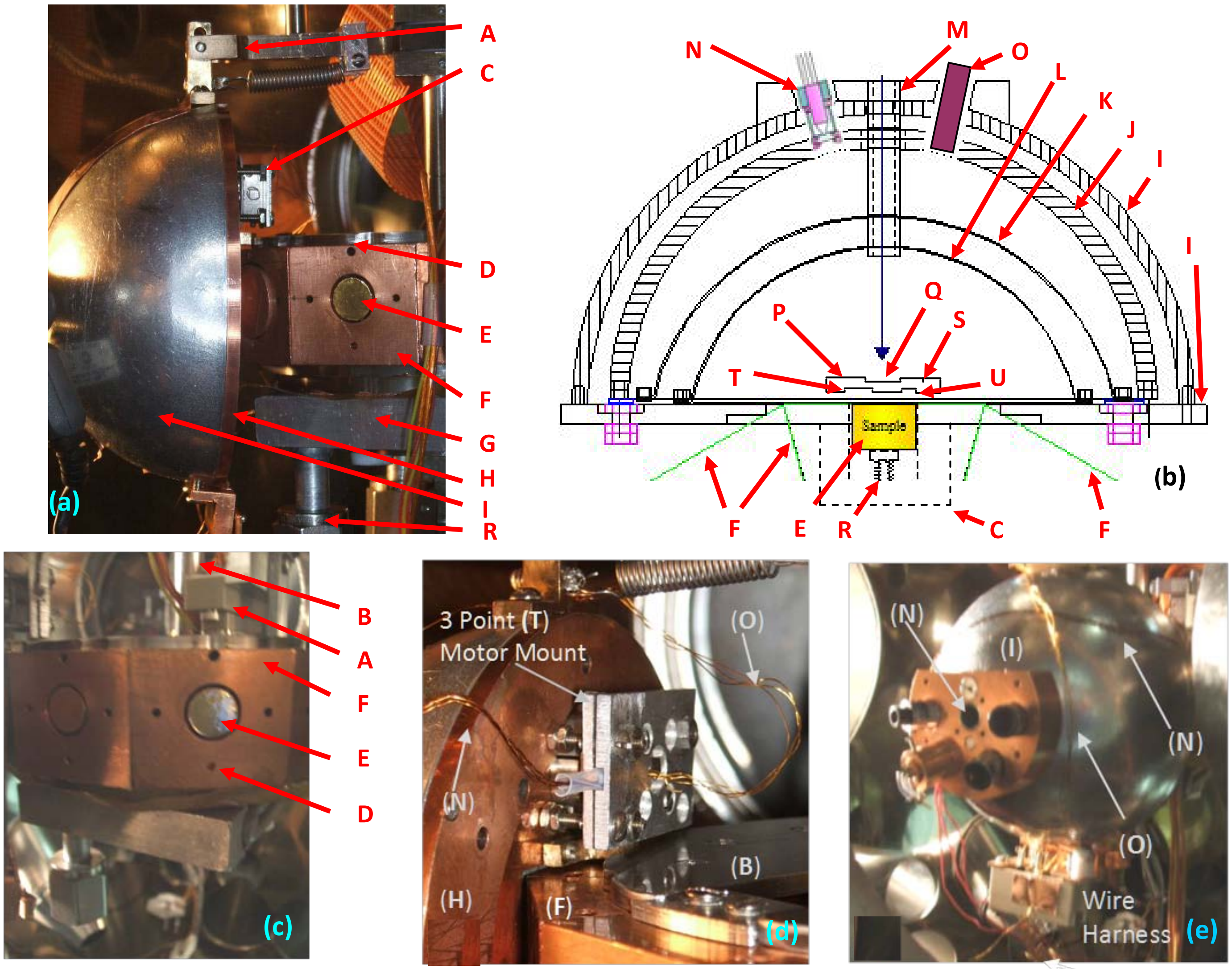
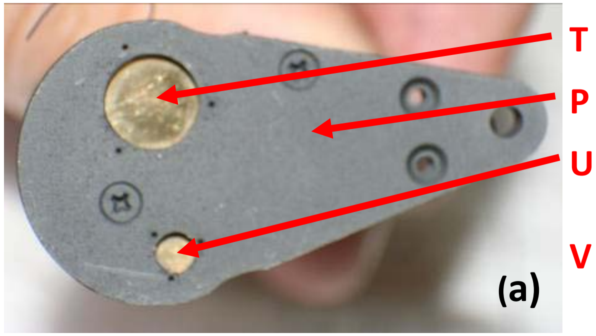
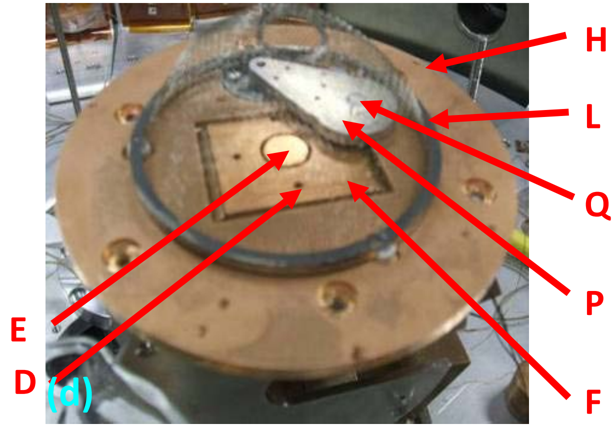
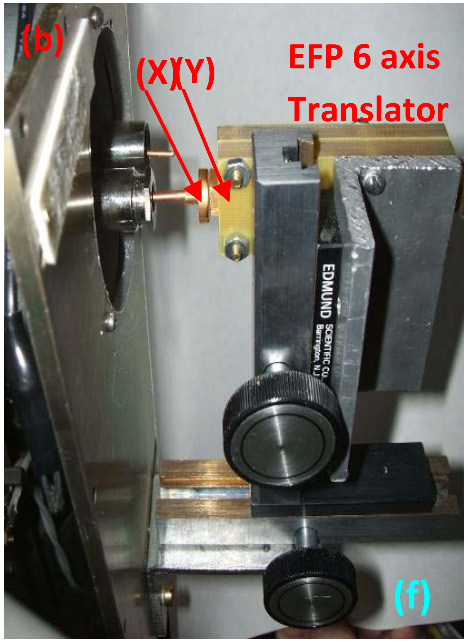


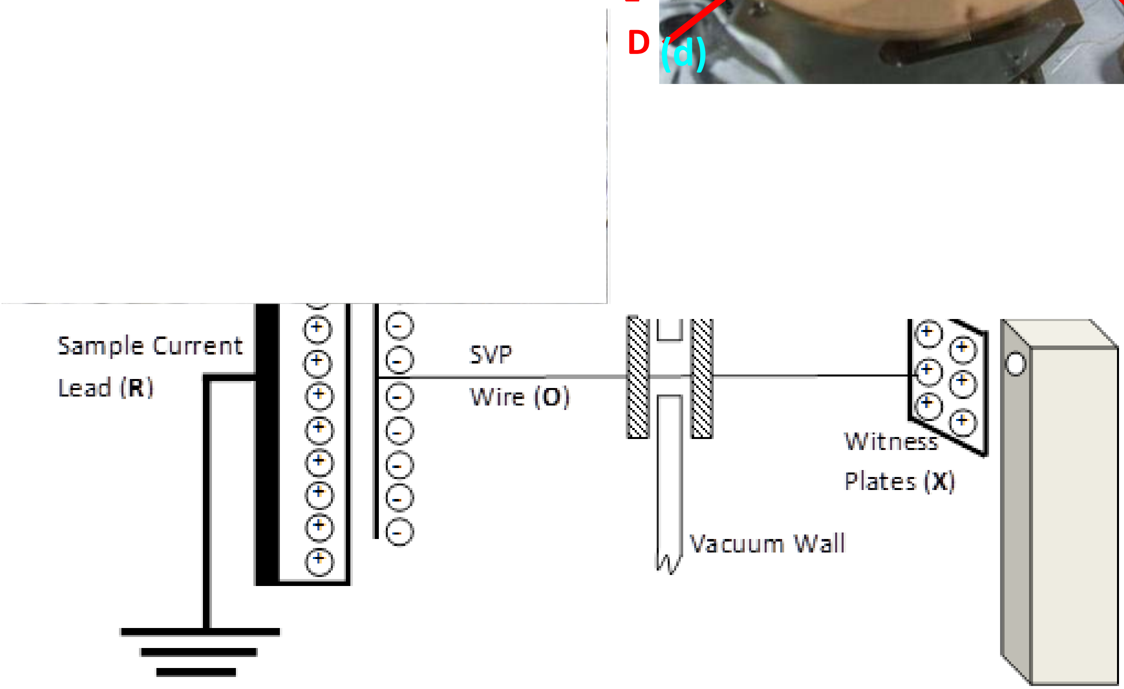

Fig. 2. **Hemispherical Grid Retarding Field Analyzer (HGRFA).** ***(a) Photograph of sample stage and HGRFA detector (side view). (b) Cross section of HGRFA. (c) Photograph of sample stage showing sample and cooling reservoir. (d) Side view of the mounting of the stepper motor. (e) Isometeric view of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

# Surface Voltage

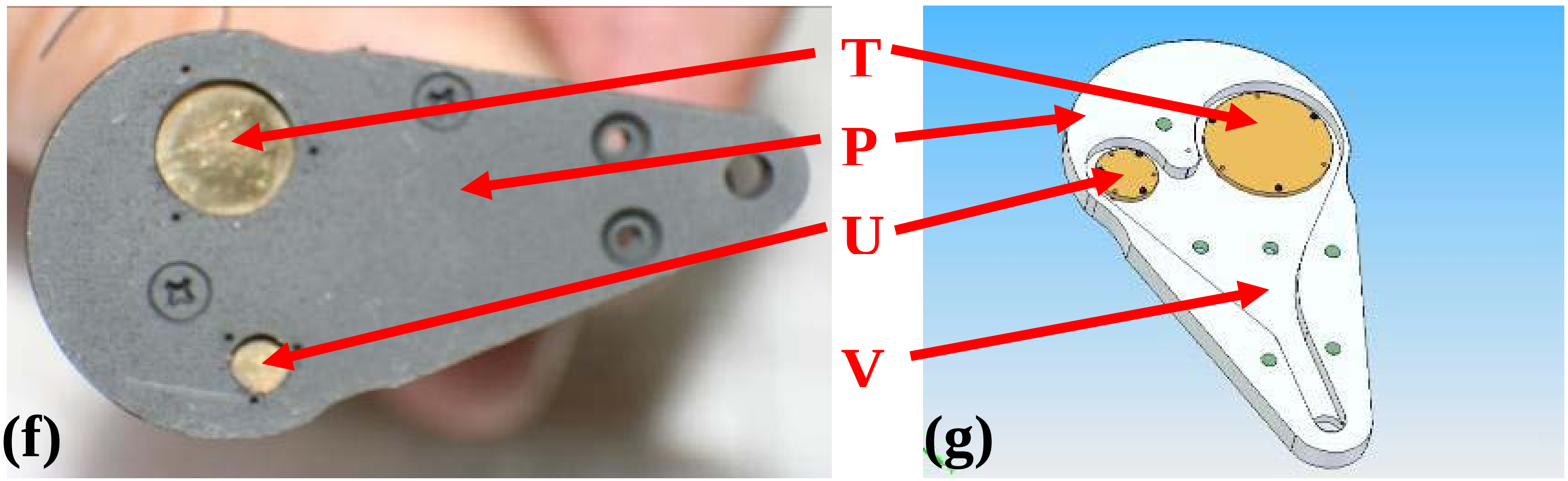


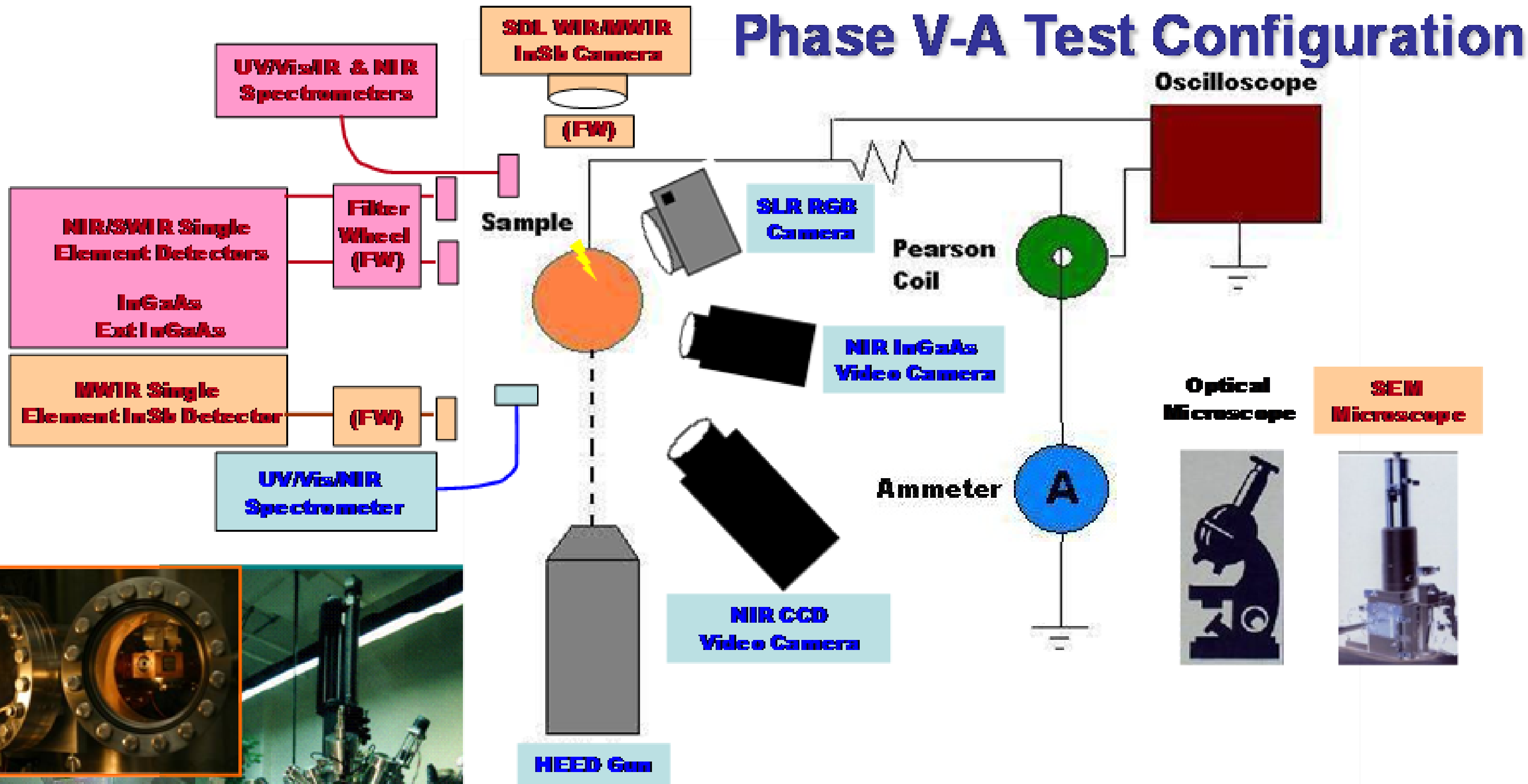



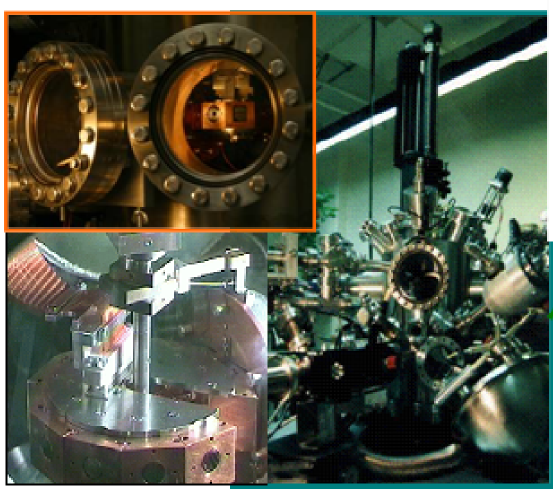
# SVP (Surface Voltage Probe)




A HGRFA Hinged Mount
B Sample Carousel/HGRFA Rotation Shaft
C UHV Stepper Motor
D Sample Block Faraday Cup
E Sample (10 mm)
F Sample Block
G Cryogen Reservoir
H HGRFA Face Plate
I HGRFA Hemispherical Shield
J HGRFA Collector
K HGRFA Bias Grid
L HGRFA Inner Grid
M HGRFA Drift Tube
N Electron Flood Gun
O LED Light Source
P Surface Voltage Probe (SVP)
Q Au disc Electron Emission Standard
R Sample Current Lead
S SVP Faraday Cup
T SVP 7 mm Diameter Au Electrode
U SVP 3 mm Diameter Au Electrode
V SVP Wiring Channel
W EFTP Vacuum Feedthrough
X EFTP Witness Plate
Y Electrostatic Field Probe
Z Probe XYZ Translator

# Luminescence/Arc/Flare Test Configuration



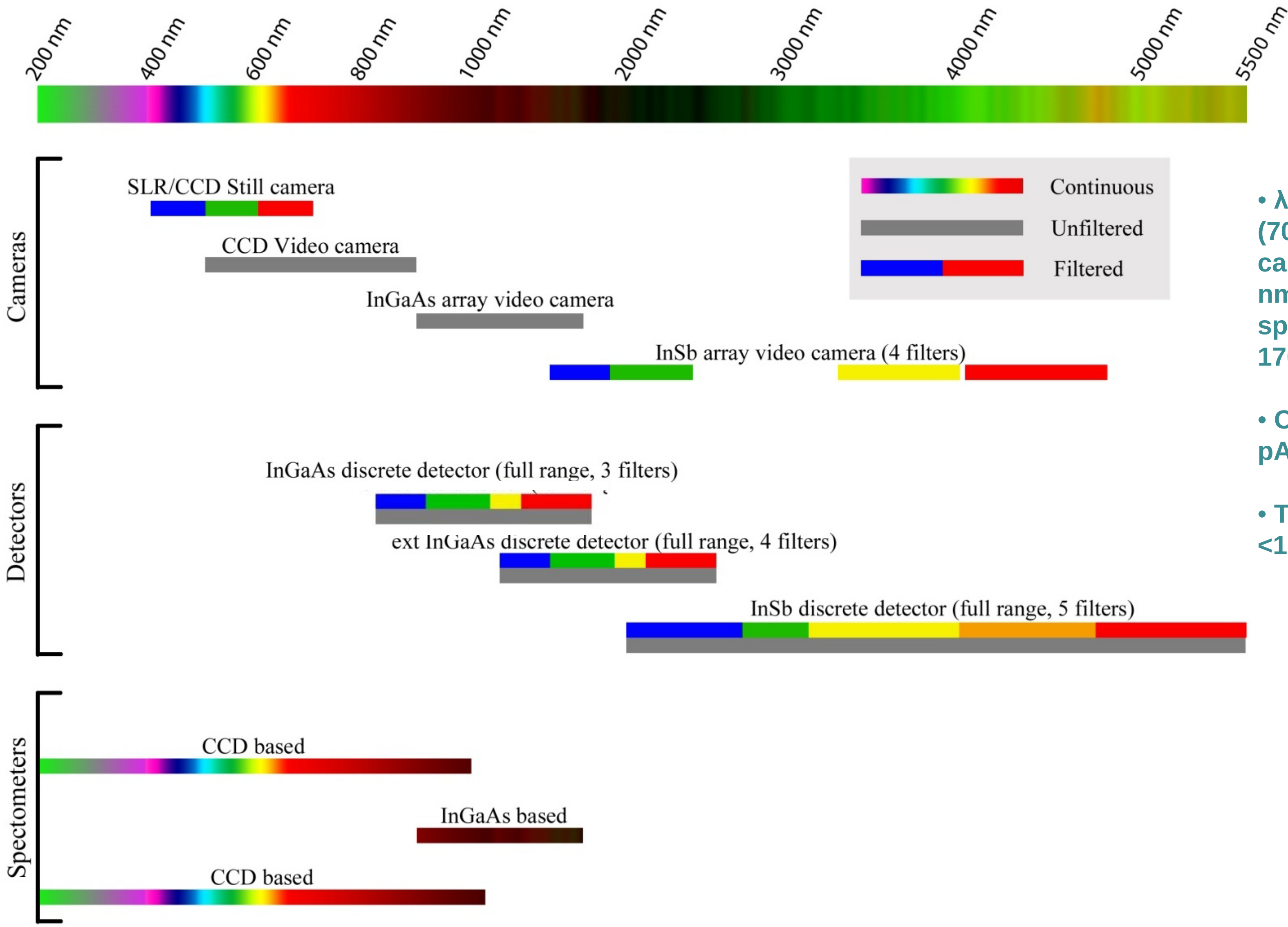
USU Electron Emission Test Chamber

**Legend**

- Enhanced Test / Existing Equipment
- New Tests / Existing Equipment
- New Tests / New Equipment

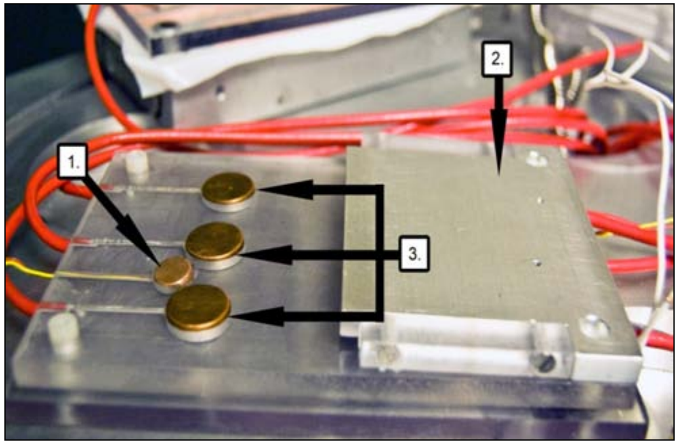
Sample cooled with l-$N_2$ to 100-135 K.
Chamber walls at ambient.

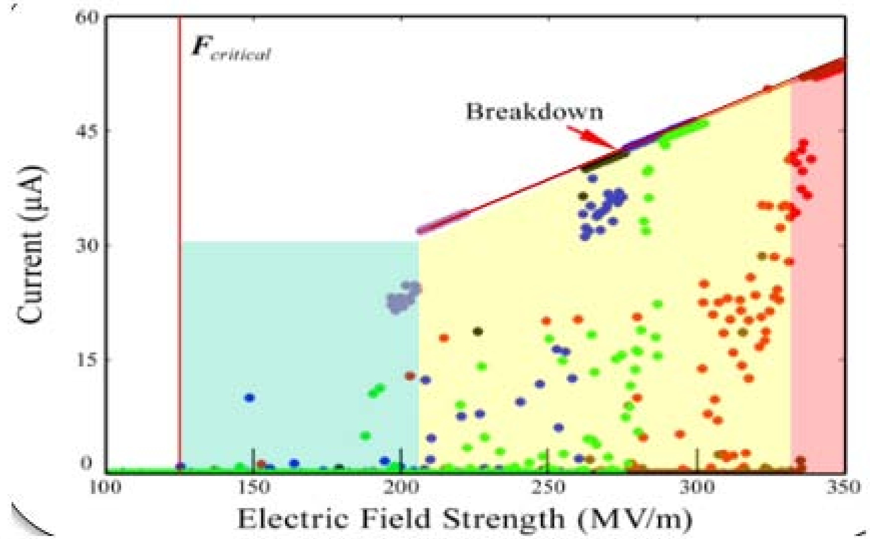
# Luminescence/Arc/Flare Test Configuration

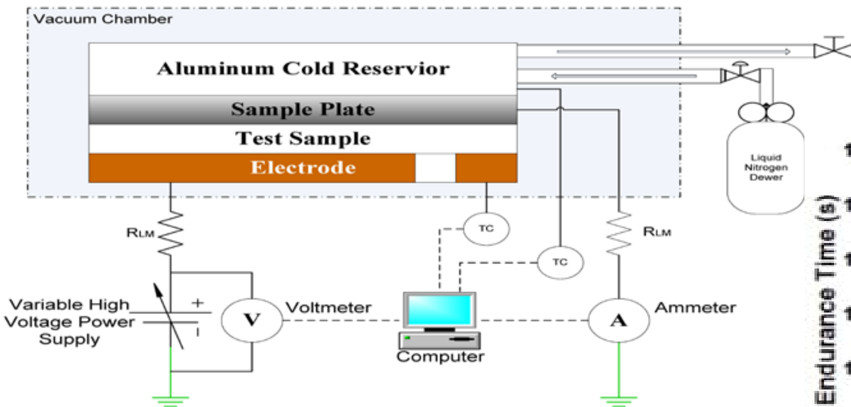


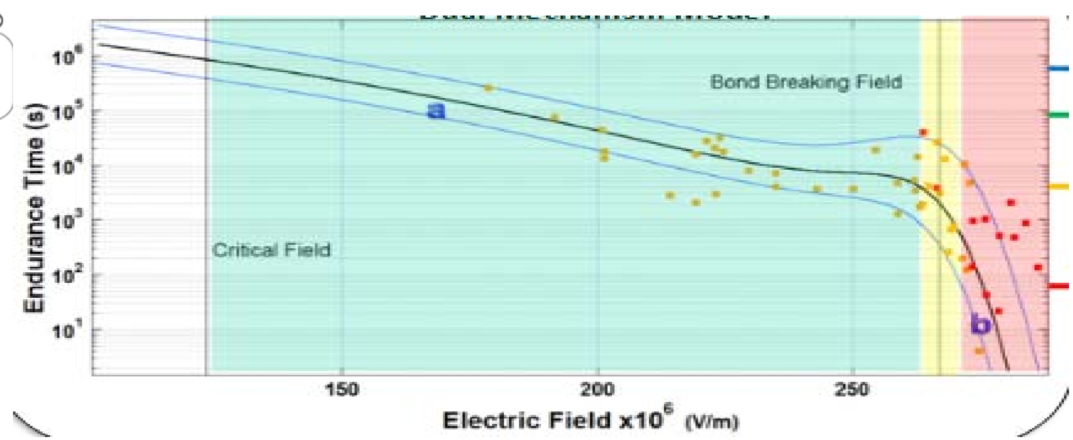

- λ range: detectors (700-5500 nm), cameras (400-5000 nm), and spectrometers (200-1700 nm)
- Current range: (0.1 pA to 1 mA)
- Temporal range: $<10^{-9}$ s to $>10^{4}$ s

# Electrostatic Breakdown



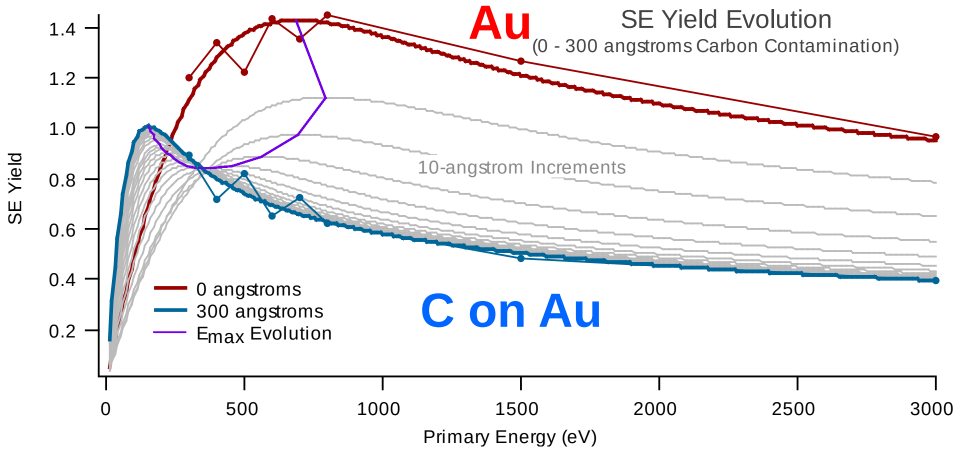



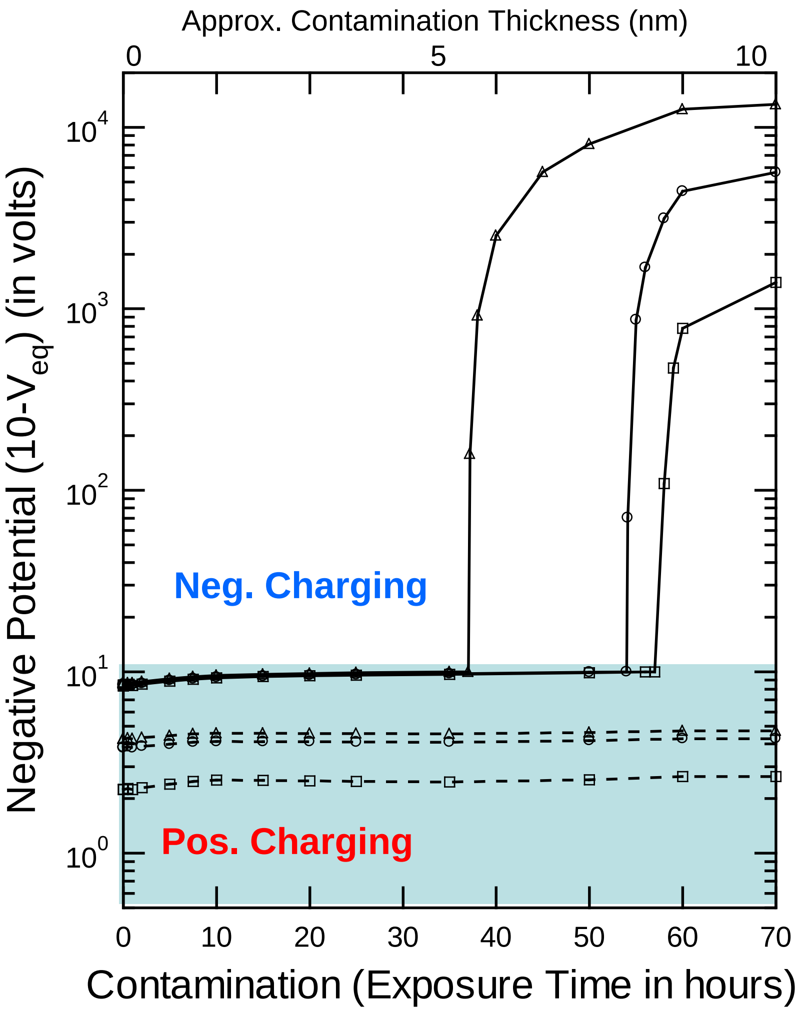

# Recent and Current Projects

# Case I: Evolution of Contamination and Oxidation

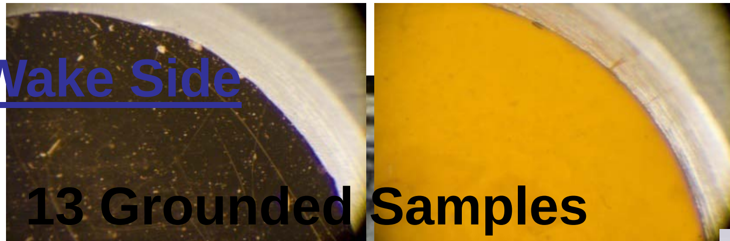
**"All spacecraft surfaces are eventually carbon…"**
**--C. Purvis**

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



# Case I:  Evolution of Contamination and Oxidation



Before    After

Kapton, HN

## Wake Side

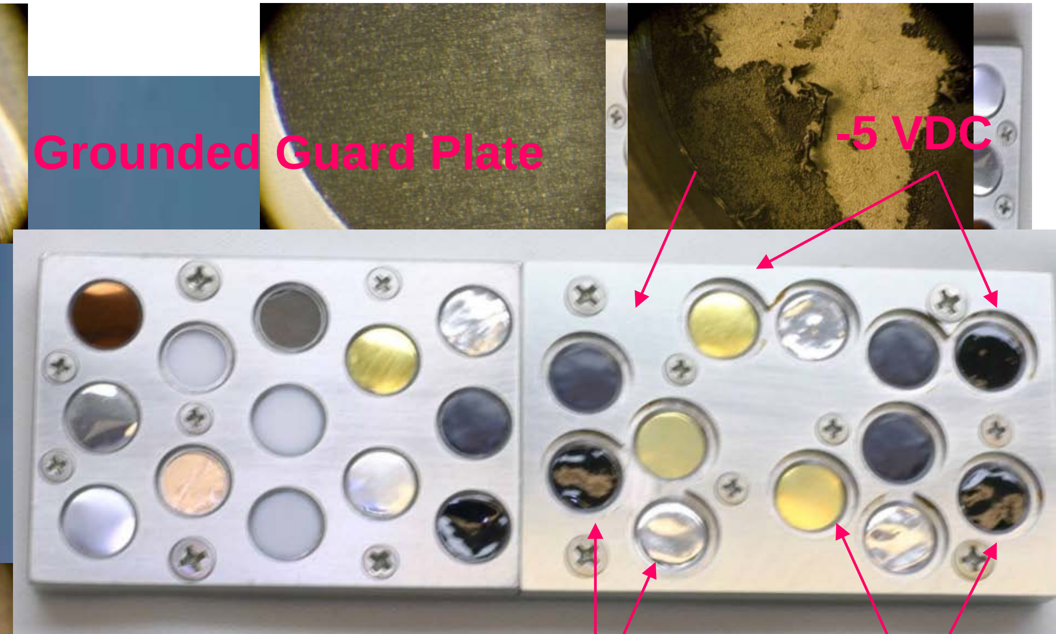
- 13 Grounded Samples
- 12 Biased Samples: for 3 sets of 4 samples with low current biases for charge-enhanced contamination studies.
- 6 Concealed Samples

Before    After

Black Kapton

## Sample Holders

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




Before    After

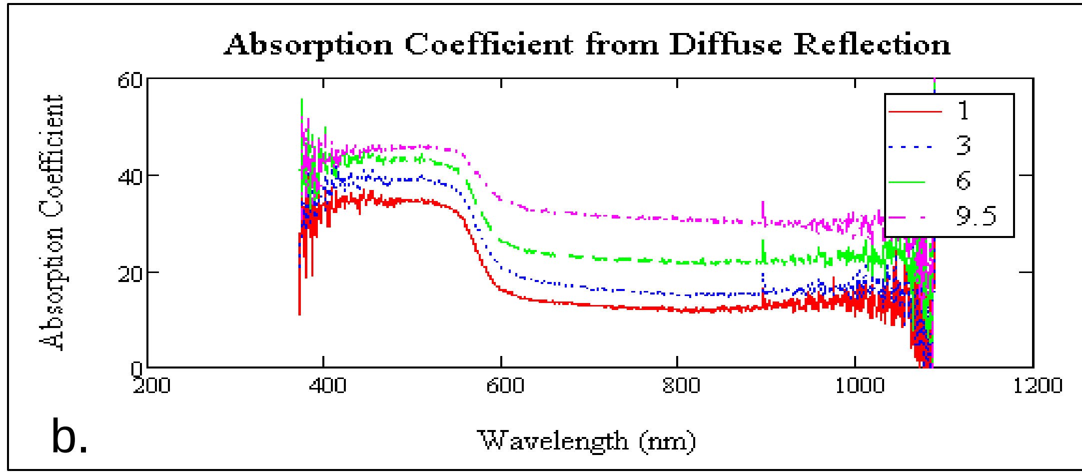
Ag coated Mylar with micrometeoroid impact

***SUSpECS* on MISSE-6**

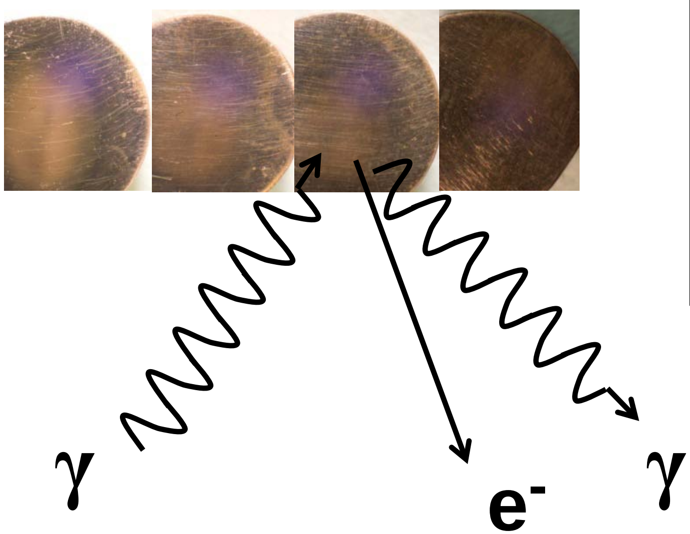
**See poster by Dennison, Evans and Prebola**

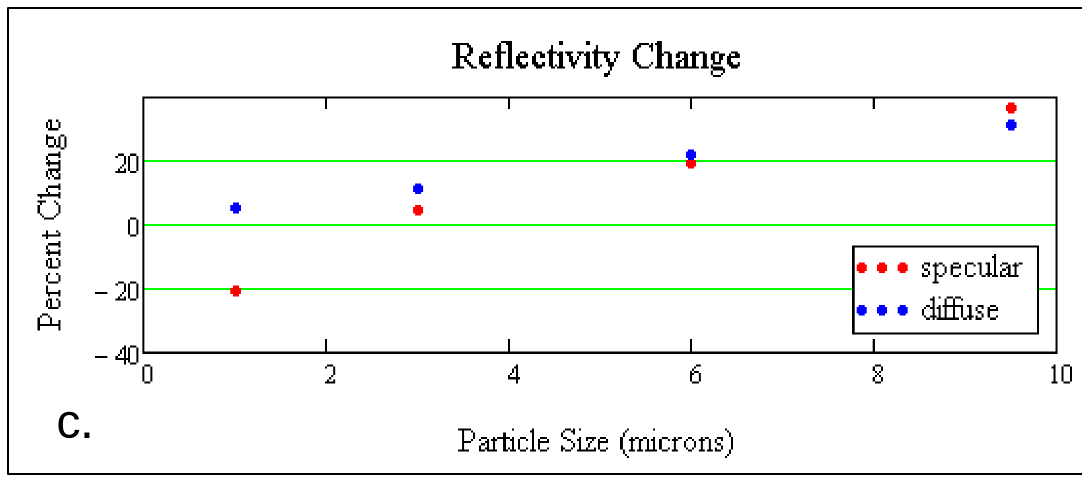
# Case II: Surface Modification

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 )

# Case III: Temperature Effects

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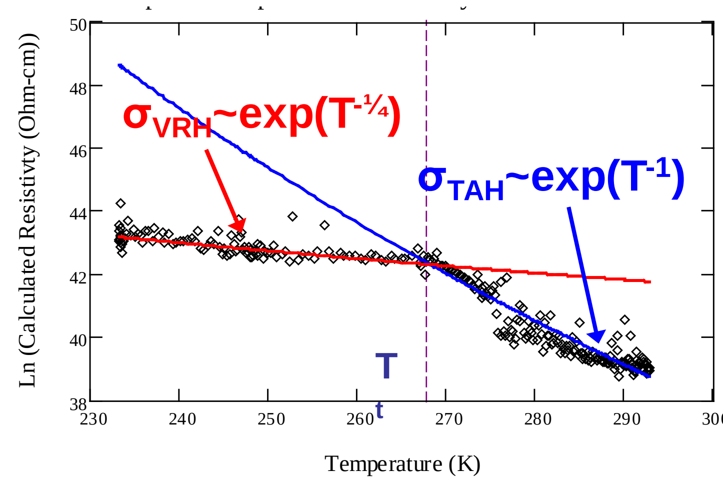
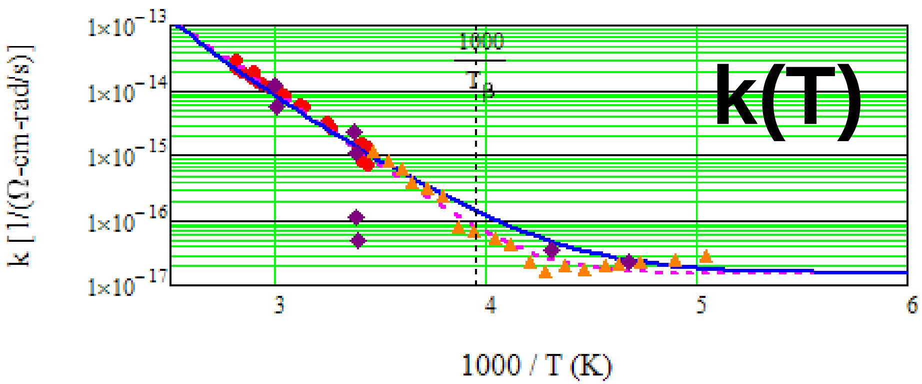
MATERIALS PHYSICS GROUP

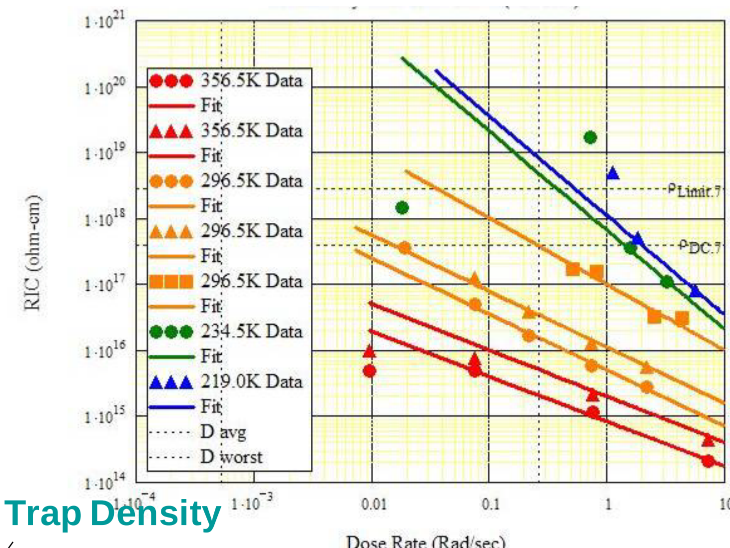



## Strong T Dependence for Insulators

**Charge Transport**

- Conductivity
- RIC
- Dielectric Constant
- ESD




**Uniform Trap Density**

$$\Delta(T) \rightarrow 1$$

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

**Exponential Trap Density**

$$\Delta(T) \rightarrow T_c / (T + T_c)$$

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

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

# Case V:  Temperature and Dose Effects

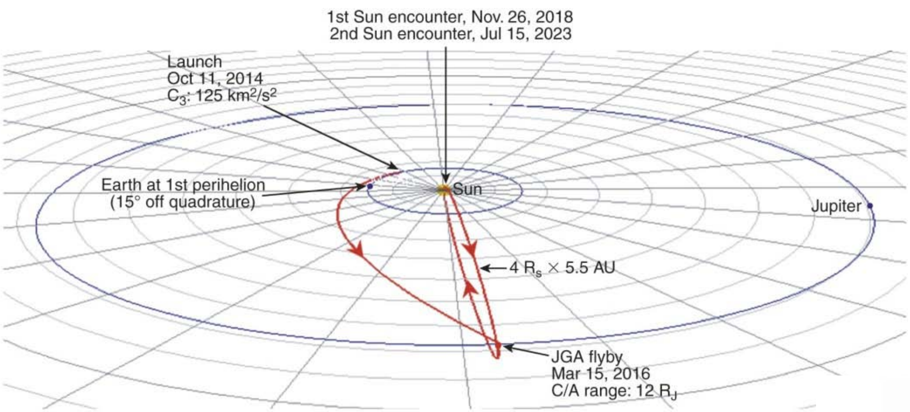



**Figure 4-1.** Solar Probe mission summary.

**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 $R_s$**

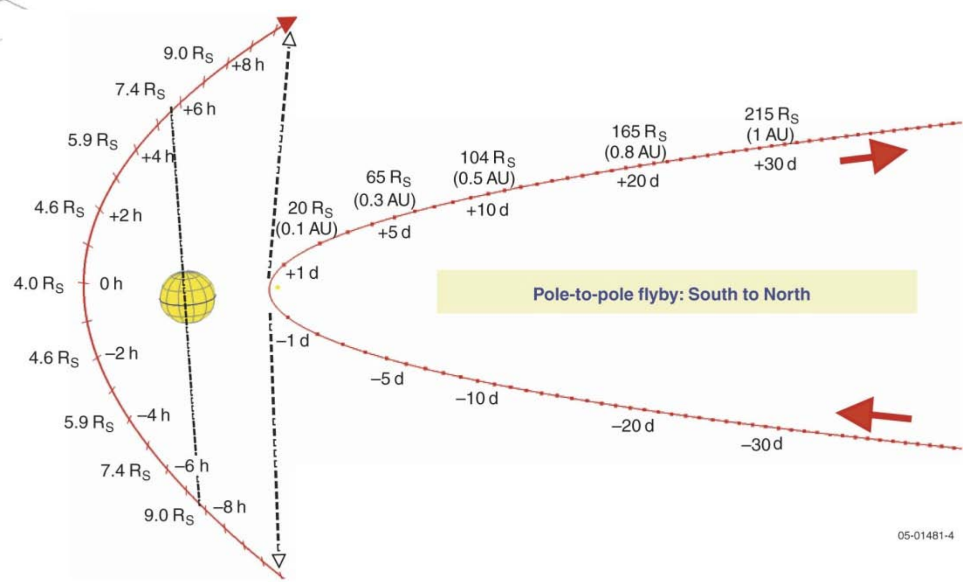


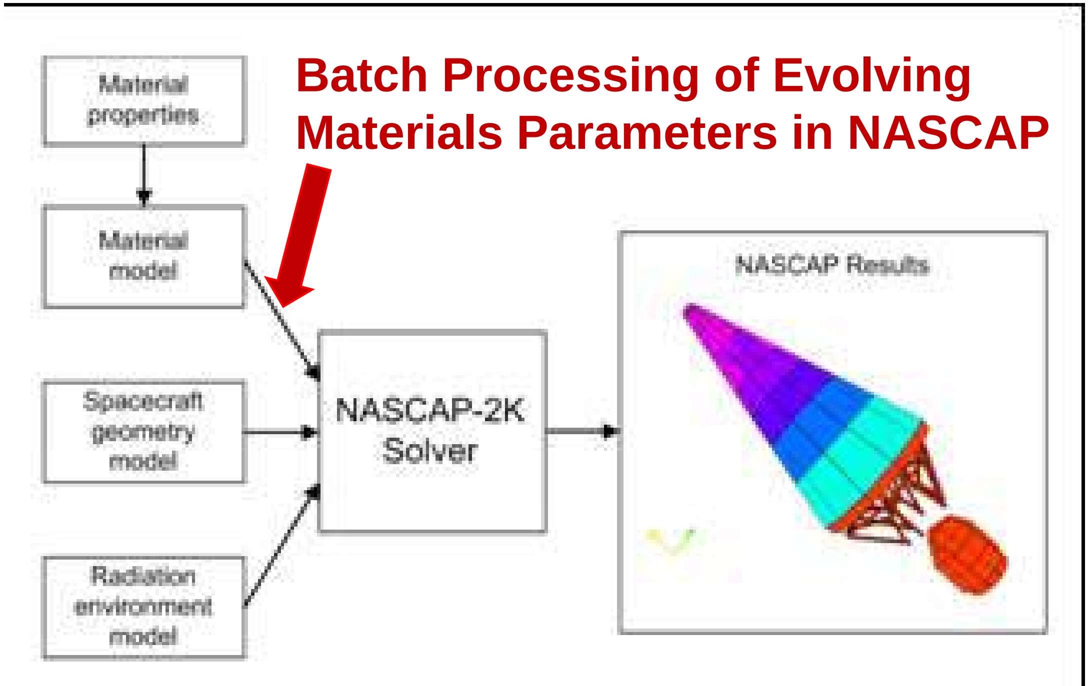

**Figure 4-2.** Solar encounter trajectory and timeline. Science operations begin at perihelion —5 days (65 $R_s$) and continue until perihelion +5 days.

# Case V: Temperature and Dose Effects

UtahState University MATERIALS PHYSICS GROUP

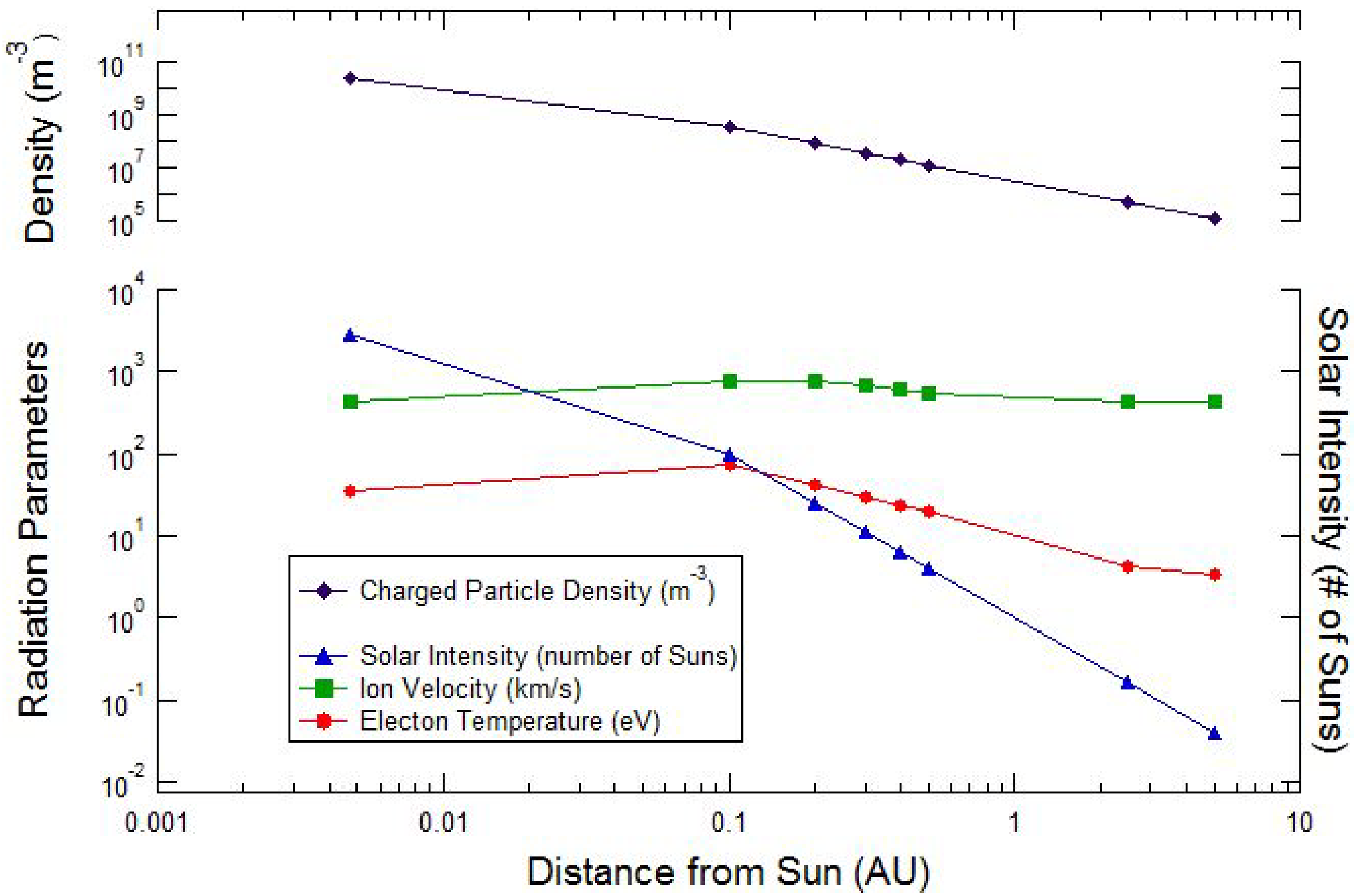
**"We anticipate significant thermal and charging issues."**

***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



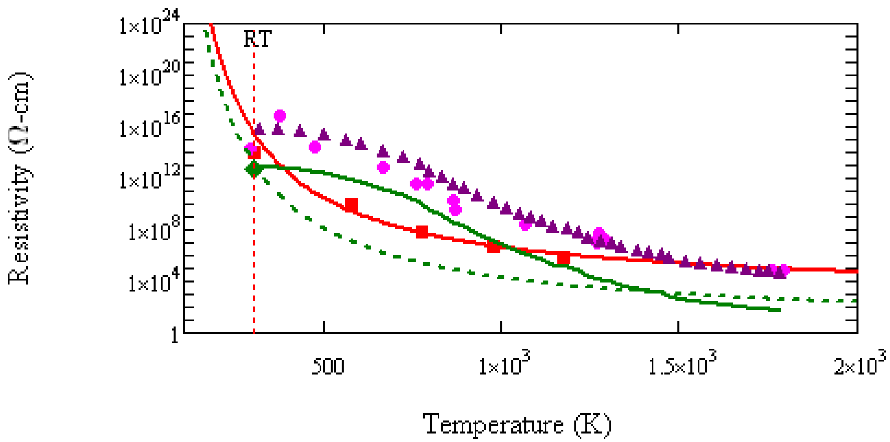

***Wide Orbital Range***
**Earth to Jupiter Flyby**
**Solar Flyby to 4 $R_s$**

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

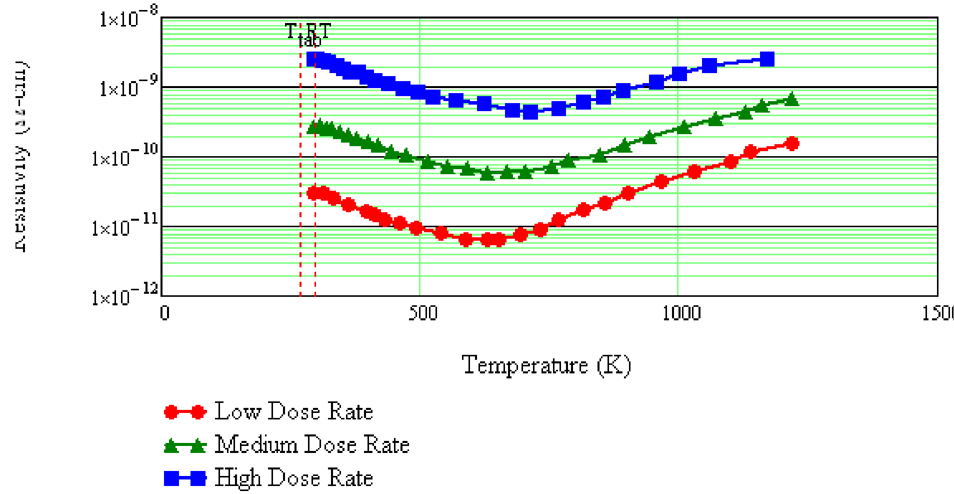
***Wide Dose Rate Range***
**Five orders of magnitude variation!**

# 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**

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

**Dielectric Constant**

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

**Electrostatic Breakdown**

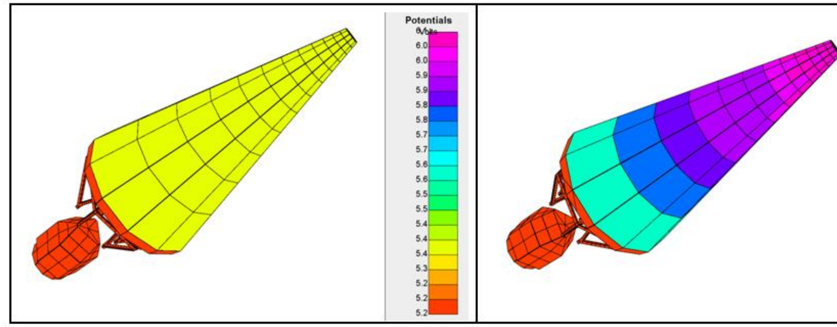
$$E_{ESD}(T) = E_{ESD}^{RT}\, e^{-\alpha_{ESD}(T-298\,K)}$$

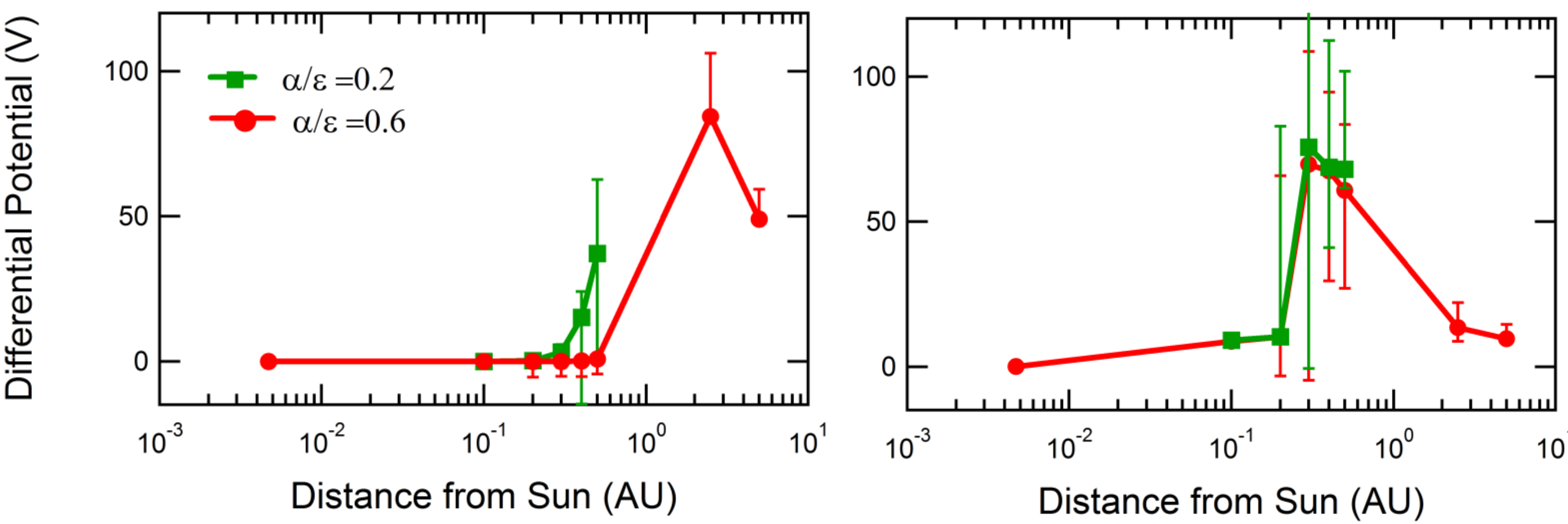
# Case V: Temperature and Dose Effects

## A peak in charging at ~0.3 to 2 AU

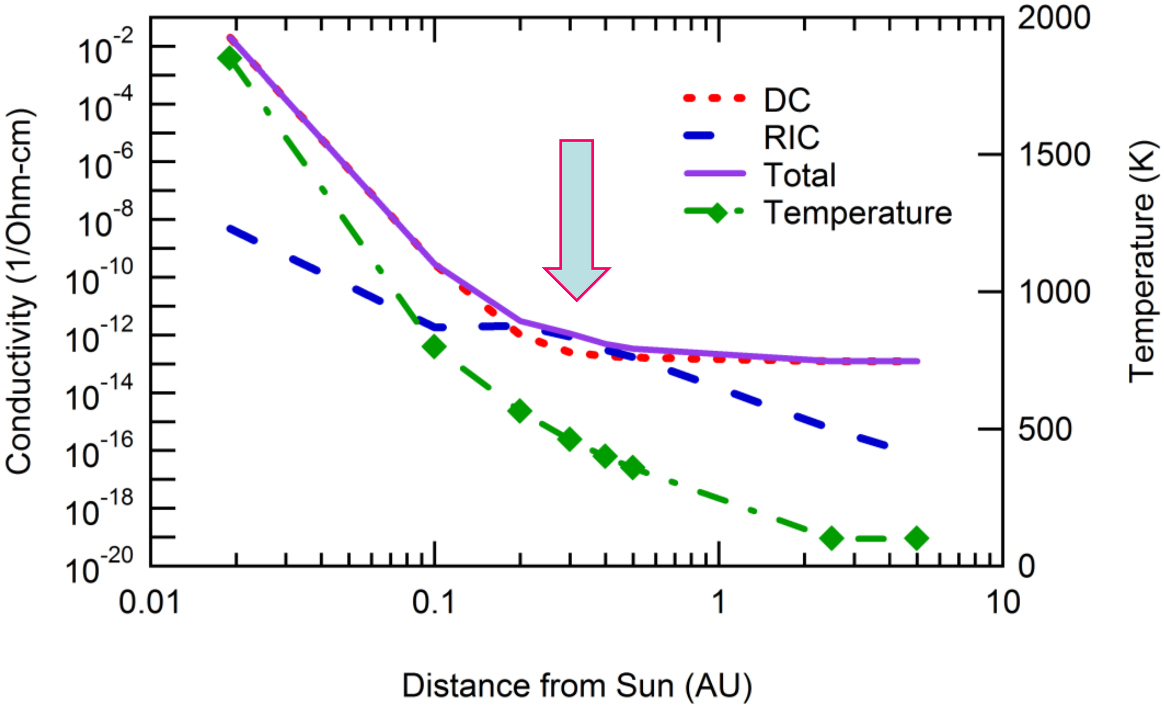
*"…Curiouser and curiouser…"*

*--Alice*



# Case V: Temperature and Dose Effects




## General Trends

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

## A fascinating trade-off

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

# Case VI:  Multilayer/Nanocomposite Effects



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

## Length Scale

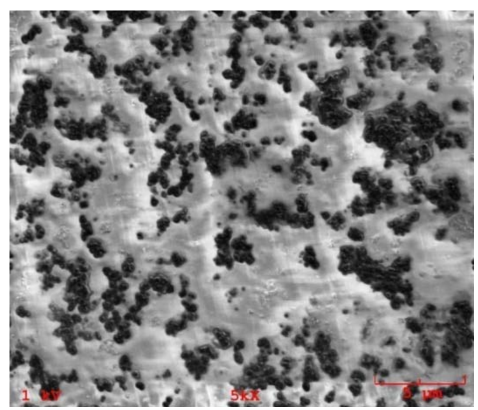
- Nanoscale structure of materials
- Electron penetration depth
- SE escape depth

## *Time Scales*

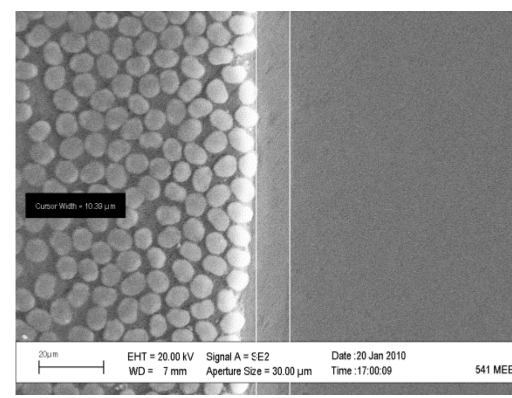
- Deposition times
- Dissipation times
- Mission duration

**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



# Model for Luminescence Intensity in Fused Silica

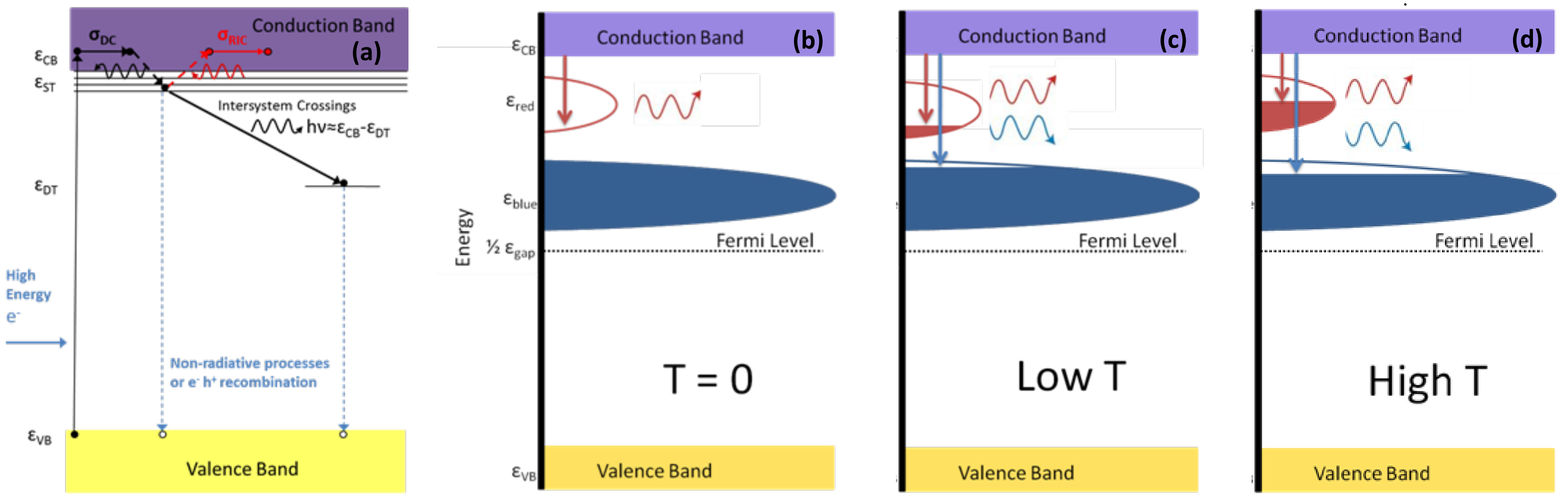



**Fig. 2.** Qualitative two-band model of occupied densities of state (DOS) as a function of temperature during cathodoluminescence. **(a)** Modified Joblonski diagram for electron-induced phosphorescence. Shown are the extended state valence (VB) and conduction (CB) bands, shallow trap (ST) states at $\varepsilon_{ST}$ within ~$k_BT$ below the CB edge, and two deep trap (DT) distributions centered at $\varepsilon_{DT}=\varepsilon_{red}$ and $\varepsilon_{DT}=\varepsilon_{blue}$. Energy depths are exaggerated for clarity. **(b)** At $T\approx0$ K, the deeper DT band is filled, so that there is no blue photon emission if $\varepsilon_{blue}<\varepsilon_{eff}$. **(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

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

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

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

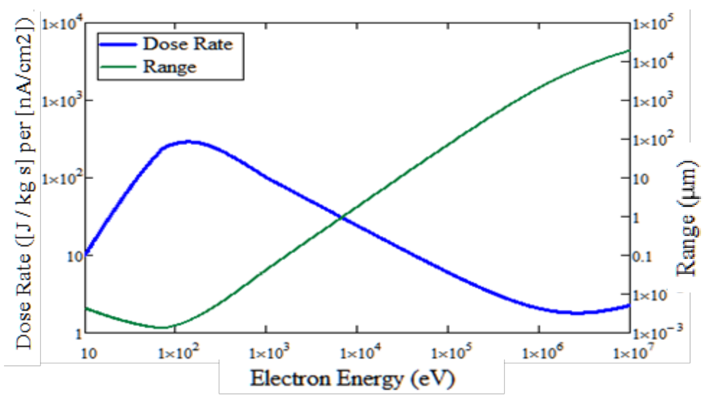



Fig. 3.Range and dose rate of disordered $SiO_2$ as a function of incident energy using calculation methods and the continuous slow-down approximation described in [5].

# Measured Cathodoluminescence Intensity in Fused Silica

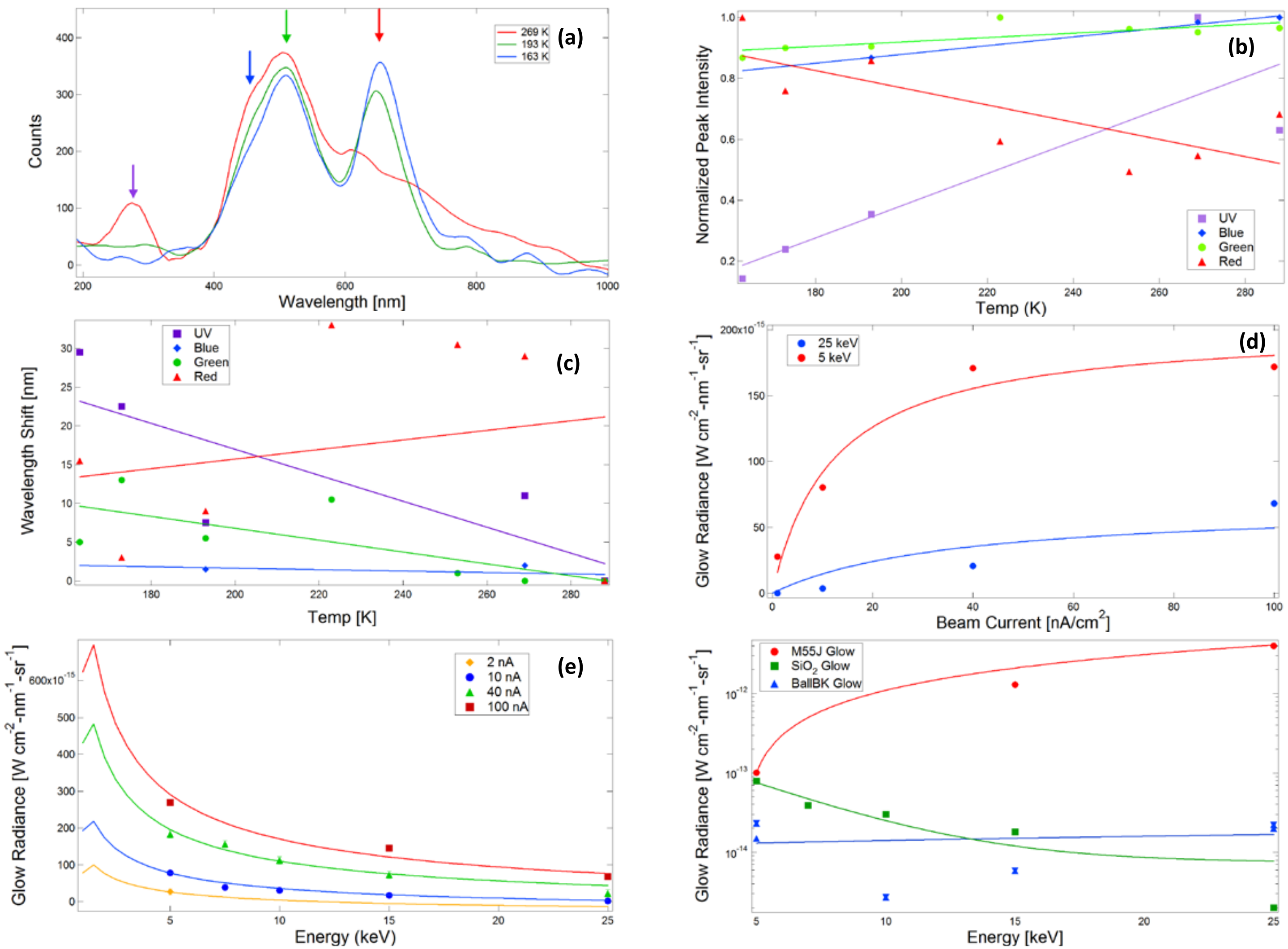
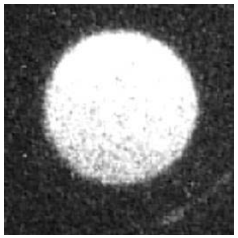



**Fig. 1.** Optical measurements of luminescent thin film disordered $SiO_2$ samples. **(a)** Three luminescence UV/VIS spectra at decreasing sample temperature. Four peaks are identified: red (~645 nm), green (~500 nm), blue (~455 nm) and UV (275 nm). **(b)** Peak amplitudes as a function of sample 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

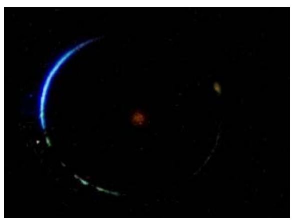
# Diversity of Emission Phenomena in Black Kapton

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



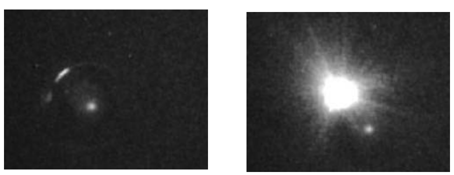
**Surface Glow**

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



**Edge Glow**

Similar to Surface Glow, but present only at sample edge

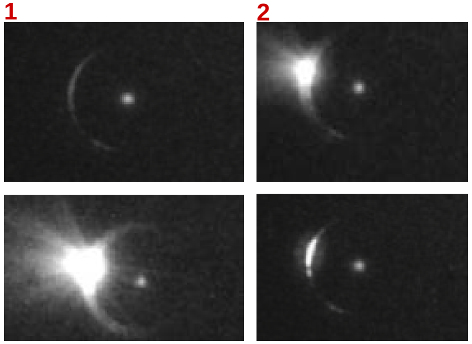


1 2

**"Flare"**

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

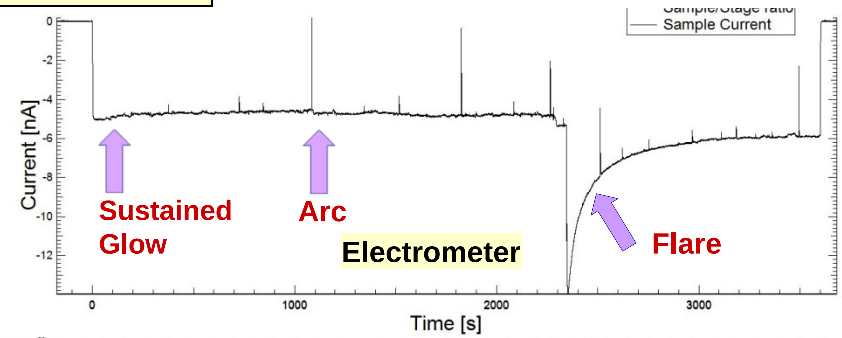
1 2

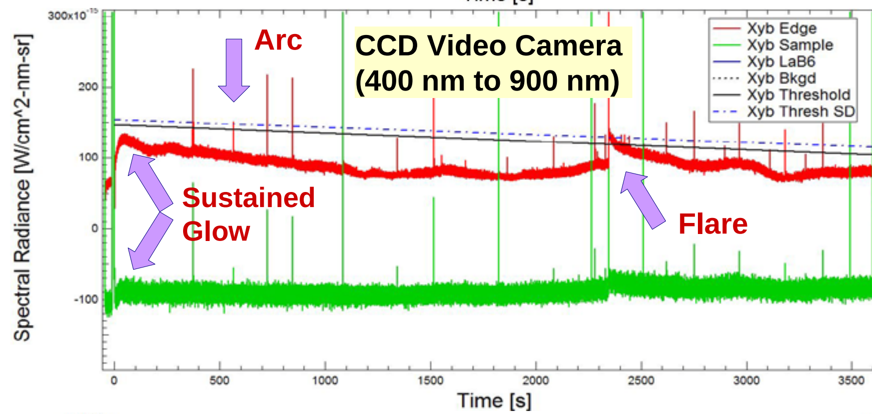


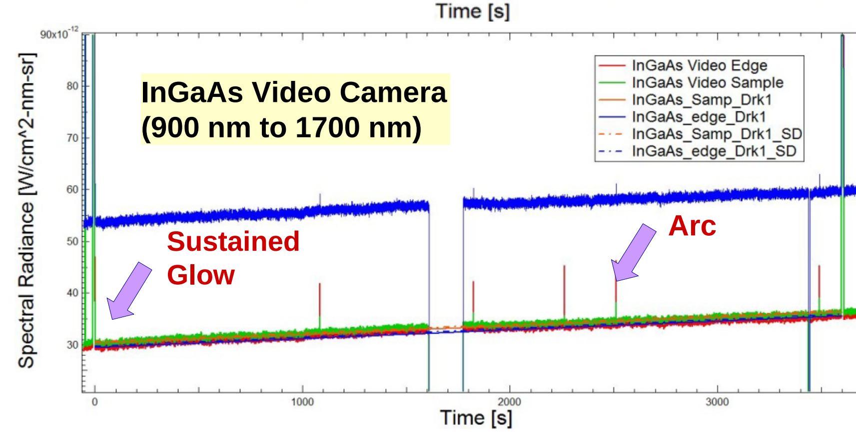
3 4

**Arc**

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



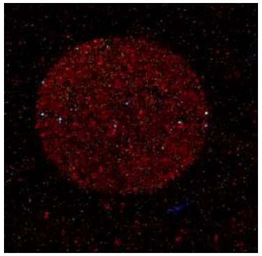



# Comparison of Luminescence Images

## Sustained Glow

Kapton XC

500 nA/cm$^2$
22 keV
150 K



M55J

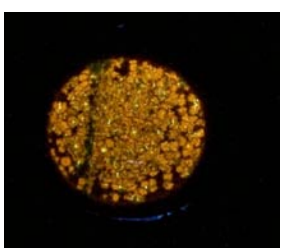
1 nA/cm$^2$
22 keV
100 K

IEC Shell Face Epoxy Resin with Carbon Veil

1 nA/cm$^2$
22 keV
100 K

Kapton E

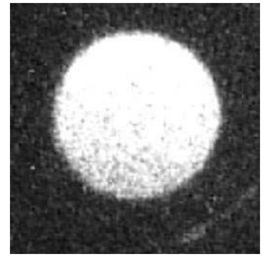
500 nA/cm$^2$
22 keV
150 K



## "Flare"

Kapton XC

50 nA/cm$^2$
22 keV
150 K



M55J

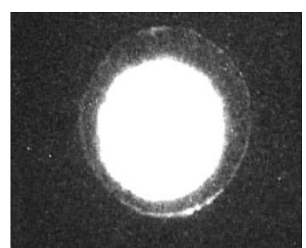
1 nA/cm$^2$
22 keV
100 K

IEC Shell Face Epoxy Resin with Carbon Veil

1 nA/cm$^2$
22 keV
100 K

Kapton E

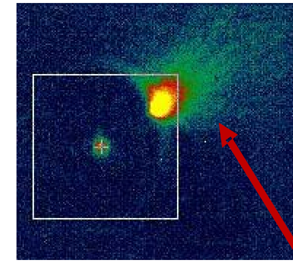
5 uA/cm$^2$
22 keV
150 K



## Arcs

Kapton XC

5 nA/cm$^2$
22 keV
1350 K

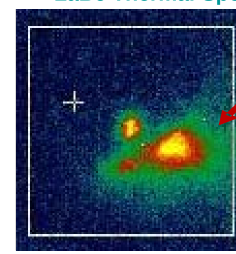


LaB6 Thermal Spot

Arc

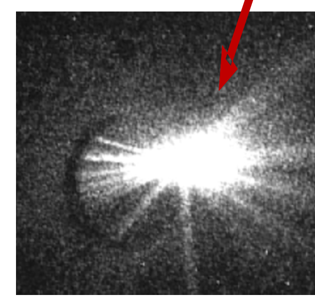
M55J

5 nA/cm$^2$
22 keV
135 K



IEC Shell Face Epoxy Resin with Carbon Veil

5 nA/cm$^2$
22 keV
100 K



**1 cm Dia test samples**

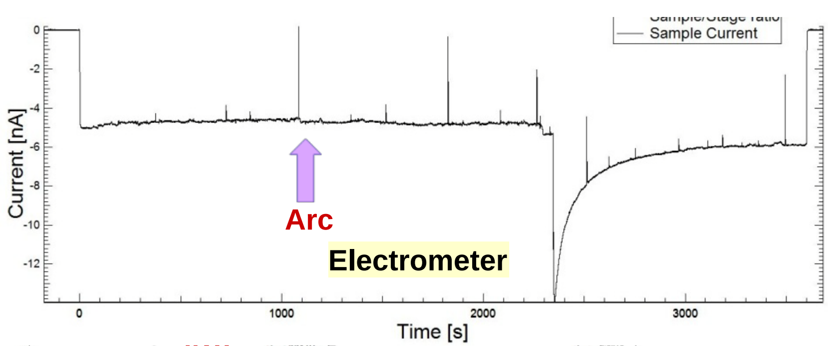
**30 s Exposure SLR Camera (400nm-640nm)**

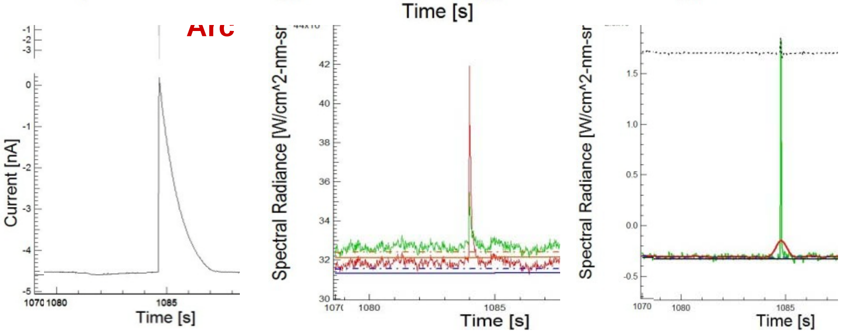
**33 ms Exposure CCD Video Camera (500nm-900nm)**

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

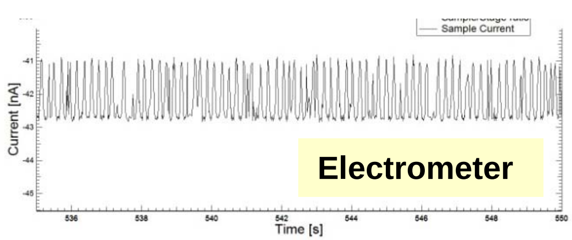
# Arcs Observed in Black Kapton and M55J

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**



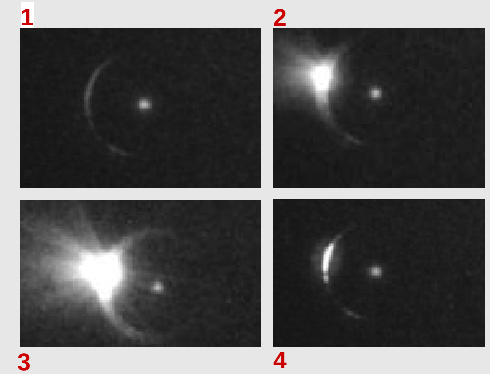

**Rapid Arcing at 4 mW/cm$^2$ ~20000 ars/hr**

## Arc Characteristics

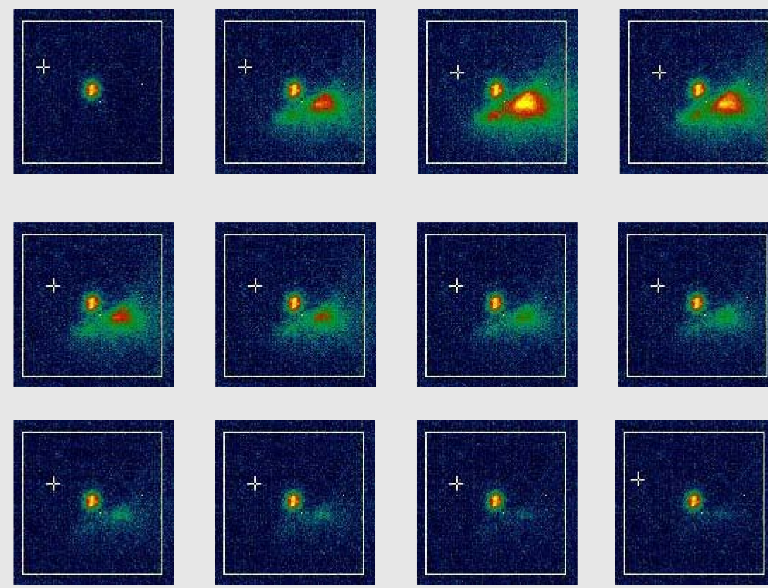
**Arc duration:**
**~0.2 to 0.8 s in electrometers and video cameras**

**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**



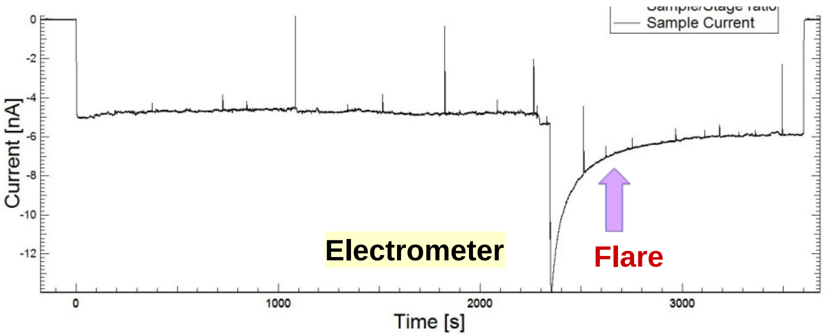

**CCD camera (400nm-900nm)**

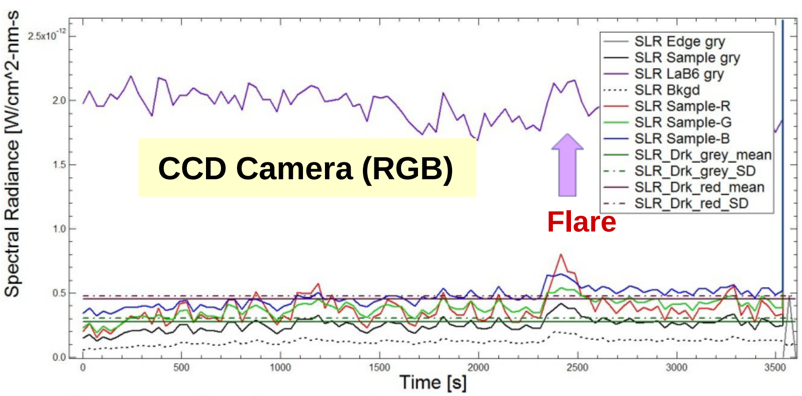


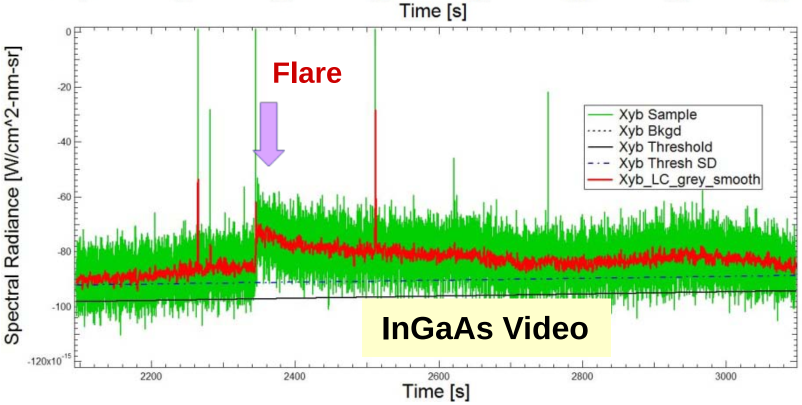
**Consecutive frames of discharge event (60 frames/sec)**

**InGaAs camera (900nm-1700nm)**

# “Flares” Observed in Black Kapton



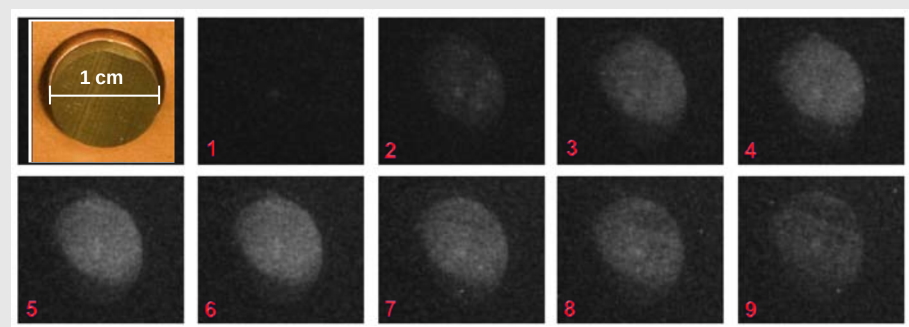

Ball Black Kapton
Runs 131
110 uW/cm²
5 nA/cm²
22 keV
135 K

## “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**

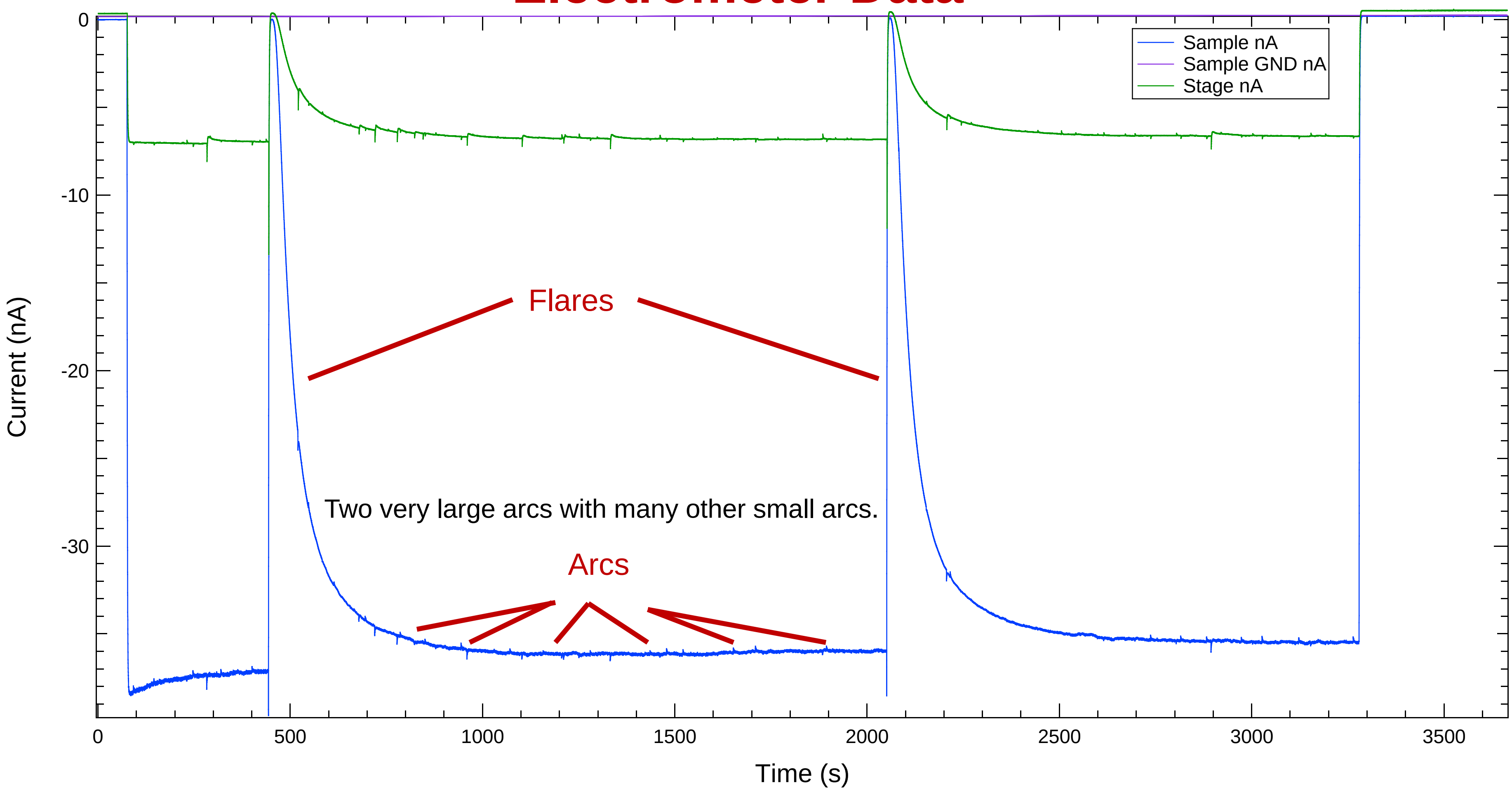



**CCD camera (400nm-900nm)**

M55J
5 nA/cm²
22 keV
135 K

# Details of Electrometer “Flare” Signature

## Electrometer Data




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

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

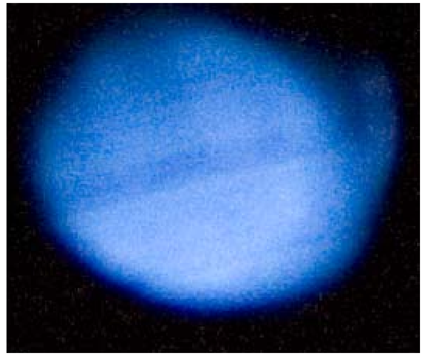
# Glow Increases with Increasing Flux, Energy and Power

**$e^-$ Energy**

M55J

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

Run 122



M55J

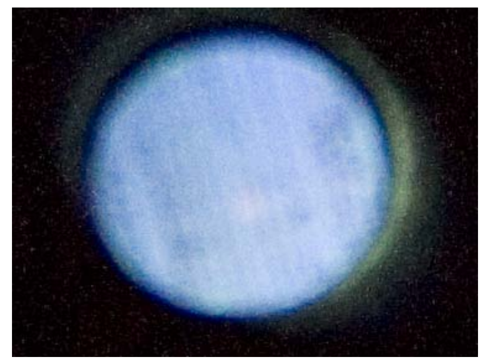
~4100 uW/cm$^2$
~188 nA/cm$^2$
22 keV
135 K

Run 122A

M55J

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

Run 121



M55J

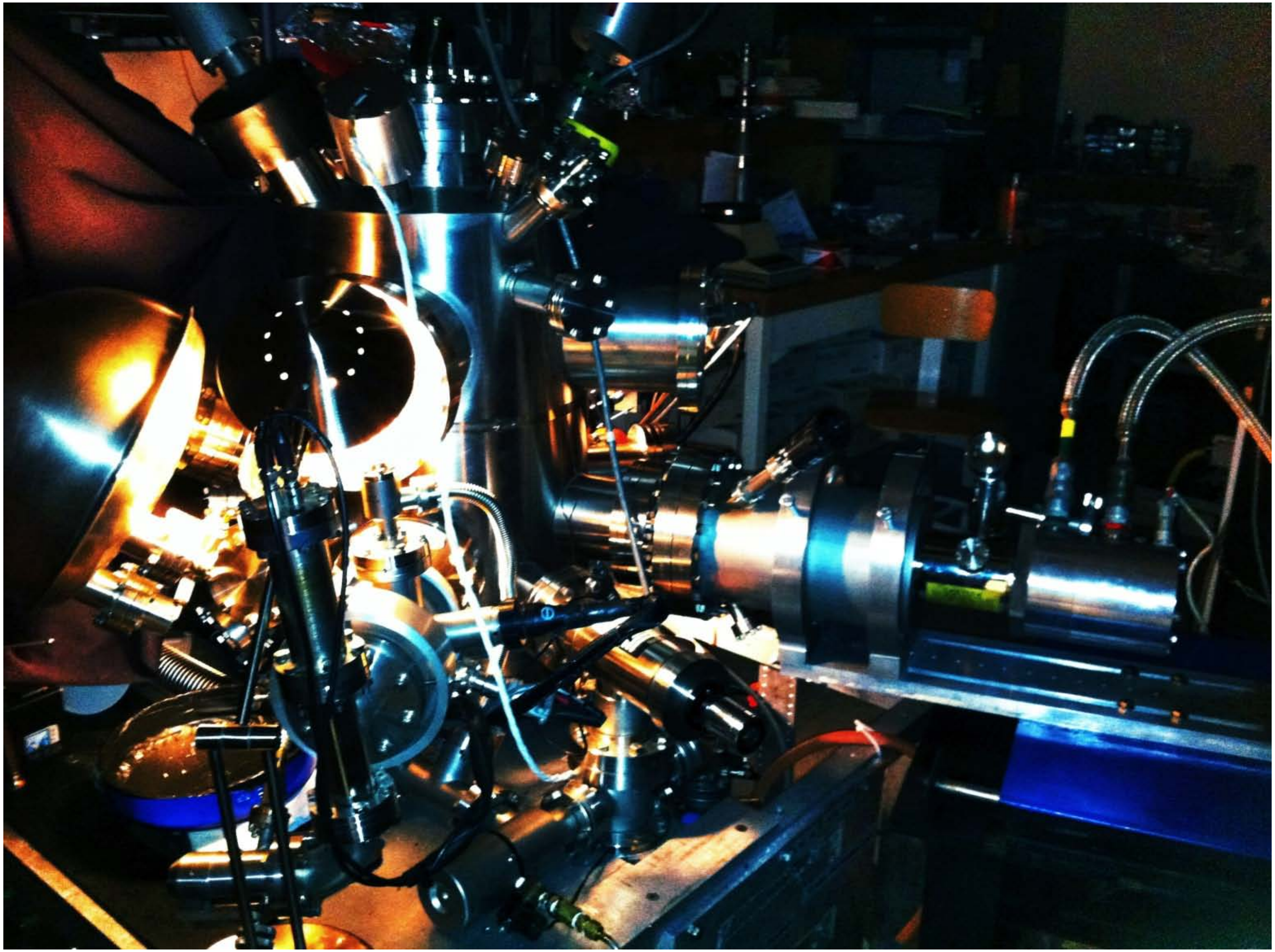
~1300 uW/cm$^2$
~188 nA/cm$^2$
7 keV
128 K

Run 121A

**$e^-$ Flux**

- **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**

# End with a Bang



# Supplemental Slides

# Potential Areas of Collaboration

**Theoretical modeling of the interplay between electron-induced luminescence and radiation induced conductivity in highly disordered insulating materials.**

**Grisseri, Teyssedre and others have done groundbreaking work on electron induced luminescence that Jensen and Dennison at USU have extended to lower temperatures.**

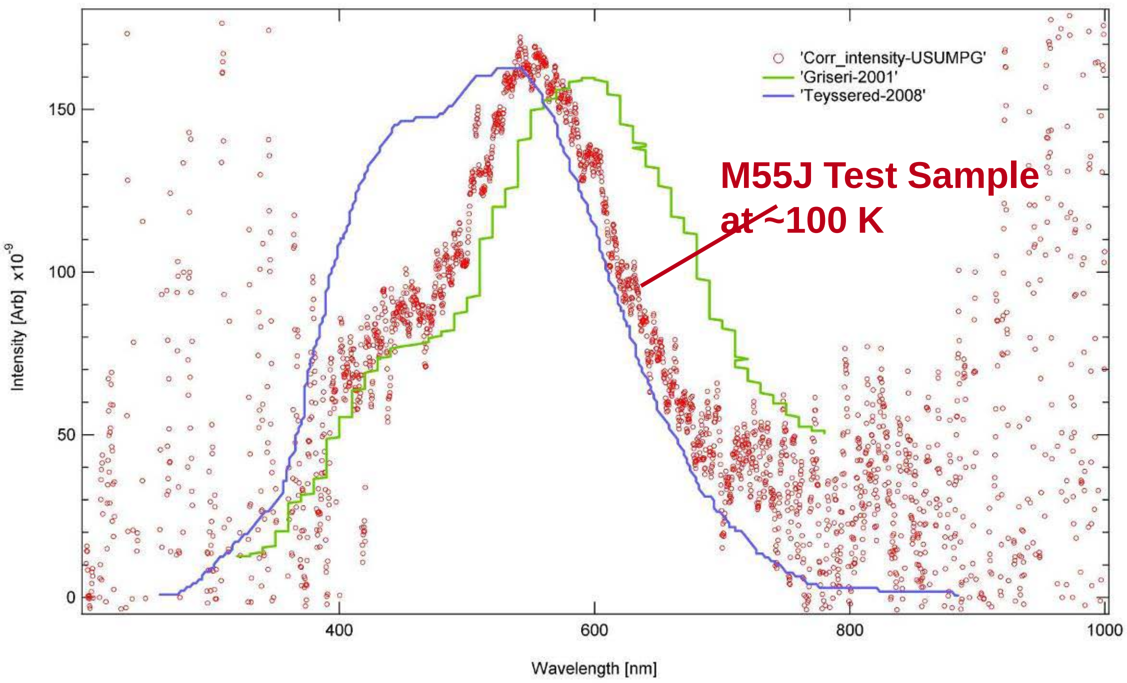
**Merging our work should lead to interesting results.**

# Absolute Intensity & Spectra of Glow

## Absolute Photon Yield per Incident Electron

**Current Best Estimate of Photon Invariant Factor for M55J Glow at L2 "High Storm" Incident Electron Flux at Cryogenic Temperatures**

**$7*10^7$ photon/cm$^2$-s-sr-nm**

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**±200% based of average of 4 independent calibration methods and uncertainties in optics losses, spectral profiles, sample geometries and experimental methods**

## Electron-Induced Luminescence Spectra

- Observed first at USU
- Glow visible on Kapton XC, Kapton E and M55J, T300 and Fiberglass composite materials
- Tests qualitatively confirmed at MSFC and Northrop-Grumman
- Consistent with RT test of similar materials in literature by ONERA and limited available physics models

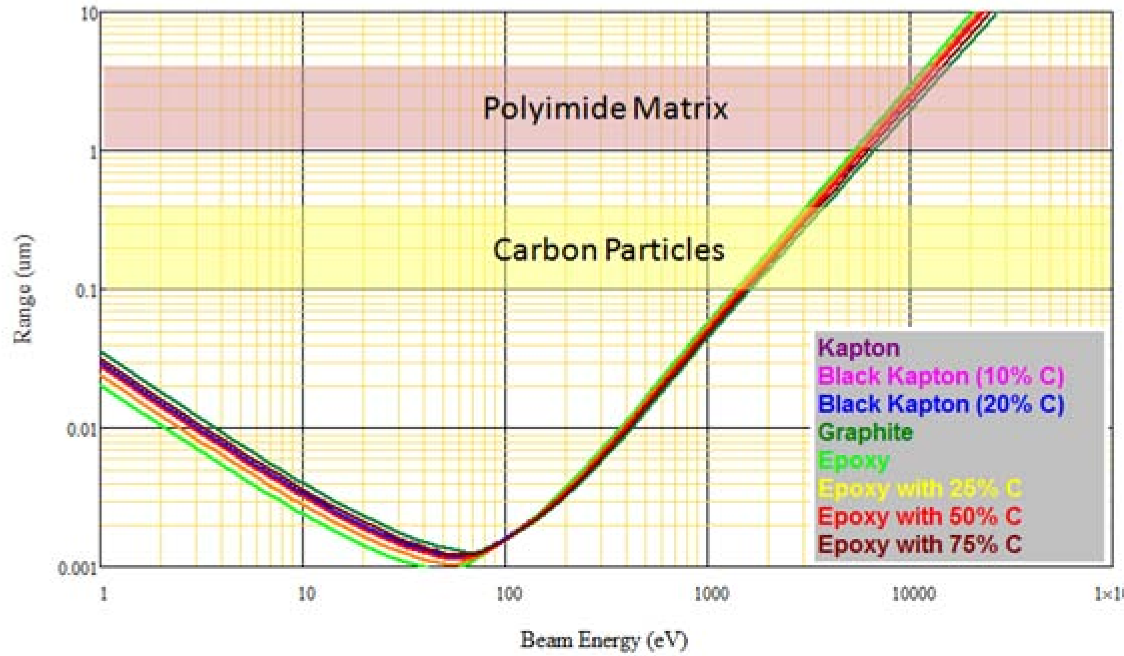
# Potential Areas of Collaboration

- Overlap of work that Griseri and Dennison are both currently engaged in, related to use of the pulsed electroacoustic (PEA/PWP) method for probing embedded charge layers.

**USU had our first successful PEA measurement of charge layer dynamics last night.**

**The lesson is that it pays to leave the lab and go enjoy fine French cuisine!**

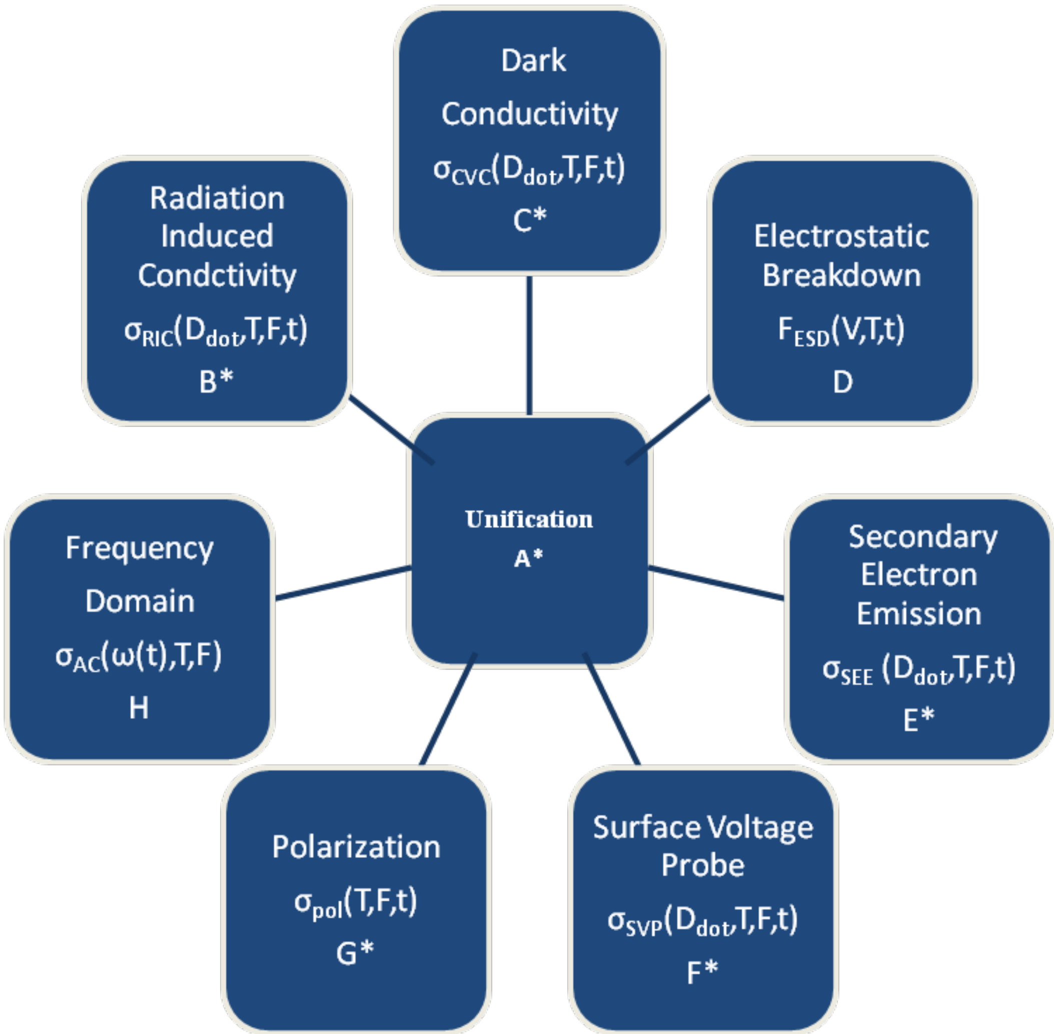
- Comparison of codes to model electron penetration and charge deposition in insulators. This has important overlaps with the PEA work listed above.



# Potential Areas of Collaboration

**Review of work on generalized density of states models for localized trap states in highly disordered materials developed at USU, and their applications to theoretical models being worked on in Toulouse.**

# Just a drop in the bucket…




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

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

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

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

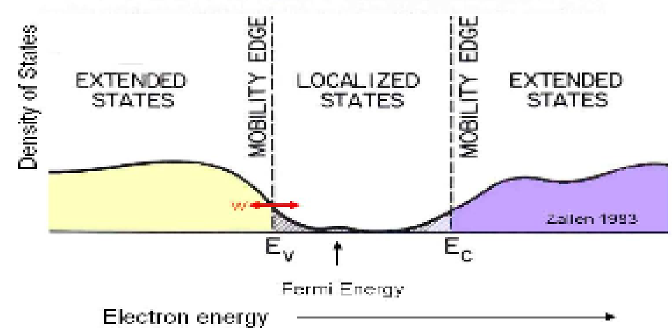
$$\alpha_{er}\, n_e(z,t)n_{tot}(z,t) + \alpha_{et}\, n_e(t)[N_t(z) - n_t(z,t)]$$

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

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

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

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

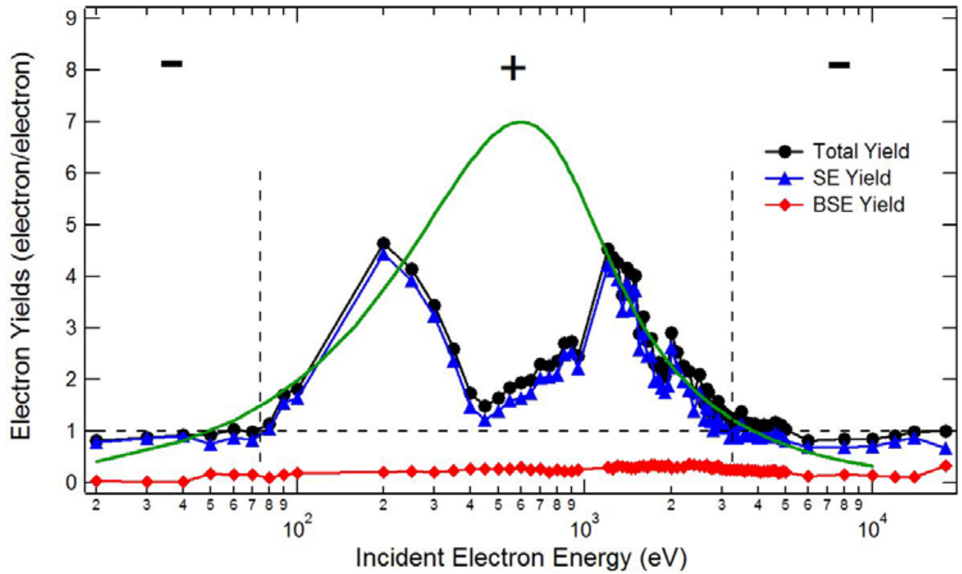


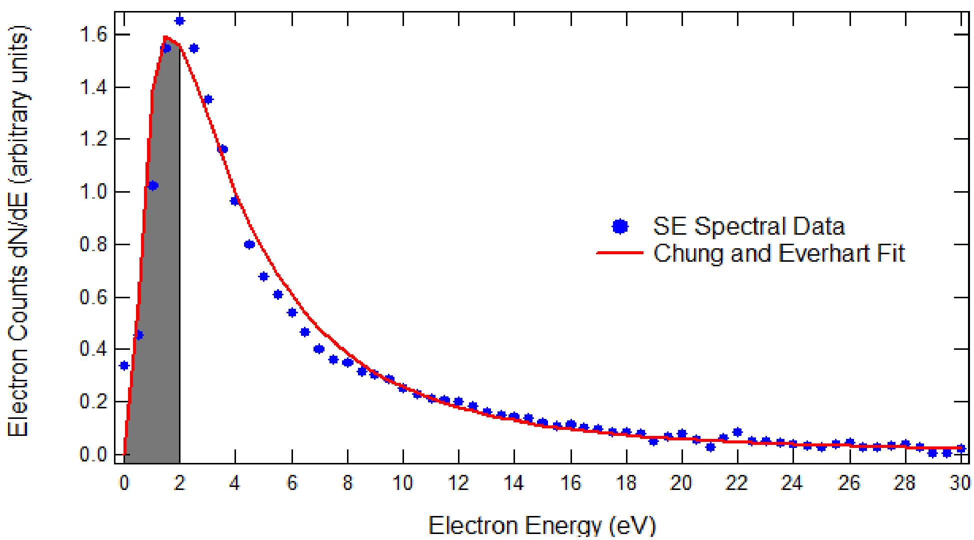
# Potential Areas of Collaboration

**Overlaps of work with secondary electron emission with Mohamed Belhaj. Specifically, it would be interesting to work in collaboration with the PhD student you mentioned (from Université Paul Sabatier, I believe) who is studying secondary electron emission measurements/effects of bulk charging. This work dovetails nicely with studies done on the subject at USU by Dennison, Wilson, Hoffmann and Hodges.**

# Low Charge Capabilities

UtahState University
MATERIALS PHYSICS GROUP



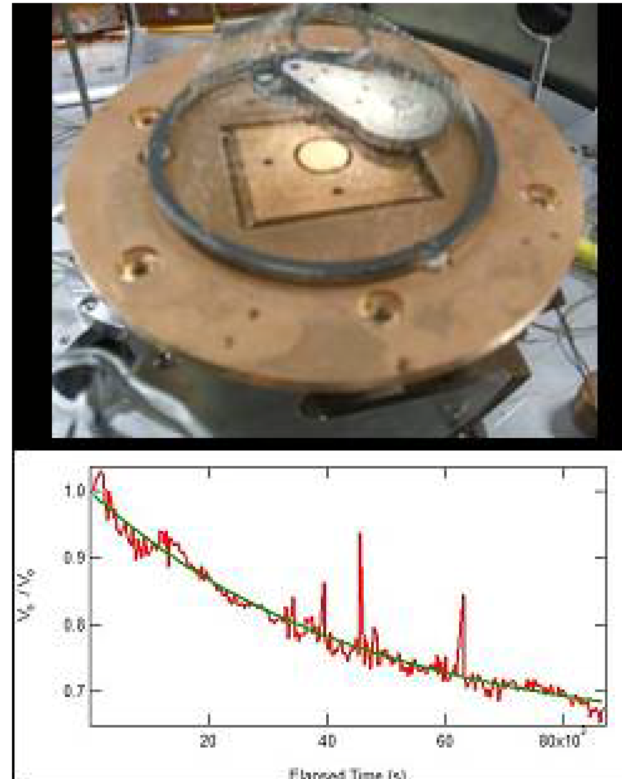




**Figure 5. (top)** Interior of Hemispherical grid retarding field analyzer detector showing sample and "flipper" to measure surface voltages with electrostatic field transfer probe. **(bottom)** Surface voltage decay curve for Kapton E sample after electron beam

# Surface Voltage Relates to “Intrinsic” Yield Model

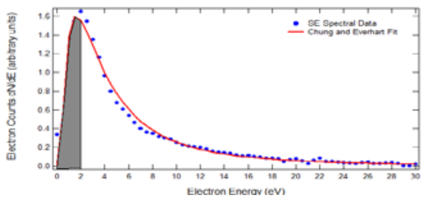
## Combining all the pieces

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

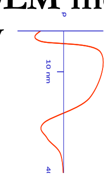
$$V_s = \frac{Q_o(\sigma-1)d}{\varepsilon_o\varepsilon_r A_o} - \frac{\sigma Q_o\lambda_{SE}+Q_oR}{2\varepsilon_o\varepsilon_r A_o}$$

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

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

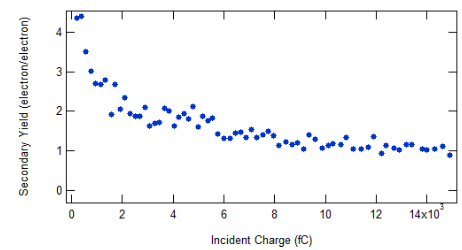



DDLM model for surface potential




Depth profile for net positive charging

Decay curve data

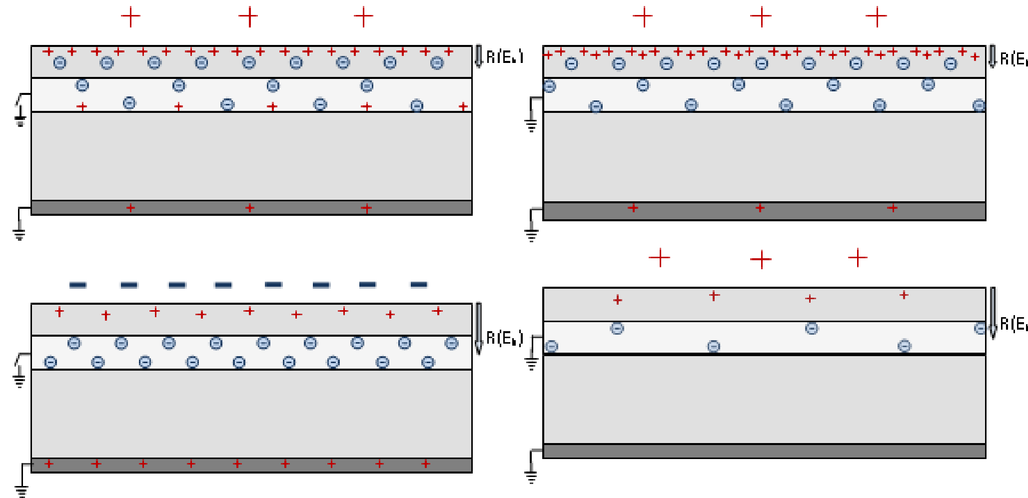



$$\delta(eV_s) = \left(\sigma_o(E_o) - 1\right)\cdot\left(1 - \frac{\lambda_{se}}{2\cdot d}\right)\cdot\left(\frac{\dfrac{h(\varepsilon_s)}{h(50\cdot eV)} - 1}{\dfrac{h(0)}{h(50\cdot eV)} - 1}\right) - \left[\eta_o\cdot\left(1 - \frac{\lambda_{se}}{2\cdot d}\right) - \left(1 + \frac{R}{2\cdot d}\right)\right]$$

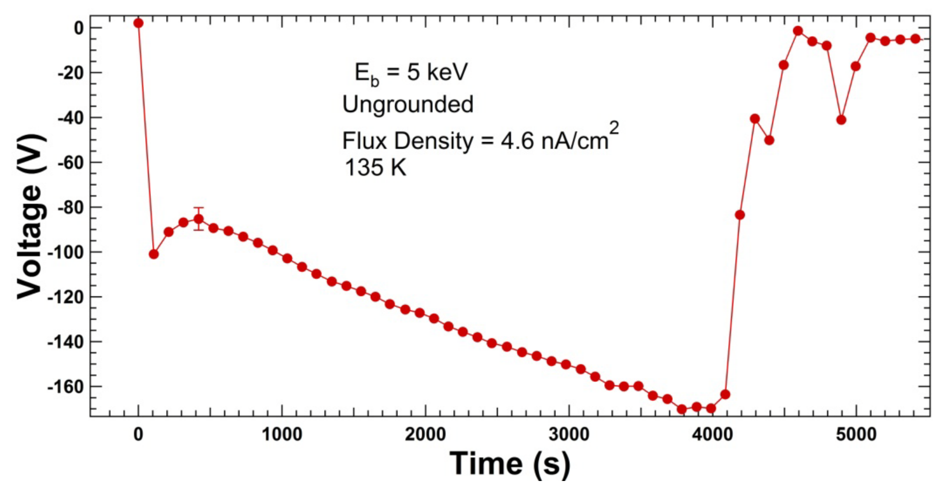
We now have an analytic solution for secondary electron yield as surface potential changes in response to incident charge.

# Potential Areas of Collaboration

**Surface conductivity of insulating materials as measured with surface potential probes and conductivity measurements. These include both lateral currents and charge transport with the RIC region.**



**Both the French group and USU have observed similar interesting annomolous behavior in materials. Thierry Paulmier, Phillipe. Molinié, Rachel Hanna and others have developed theoretical explanations for these anomalous phenomena that we hope to reconcile with our theoretical/empirical understanding. Both groups have taken complementary**



# Potential Areas of Collaboration

**Comparison of numerical fitting models for secondary and backscattered electron emission, photoemission, ion-induced emission, radiation induced conductivity and conductivity used in the US and ESA spacecraft charging codes.**

**The ISO (International Standards Organization) Workshop in Tokyo began the process of establishing an international standard for Extreme Space Environments for Spacecraft Charging Applications. This is an ongoing effort of critical importance to the spacecraft industry. Initial efforts were also begun at this meeting to organize a round robin testing of spacecraft materials properties used for simulations of spacecraft charging. USU and LAPACE/ONERA are two of the lead institutions in this effort. I propose to work with the French group to further this effort and identify concrete objectives and tests to get this going.**