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Exploring the Universe… One Electron at a Time

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One Electron at a Time

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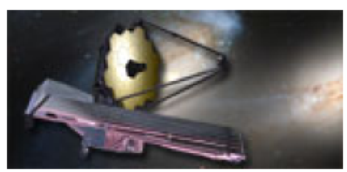
Exploring the Universe with IR Space Telescopes

The James Webb Space Telescope will be a giant leap forward in our quest to understand the Universe and our origins. The Webb will examine every phase of cosmic history: from the first luminous glows after the Big Bang to the formation of galaxies, stars, and planets to the evolution of our own solar system. The science goals for the Webb can be grouped into four themes:

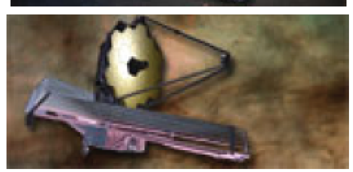
IR Space Telescopes

- SDL's Wide-field Infrared Survey Explorer
- Herschel Space Observatory
- Spitzer Space Telescope
- James Webb Space Telescope

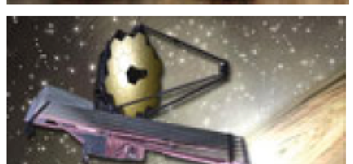
The End of the Dark Ages: First Light and Reionization seeks to identify the first bright objects that formed in the early Universe, and follow the ionization history.



Assembly of Galaxies will determine how galaxies and dark matter, including gas, stars, metals, physical structures (like spiral arms) and active nuclei evolved to the present day.



The Birth of Stars and Protoplanetary Systems focuses on the birth and early development of stars and the formation of planets.



Planetary Systems and the Origins of Life studies the physical and chemical properties of solar systems (including our own) and where the building blocks of life may be present.

What Is Different About JWST?

Extremely Faint Objects
Large sensitive optics

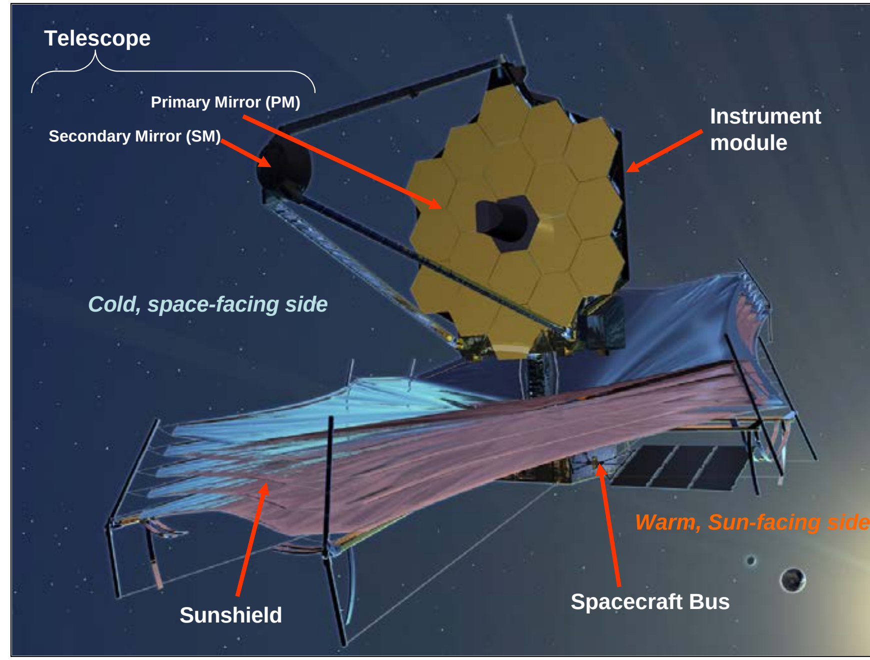
Large Open Structure
Size and weight constraints
Minimal shielding
Large fluxes

Observations in IR
Penetration through intergalactic dust clouds
Optimized for (0.6 –28 um)

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

Large Sunshield
Large areas
Constant eclipse with no photoemission

Stable, Low Light Environment
Orbit at L2
Large solar activity variations
In and out of magnetotail

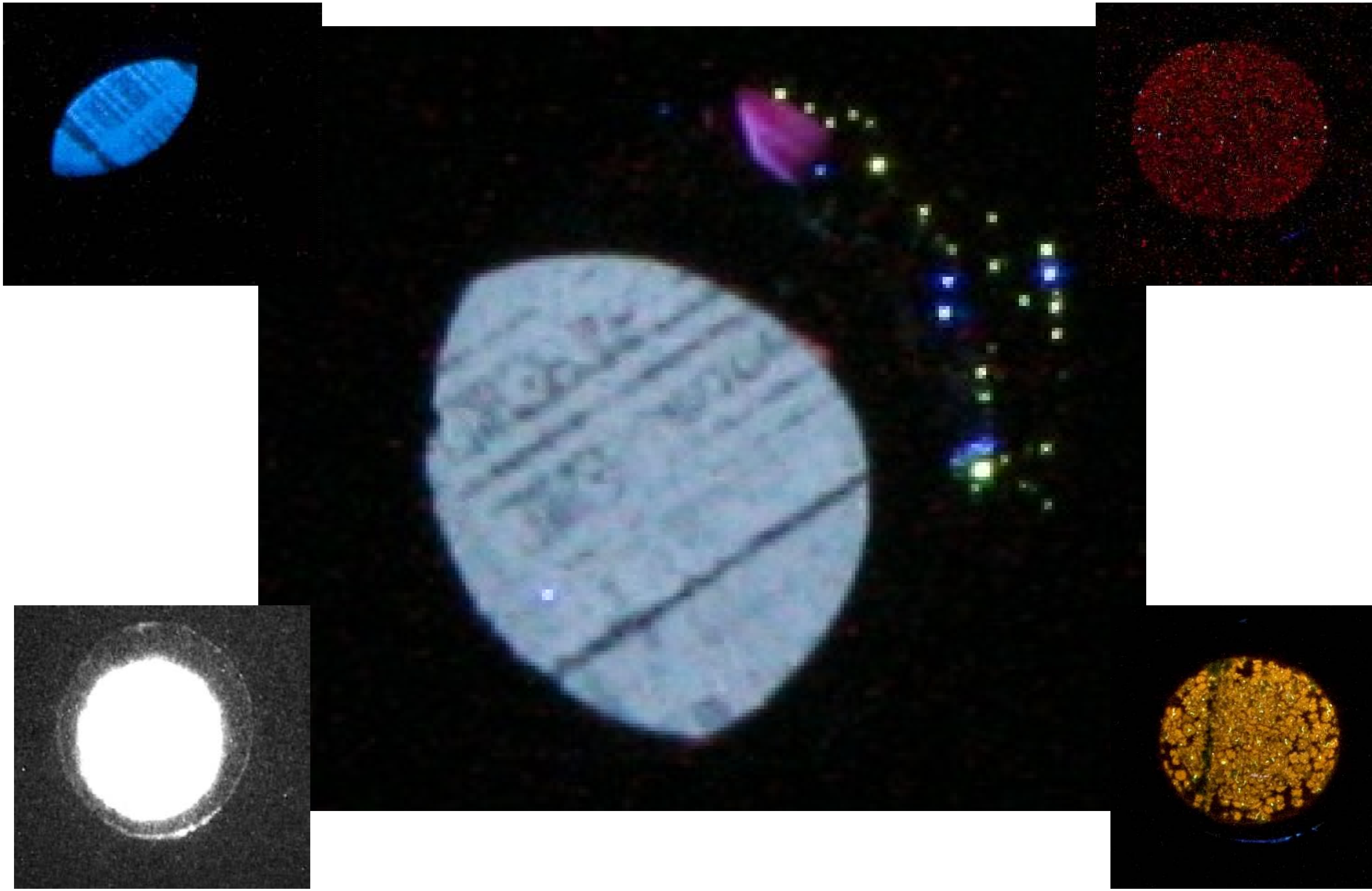


Long Mission Lifetime (10-20 yr)
No repairs
Very long integration times

Complex, Sensitive Hardware
Large sensitive optics
Complex, cold electronics

Paradigm Shift in Design Methods
To big for conventional ground tests

Images from JWST



Primary Motivation For Our Research—Spacecraft Charging

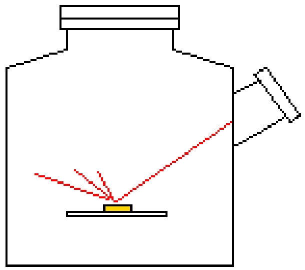
NASA's concern for spacecraft charging is caused by plasma environment electron, ion, and photon-induced currents.
Charging can cause performance degradation or complete failure.

Majority of all spacecraft failures and anomalies due to the space environment result from plasma-induced charging

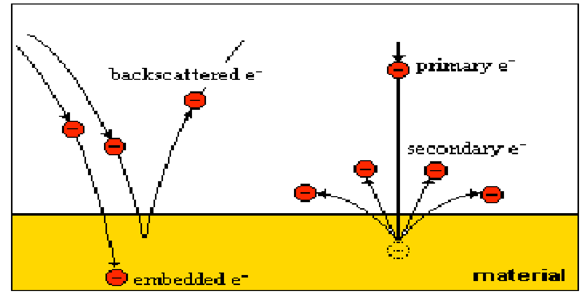
- ***Single event interrupts of electronics***
- ***Arching***
- ***Sputtering***
- ***Enhanced contamination***
- ***Shifts in spacecraft potentials***
- ***Current losses***

Solar panel damaged by localized charging event

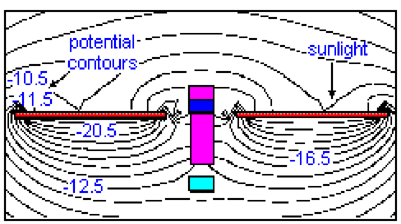
A Simplified Approach to Space Environment Interactions Modeling…

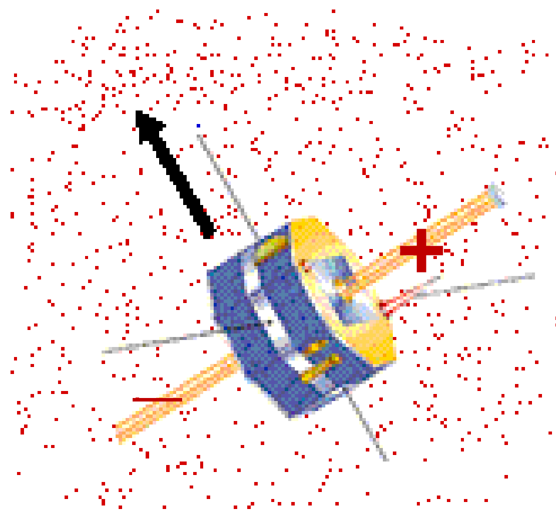


Materials Properties



Electron interactions with materials





e^-

I^+

γ

Spacecraft Potential Models

Satellite Moving through Space

Space Plasma Environment

Simulating Space at USU

JWST	USU Lab
Sunshield	Small Test Samples (~1 cm^2)
Space	UHV Chamber (~10^{-9} Torr)
Passive Cooling	Cryo Cooling (>30 K)
Light Flux	No Light (dark room & chamber)
Charge Flux	Monoenergetic e-Beam (20eV to 30keV)
Low Flux	Low Flux (<0.05 nA/cm^2 to >500 nA/cm^2)
Mission Lifetime (~20 yr)	Fountain of Youth and Pot of Au ➔ Accelerated Testing

Materials Physics Group Measurement Capabilities

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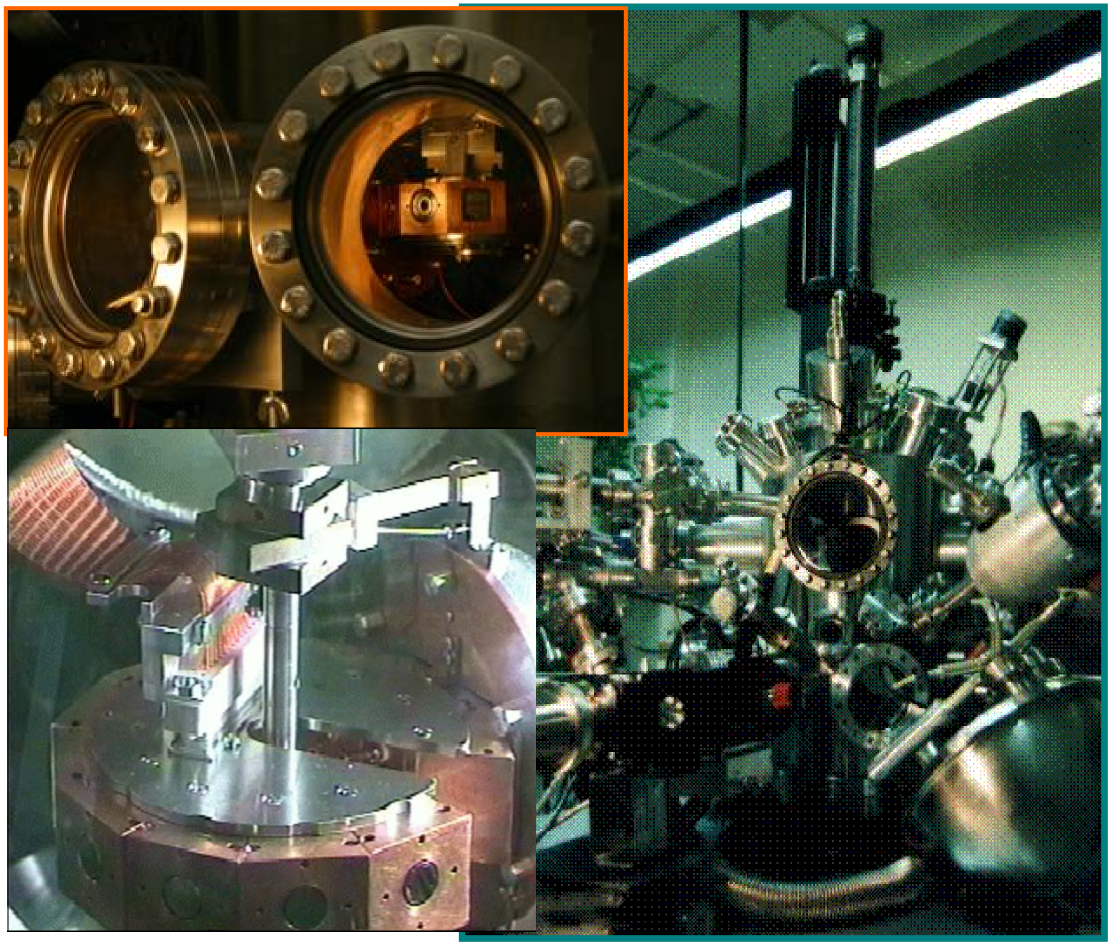
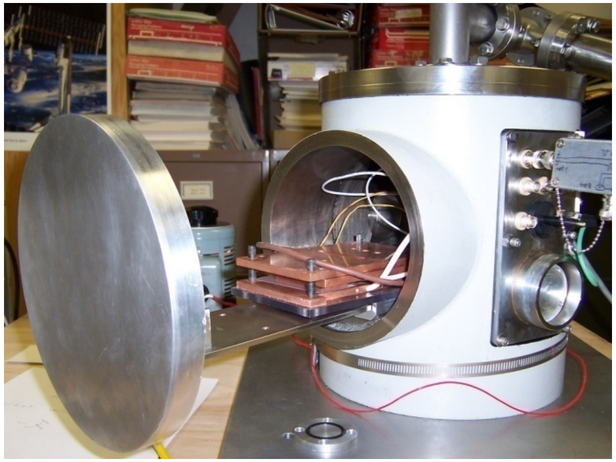
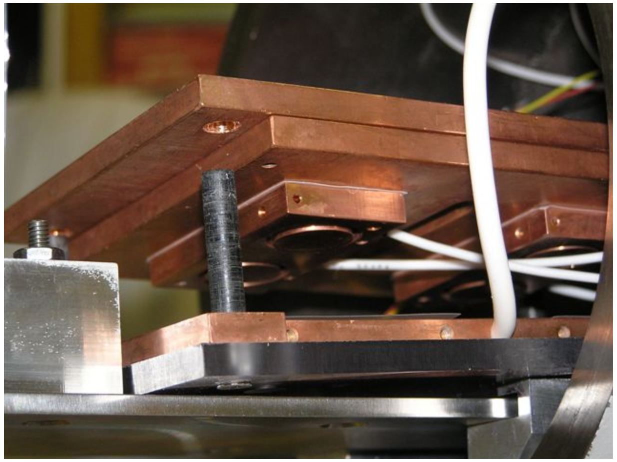
Electron Emission Ion Yield	Photoyield Luminescence	Conductivity Electrostatic Discharge	Radiation Induced Cond. Radiation Damage

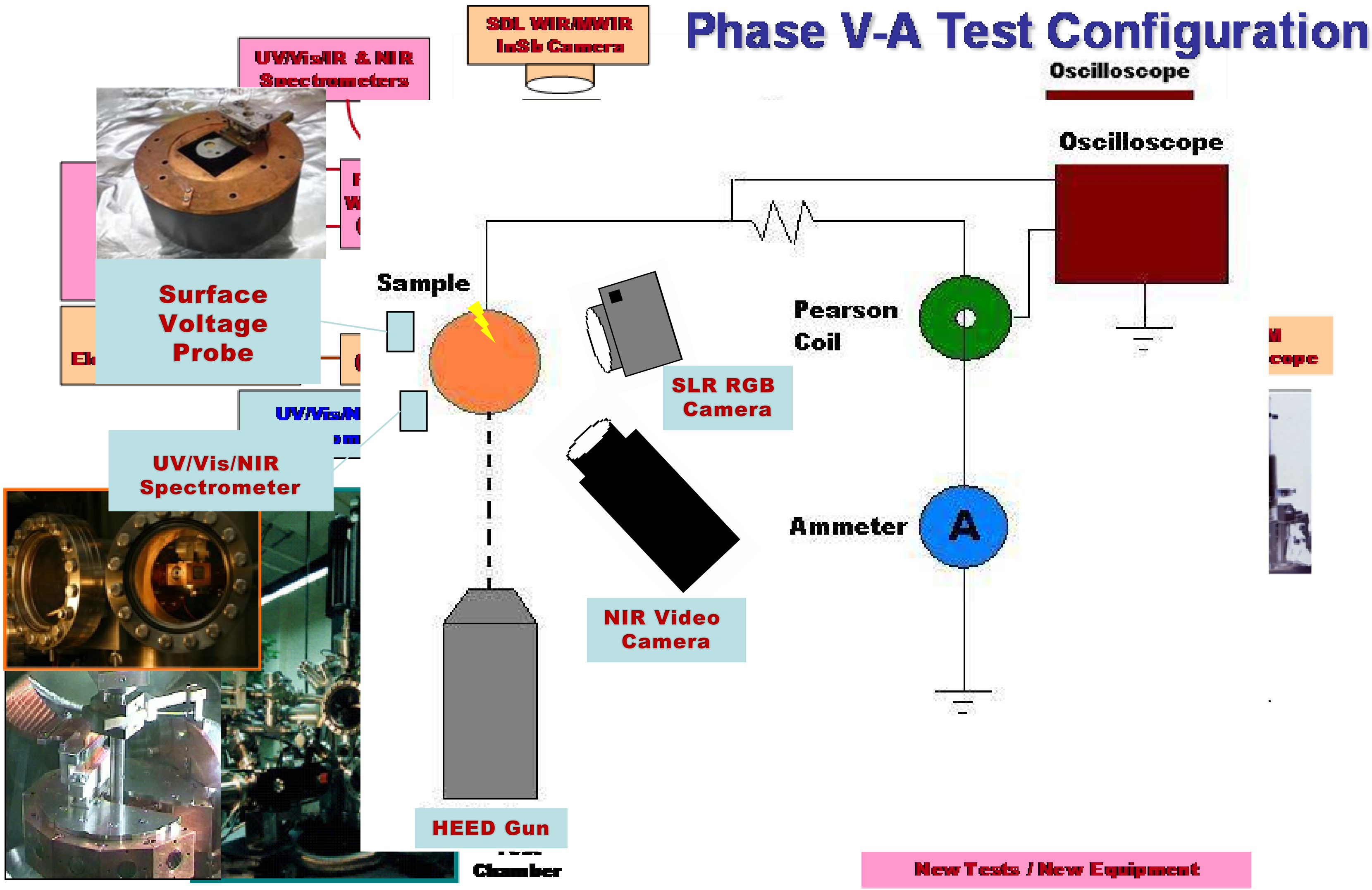






Dependence on: Press., Temp., Charge, E-field, Dose, Dose Rate

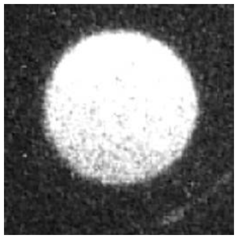
USU Arc/Glow Test Configuration



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

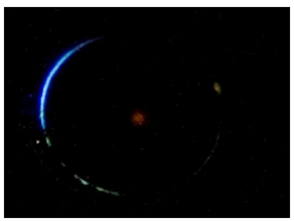
Diversity of Emission Phenomena in Time Domain

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



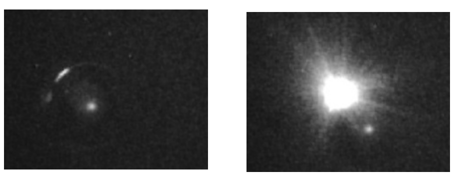
Surface Glow

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



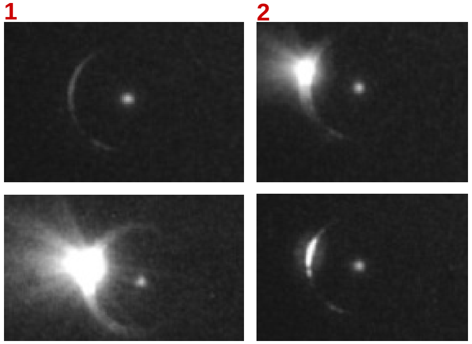
Edge Glow

Similar to Surface Glow, but present only at sample edge



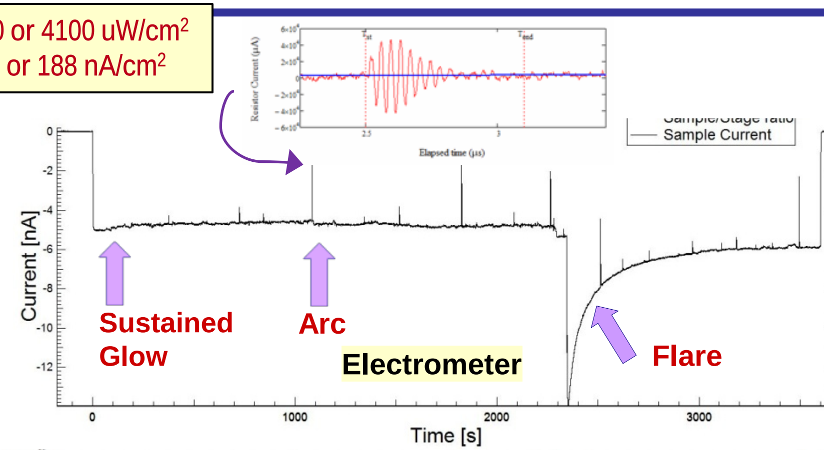
"Flare"

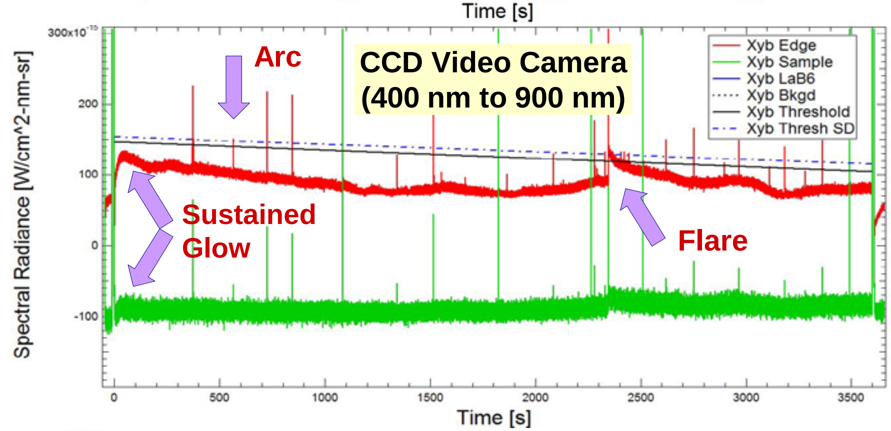
2-20x glow intensity
Abrupt onset
2-10 min decay time

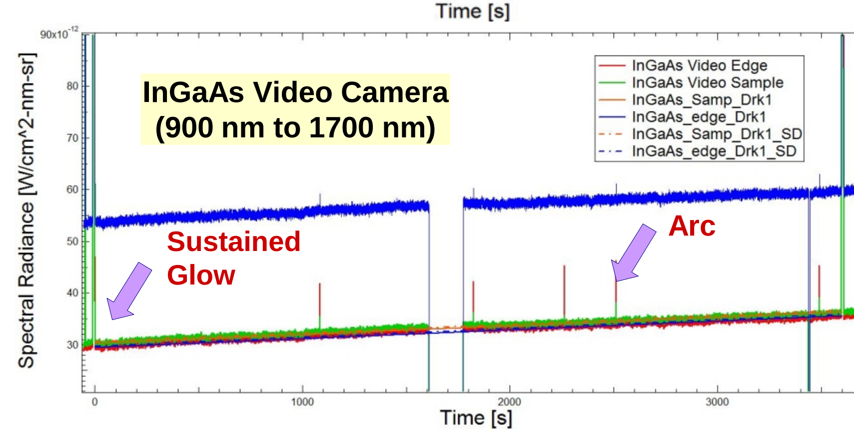


Arc

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







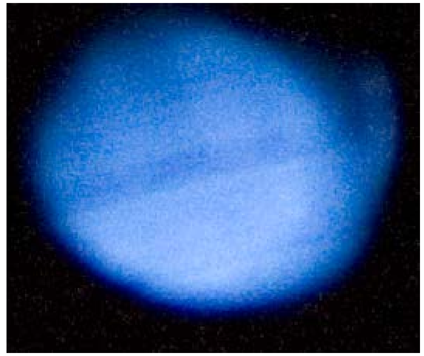
Glow Increases with Increasing Flux, Energy and Power

e^- Energy

M55J

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

Run 122



M55J

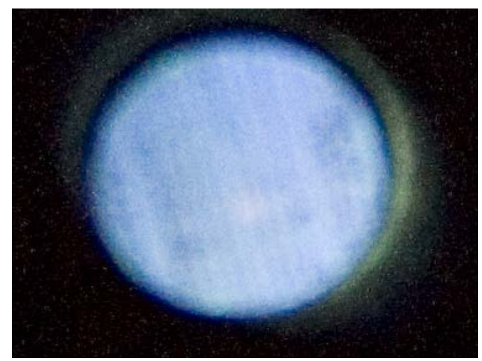
~4100 uW/cm^2
~188 nA/cm^2
22 keV
135 K

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.

A Simple Analogy for Corpuscular Charge Storage:

Problem complicated by:

- The incident electron and ion fluxes acts to fill the bucket.
- Electron (ion, and photon) emission determines how much charge splashes out of the bucket as it is being filled.
- Conductivity of insulating materials determines:

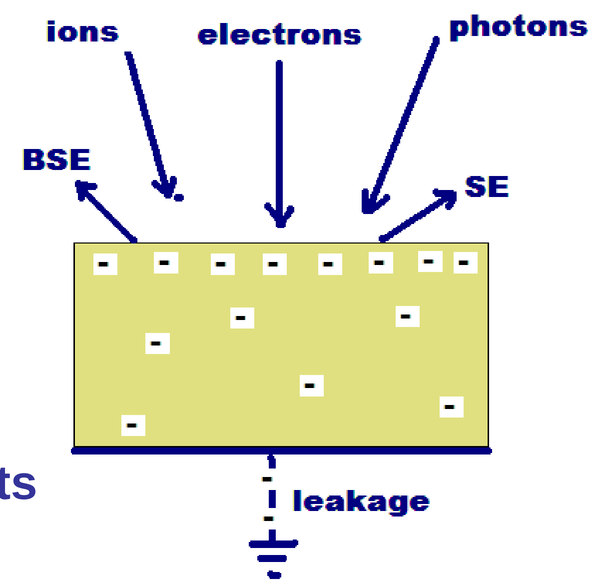
Conductors—Grates
Semiconductors—Sieves
Leaky insulators—Leaky buckets
Good insulators—Good buckets
Extreme insulators—Frozen buckets

- Two types of charge
- Charge interactions
- Charge distributions
- Different incident species
- Materials properties of charge repository

- Where charge will accumulate
- How charge will redistribute across the spacecraft.
- Time scale for charge transport and dissipation.

How full is the bucket?

Electrons as particles



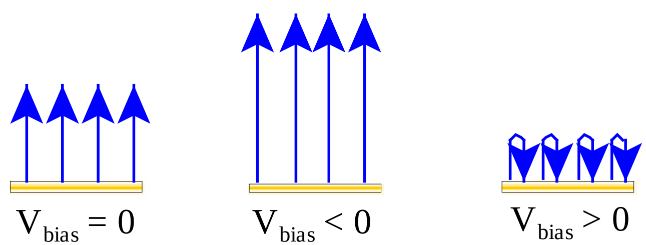
Three Critical Processes in Charging

Range

Electron Yield

Conduction

Depth electrons penetrate
is energy dependent

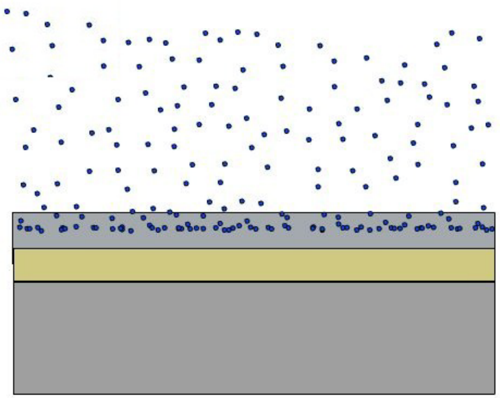


Conductivity determines
deposited charge layer
movement

It's all about where the electrons are--$n_e(z)$

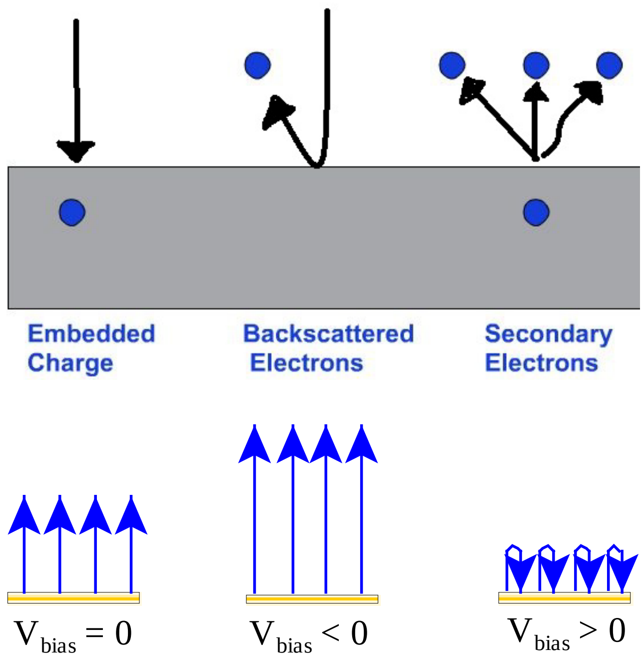
Three Critical Processes in Charging

Range

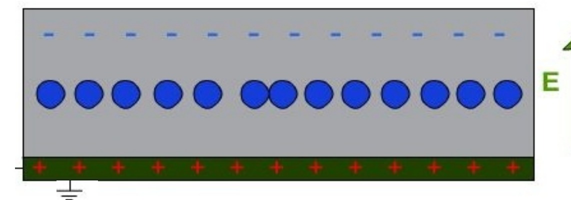


Depth electrons penetrate is energy dependent

Electron Yield



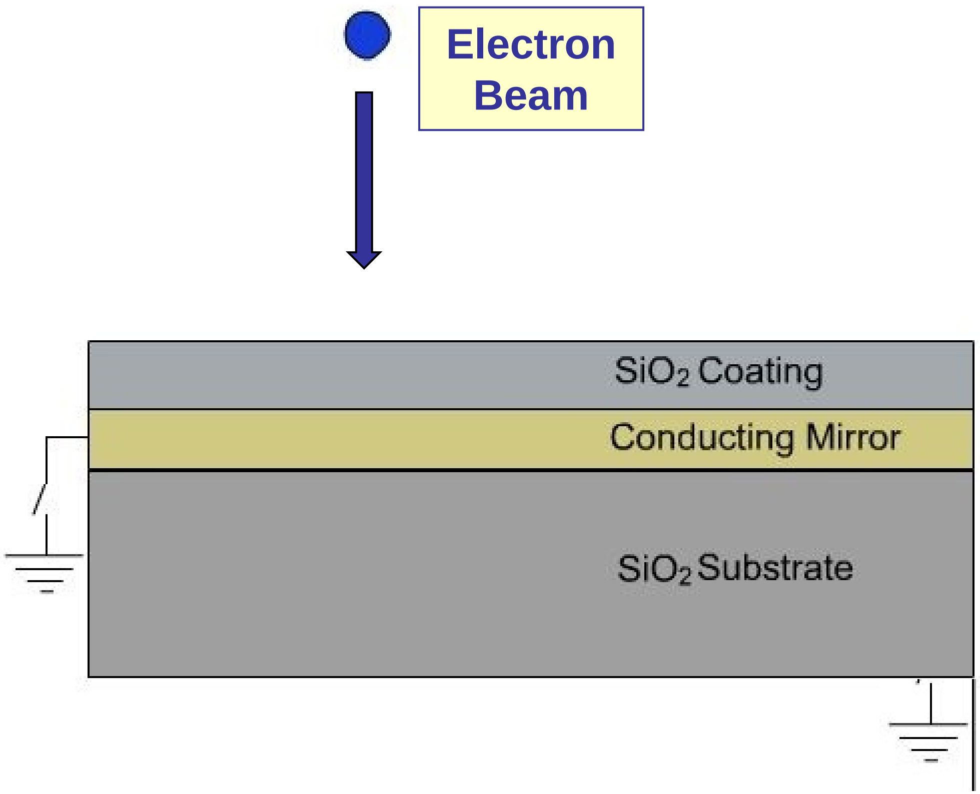
Conduction



Conductivity determines deposited charge layer movement

It's all about where the electrons are--$n_e(z)$

Charging of a Dielectric Coated Optical Mirror

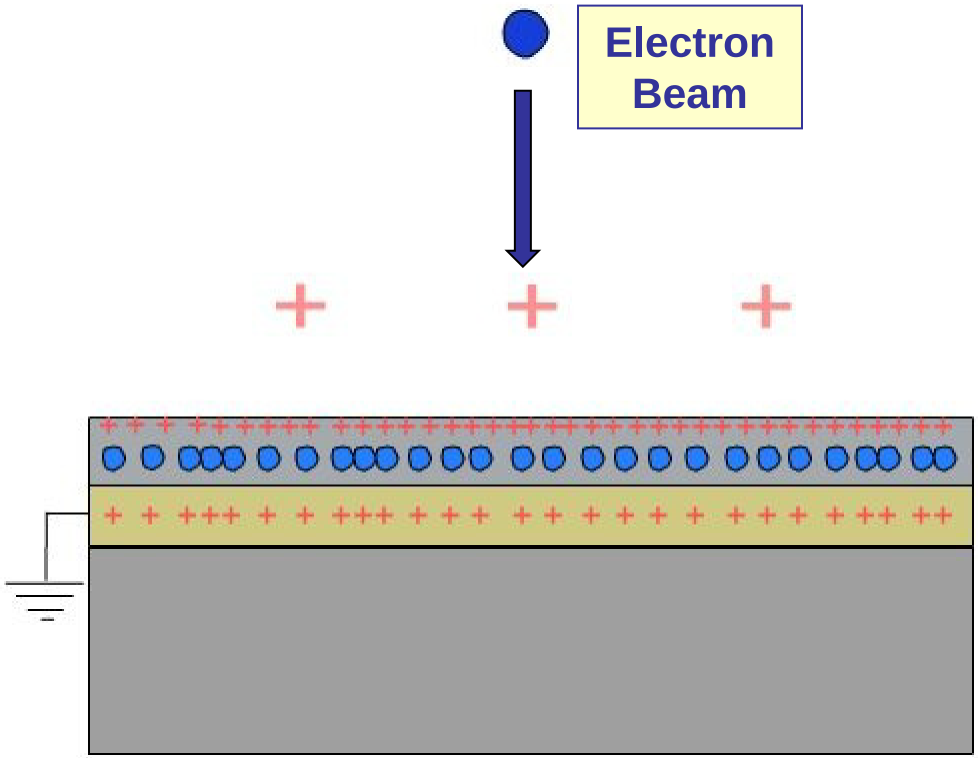


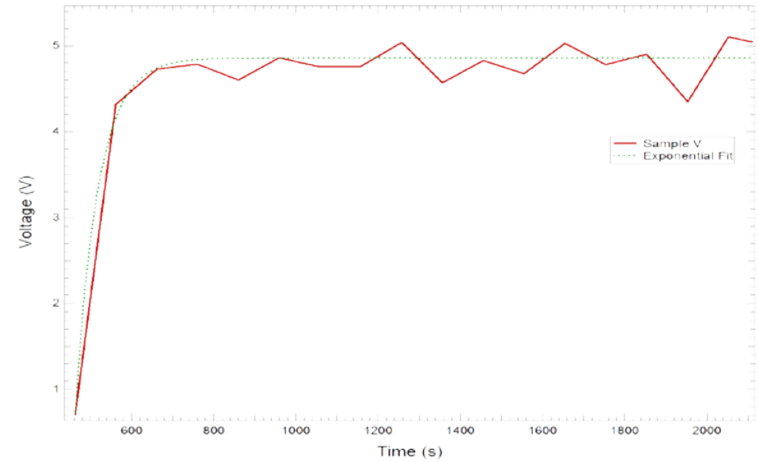
Charging Scenarios

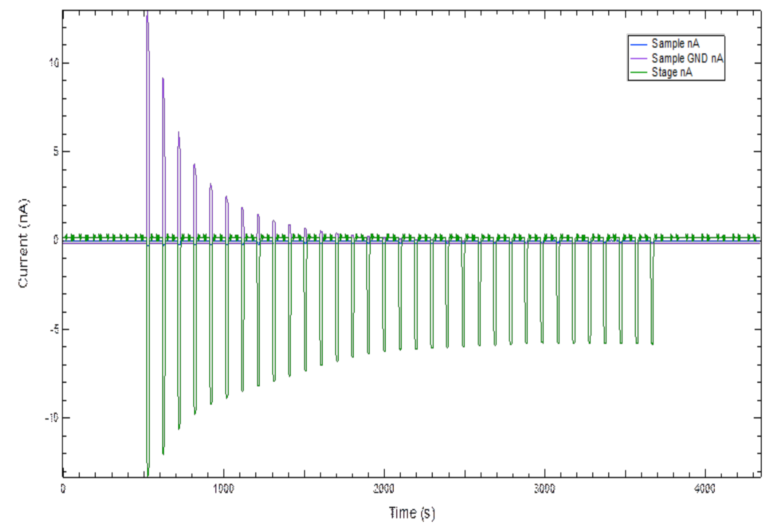
- Low Energy
  - Grounded
  - Ungrounded
- High Energy
  - Grounded
  - Ungrounded

1 cm Mirror sample

Low Energy - Grounded



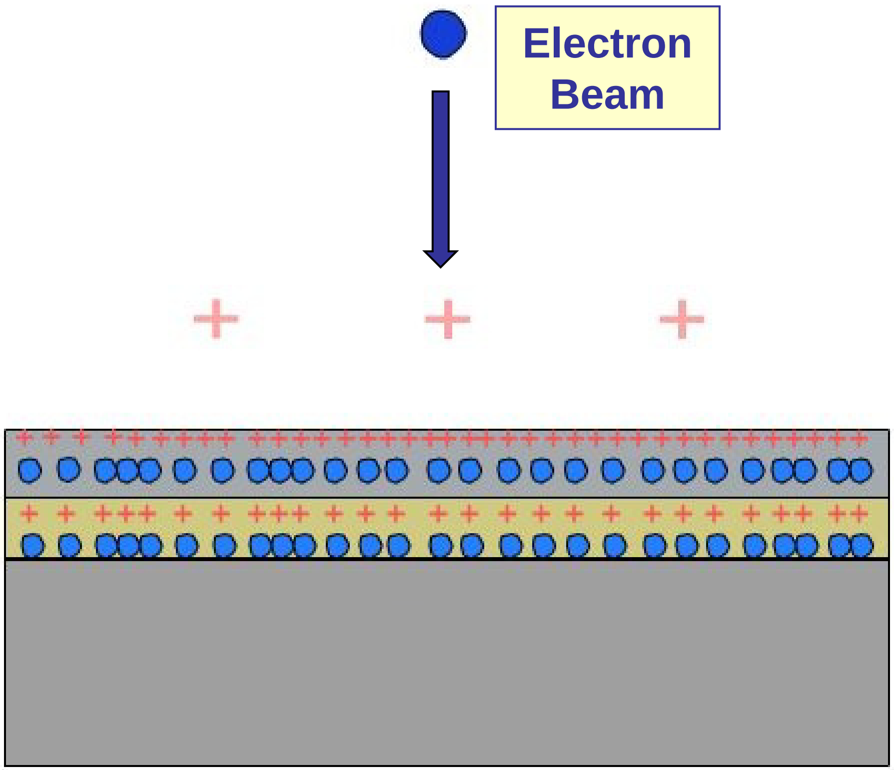


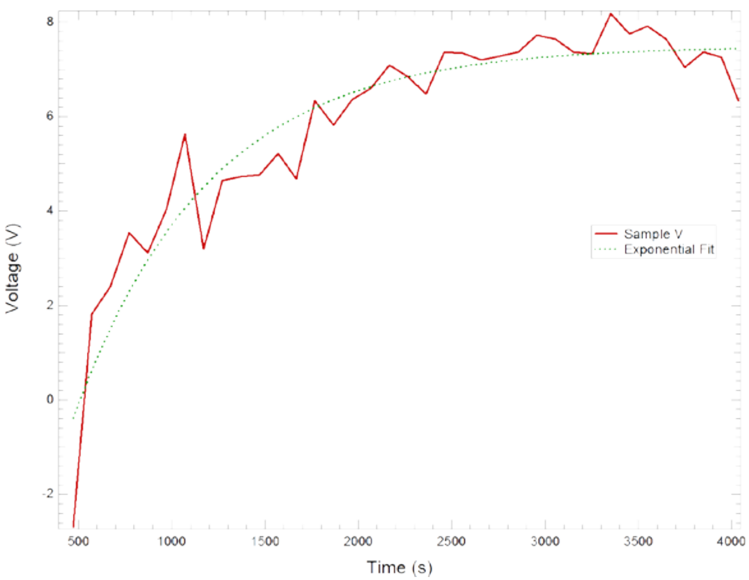


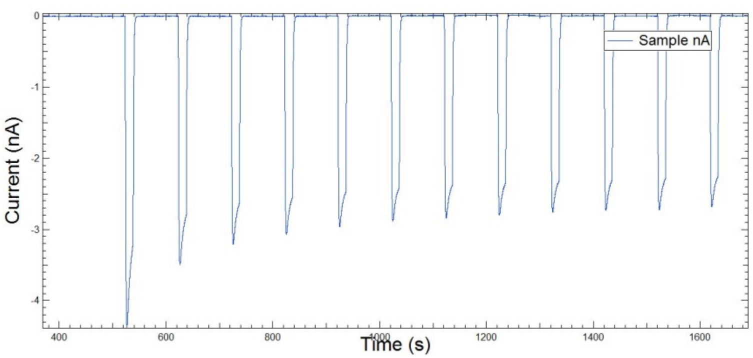
$$V_s(t) = V_o\left[1 - e^{-t\sigma_{DC}/\epsilon_o\epsilon_r}\right]$$

$$V_o = \frac{\bar{J}_0[1 - Y(E_b)]}{\sigma_{DC}} R(E_b) \frac{[D - R(E_b)]}{D}$$

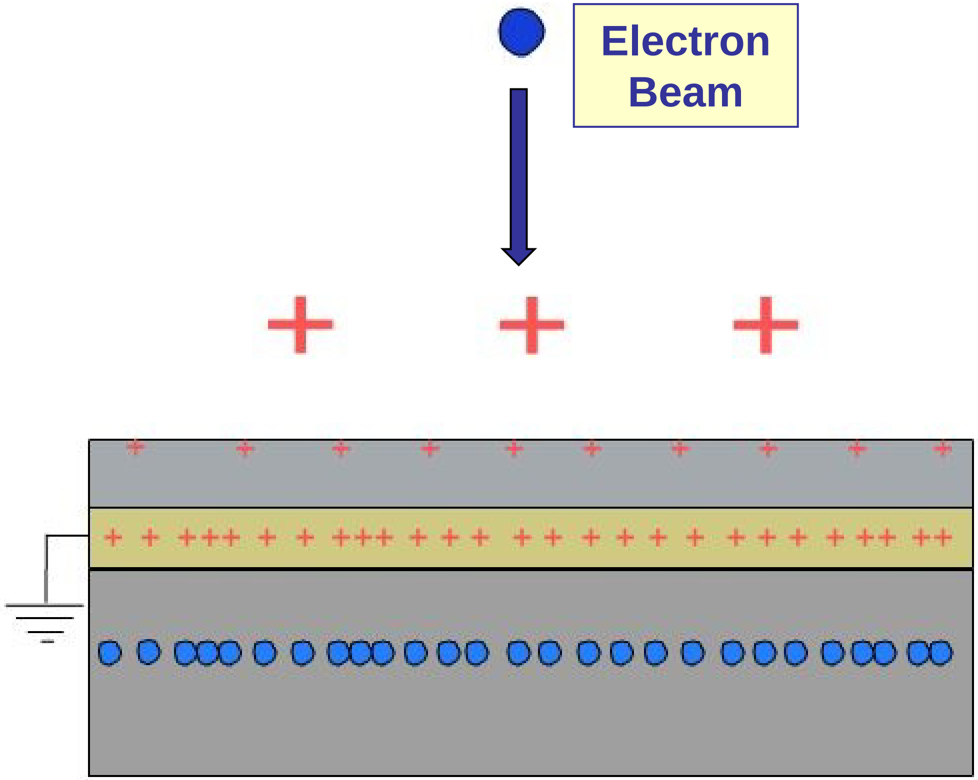
Low Energy - Ungrounded

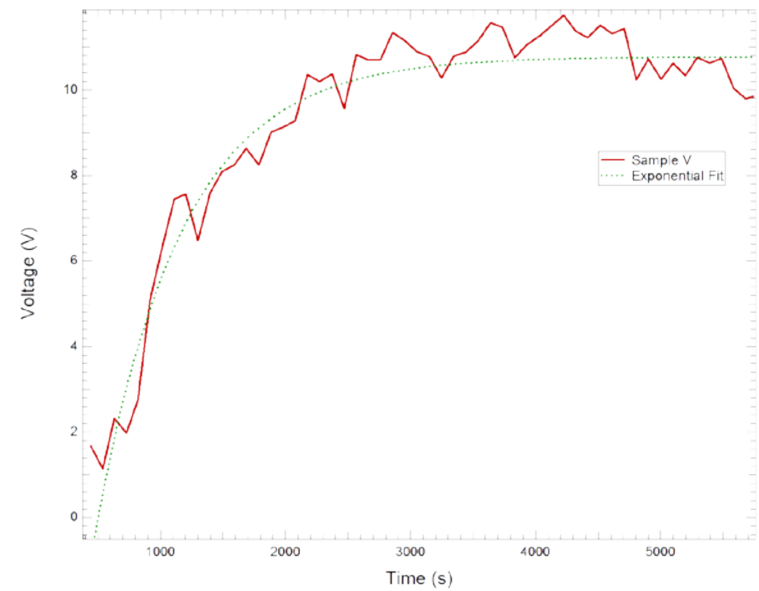


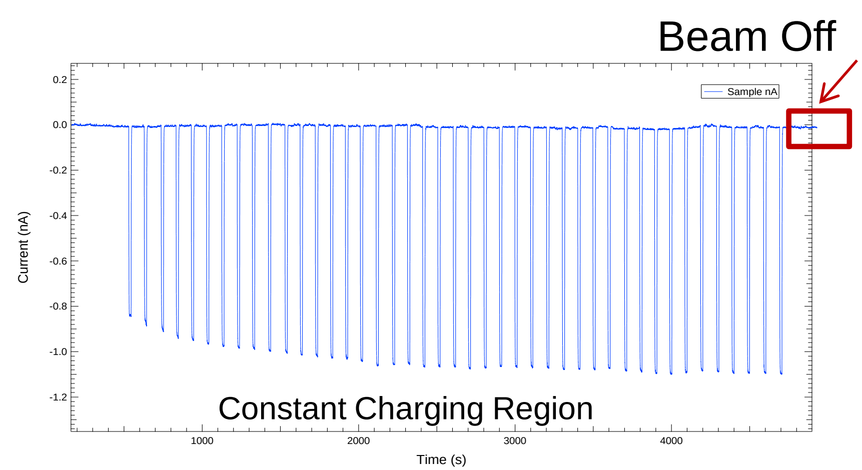




High Energy - Grounded







High Energy - Ungrounded

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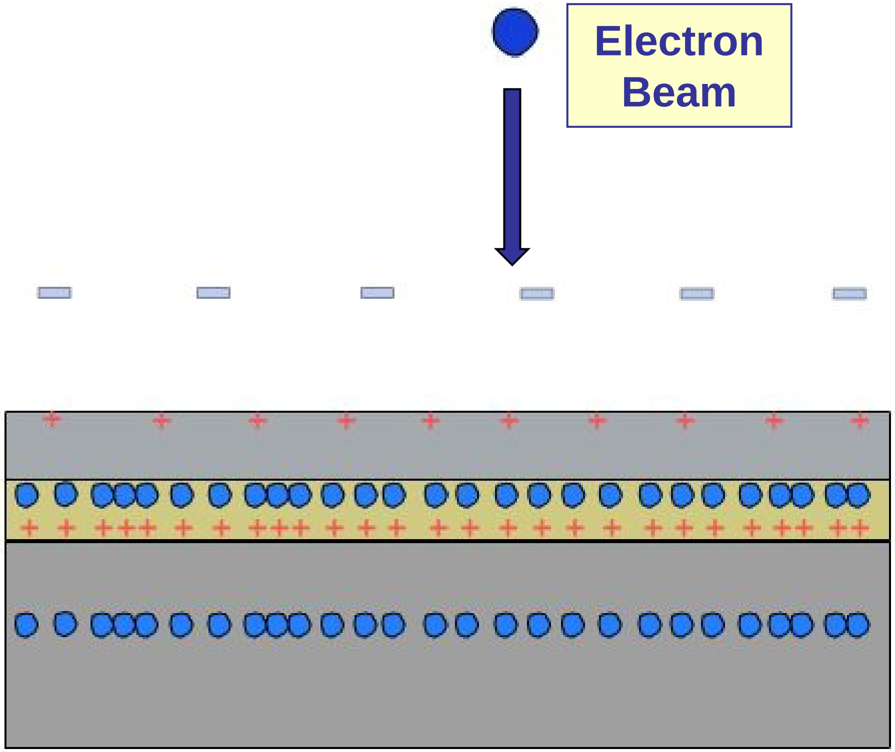
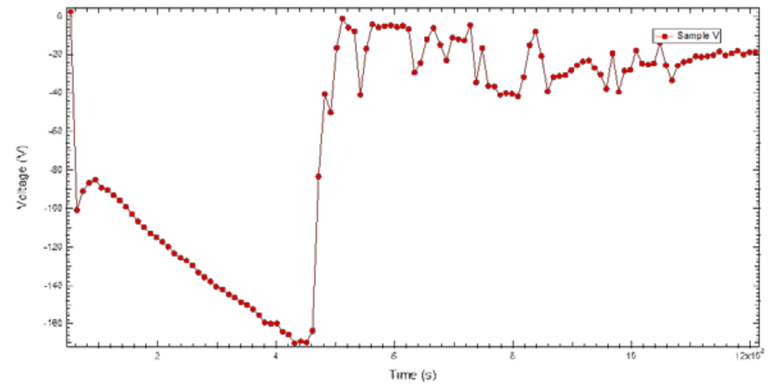
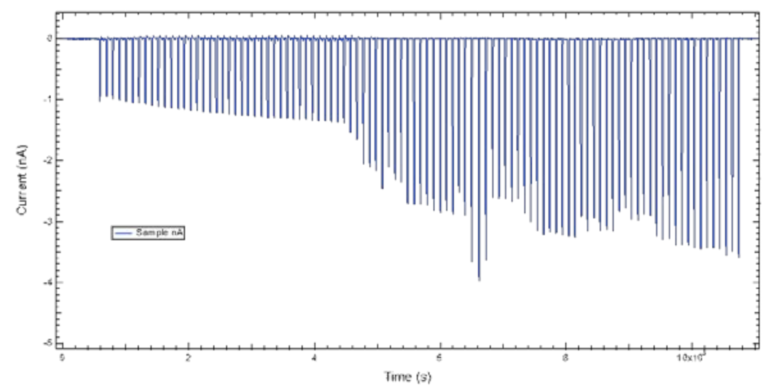
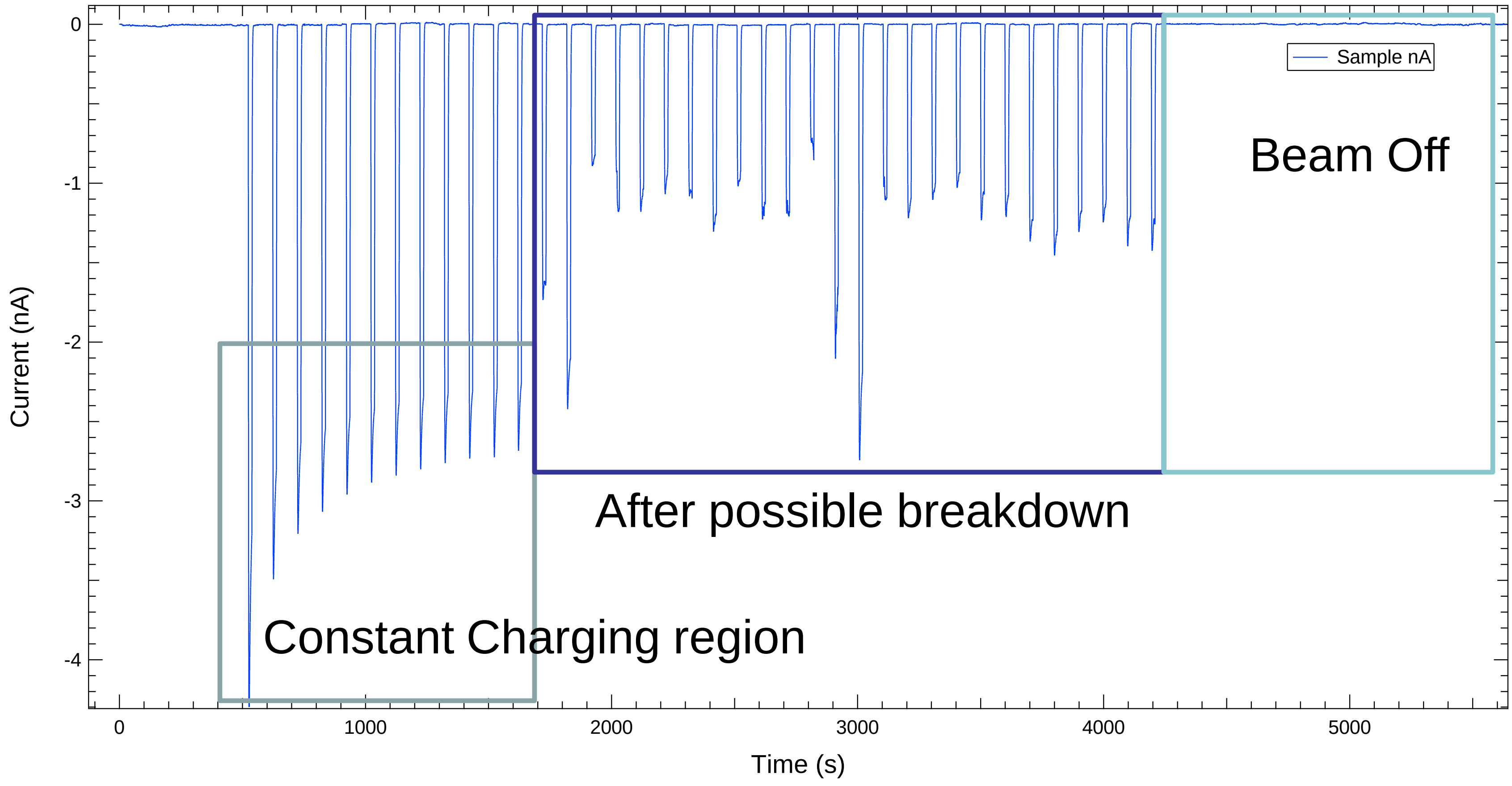




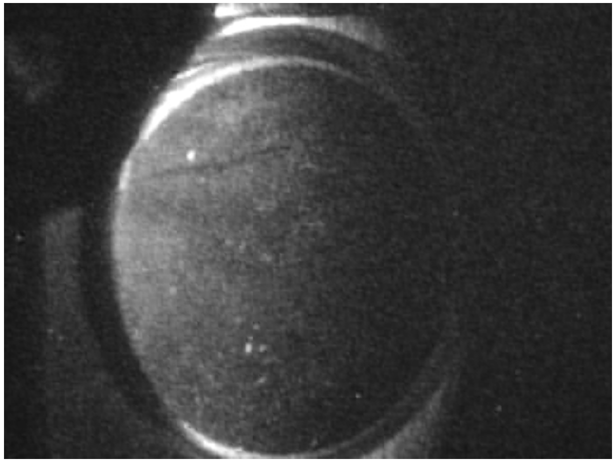


High negative net potentials led to breakdown and arcing

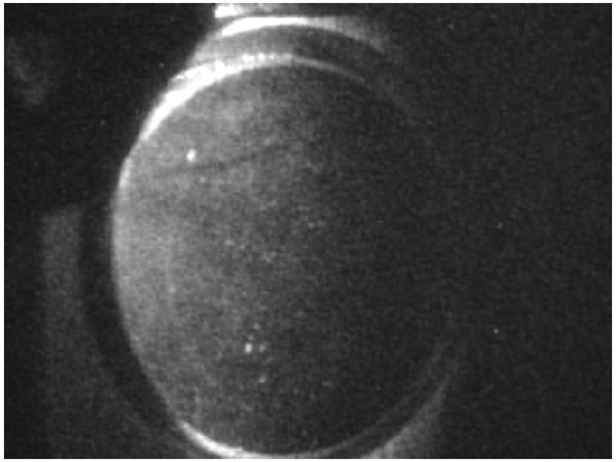
Ungrounded POM Mirror Test Results



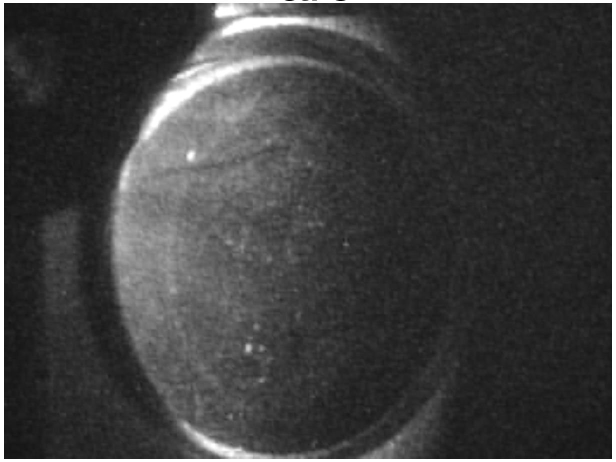
Example of POM Arc-Video



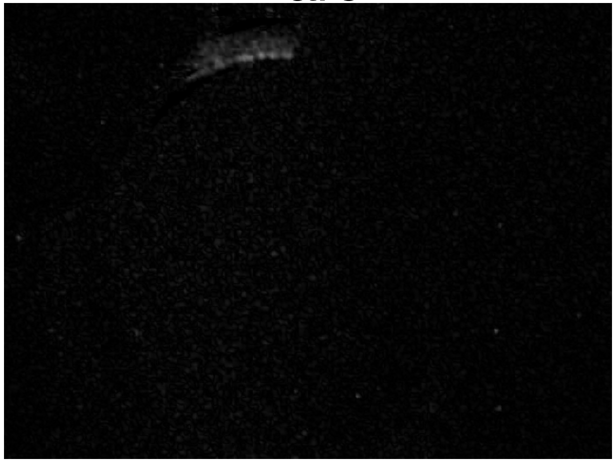
Frame before arc



Frame of arc



Frame after arc



Difference between frame before and frame of arc

An Extended Microscopic Model

Complete set of dynamic transport equations

$J = q_e n_e(z,t)\mu_e F(z,t) + q_e D \frac{dn_{tot}(z,t)}{dz}$ {Sum of electron drift and diffusion current densities J_i}

$\frac{\partial}{\partial z} F(z,t) = q_e n_{tot}/\epsilon_0 \epsilon_r$ {1D Gauss's Law}

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

{1D Continuity equation with drift, diffusion and source terms}

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

{1D hole continuity equation with Generation and recombination terms}

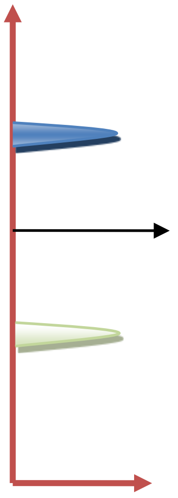
$$\frac{dn_t(z,\varepsilon,t)}{dt} = \alpha_{et} n_e(z,t)[N_t(z,\varepsilon) - n_t(z,\varepsilon,t)] - \alpha_{te} N_e exp\left[-\frac{\varepsilon}{kT}\right] n_t(z,\varepsilon,t)$$

{1D trapping continuity equation for electrons}

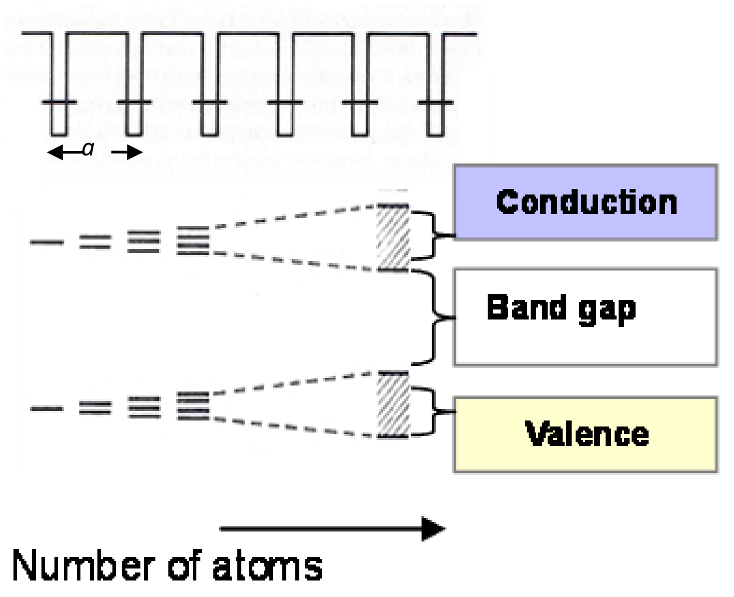
A quantum mechanical model
of the spatial and energy distribution of the electron states

Band Theory of (Crystalline) Conductors, Insulators and Semiconductors

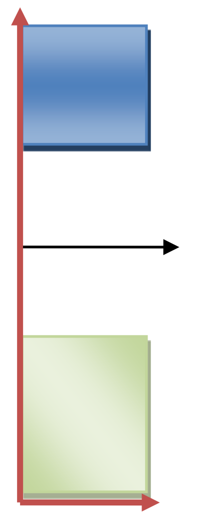
Atom
Density of States

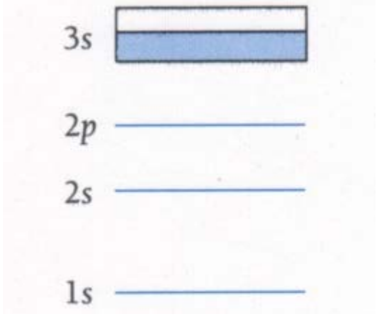


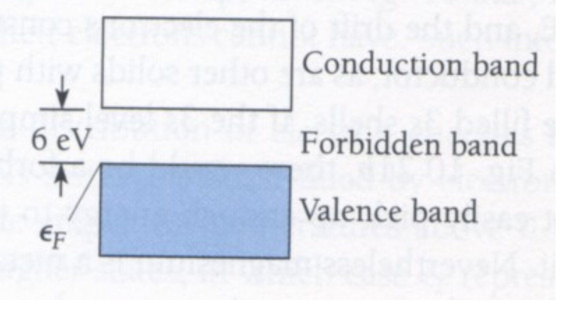
Groups of Atoms

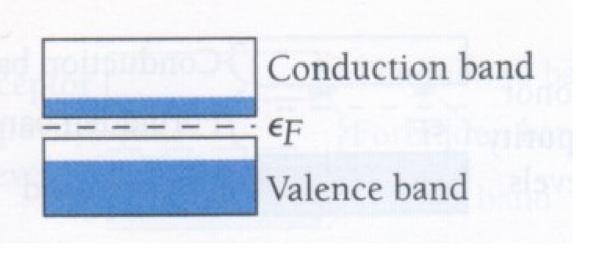


Lattice
Density of States







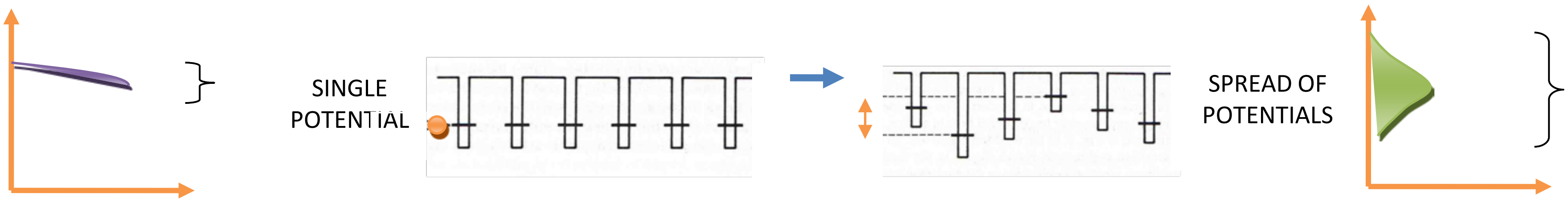


Conductor
Partially filled bands

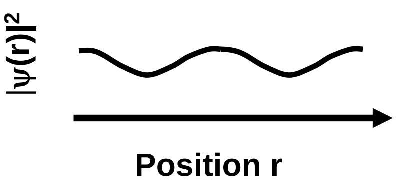
Insulator
Completely filled bands

Semiconductor
Insulators at finite T

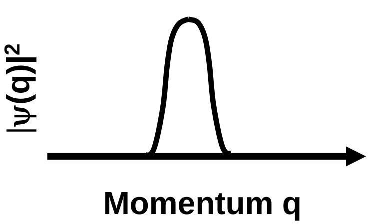
Disorder introduces localized states

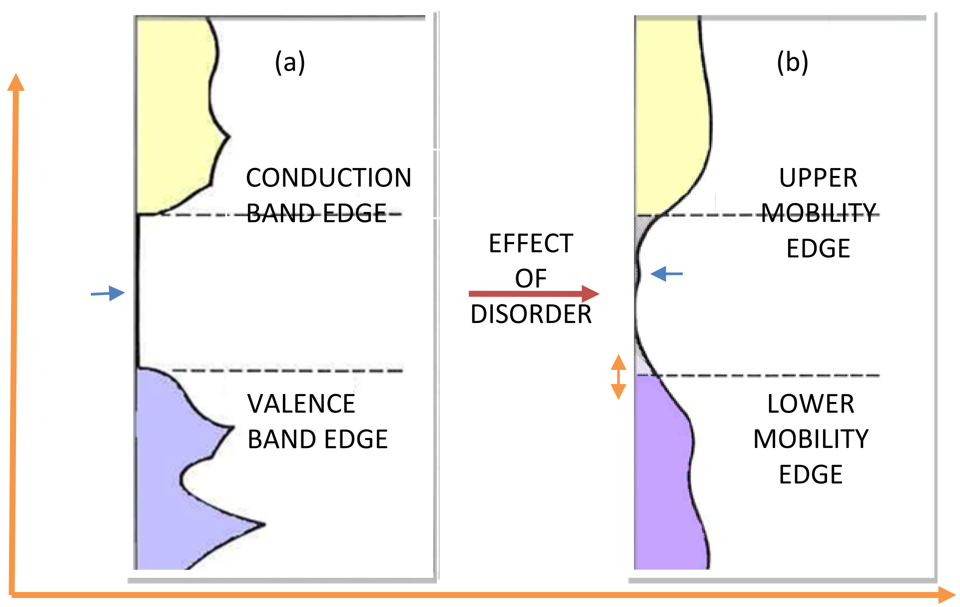


Delocalized in real space

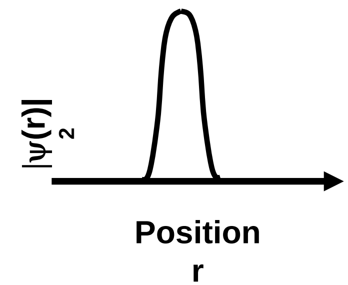


Localized in momentum space

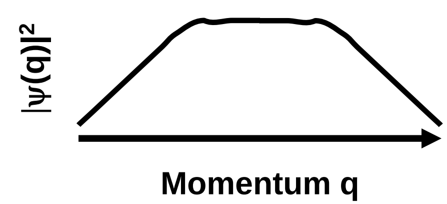




Localized in real space



Delocalized in momentum space

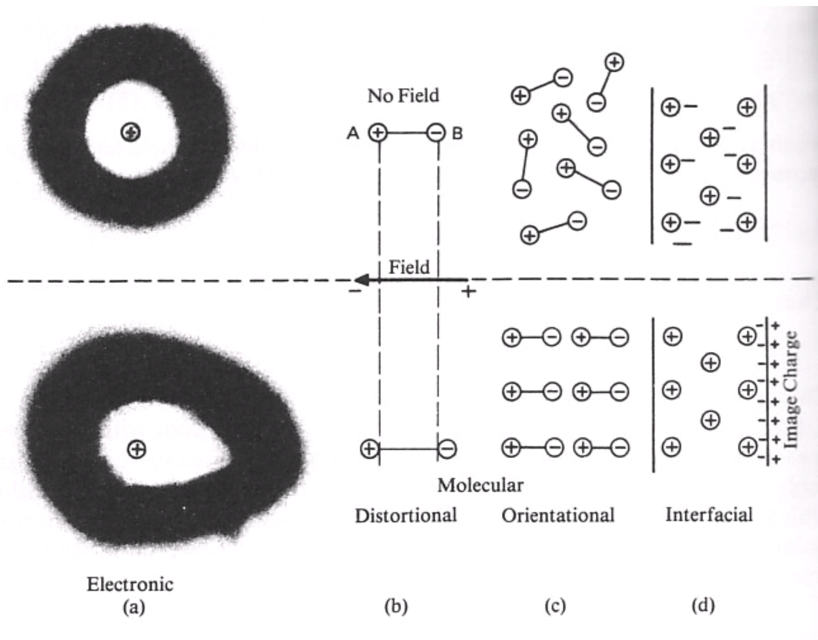


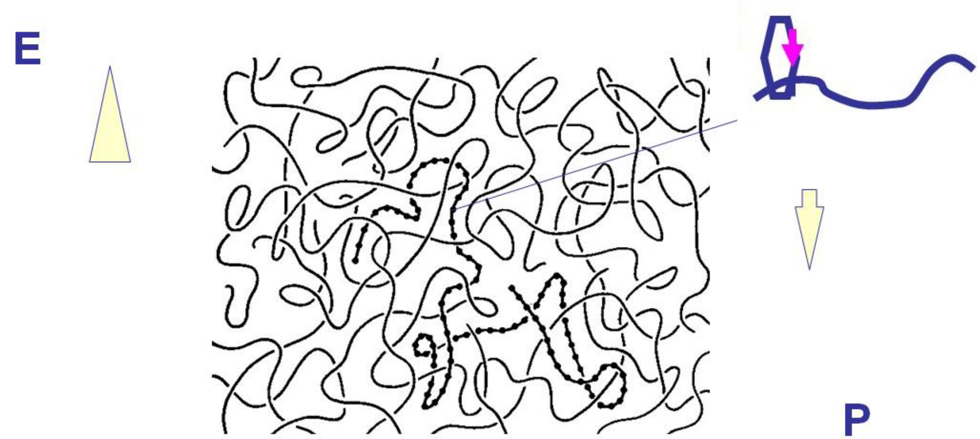
Conductivity in Highly Disordered Insulation Materials

$$\sigma(t) = \sigma_{DC} + \sigma_{Polarization}(t) + \sigma_{Diffusion}(t) + \sigma_{Dispersion}(t) + \sigma_{Transit}(t) + \sigma_{RIC}(t)$$

Polarization

$$\sigma^{o}_{Pol}e^{-t/\tau_{Pol}}$$





Drift and hopping conductivity

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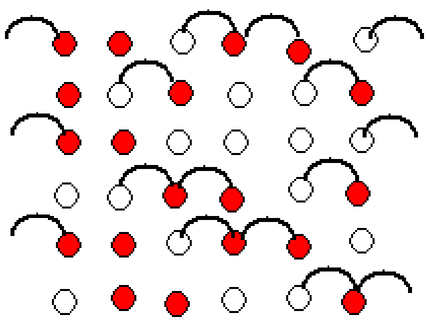
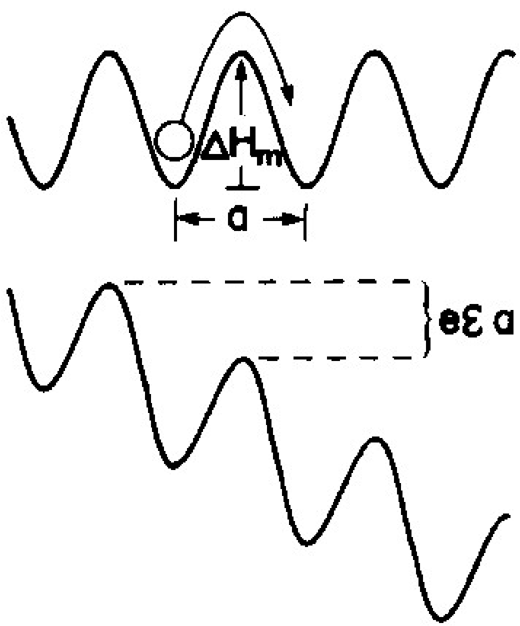
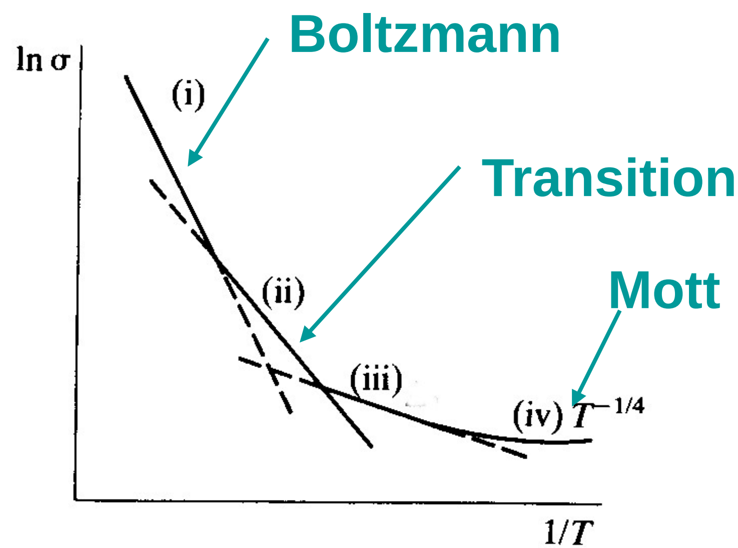
$$\sigma(t) = \sigma_{DC} + \sigma_{Polarization}(t) + \sigma_{Diffusion}(t) + \sigma_{Dispersion}(t) + \sigma_{Transit}(t) + \sigma_{RIC}(t)$$

$$\sigma^{o}_{Diff}\, t^{-1}$$

$$\sigma_{hop}(E,T) = \left[\frac{2 \cdot n(T) \cdot \nu \cdot a \quad \cdot e}{E}\right] \exp\left[\frac{-\Delta H}{k_B \cdot T}\right] \sinh\left[\frac{\varepsilon \cdot E \cdot a}{2 \cdot k_B \cdot T}\right]$$





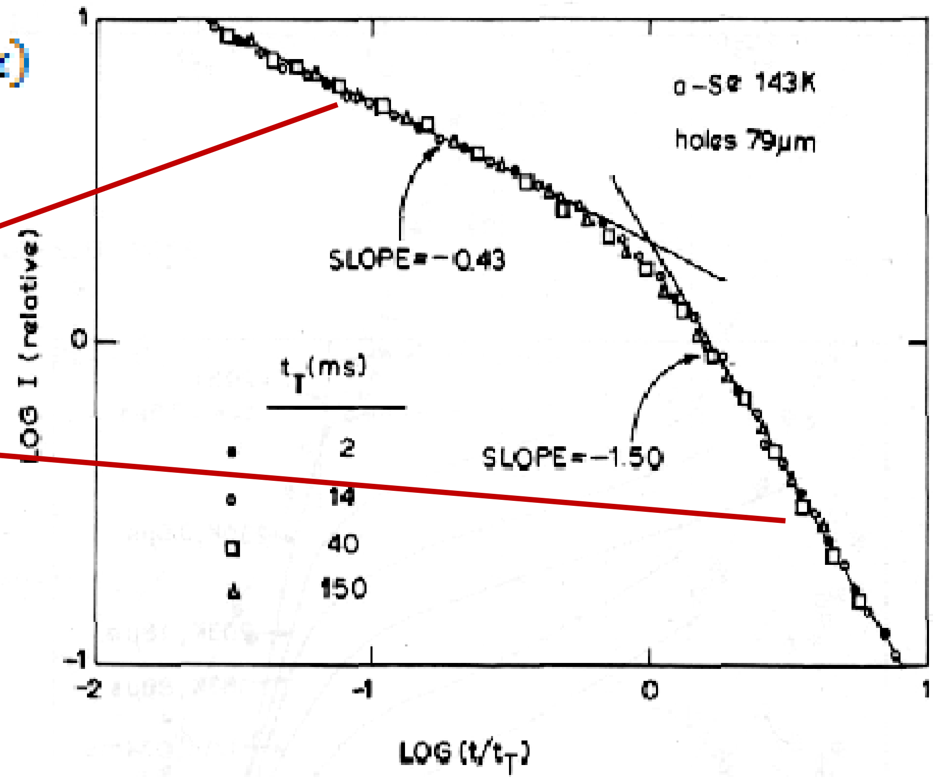


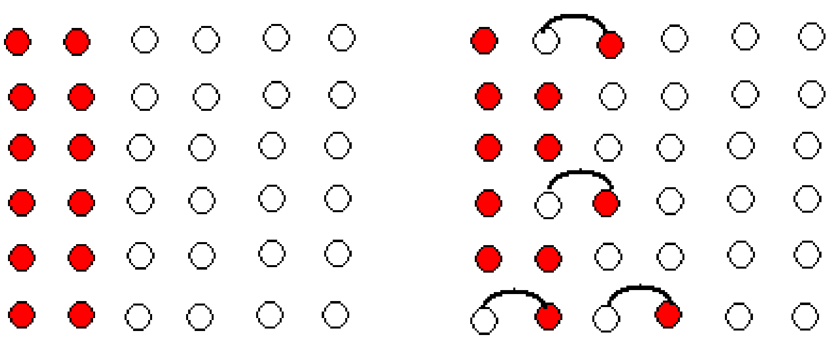
Dispersive transport

$$\sigma(t) = \sigma_{DC} + \sigma_{Polarization}(t) + \sigma_{Diffusion}(t) + \sigma_{Dispersion}(t) + \sigma_{Transit}(t) + \sigma_{RIC}(t)$$

$$\sigma^{o}_{Disp}\, t^{-(1-\alpha)} + \sigma^{o}_{Trans}\, t^{-(1+\alpha)}$$

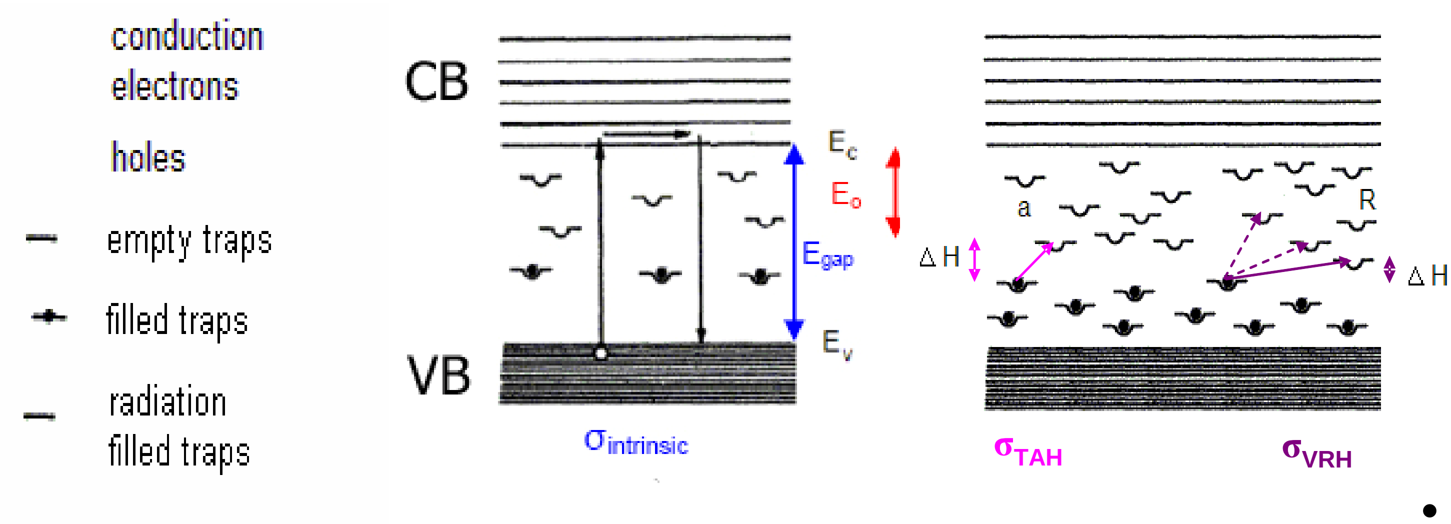
$$I(t) \sim \begin{cases} t^{-(1-\alpha)}, & t < t_T \\ t^{-(1+\alpha)}, & t > t_T \end{cases}$$



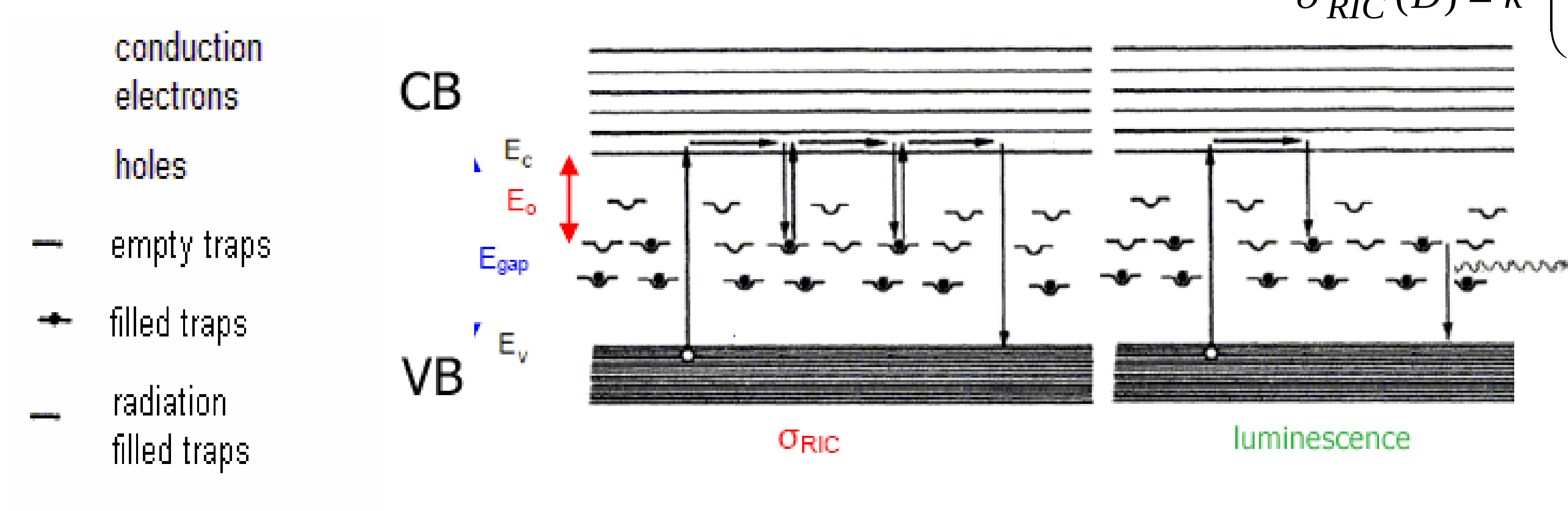


RIC and Luminescence

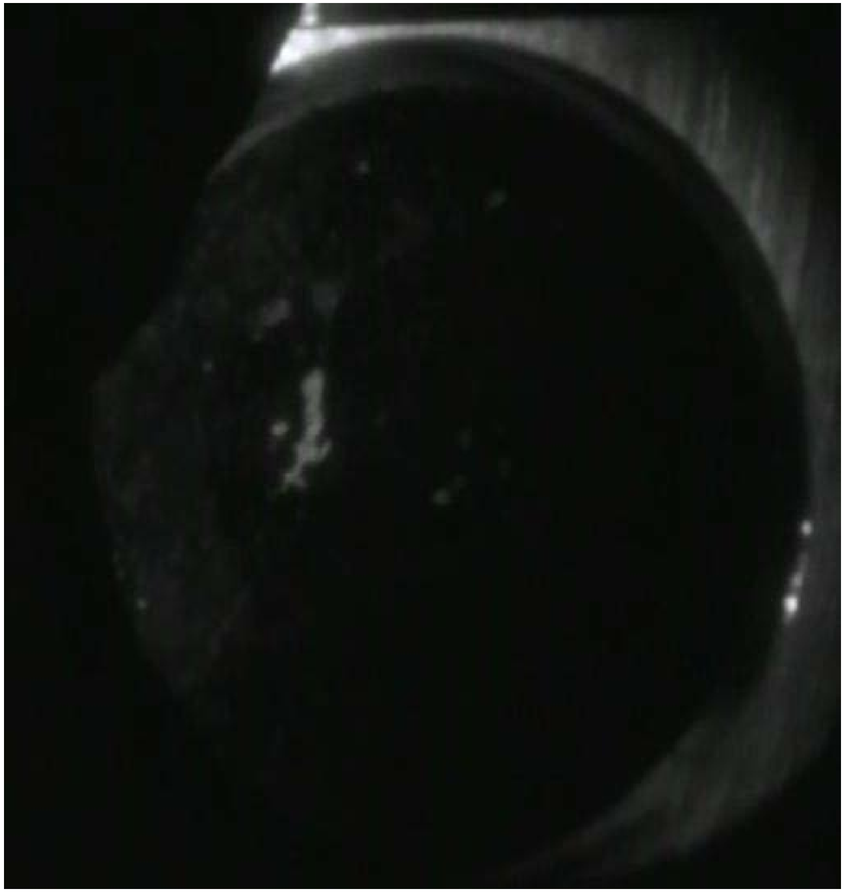
$$\sigma(t) = \sigma_{DC} + \sigma_{Polarization}(t) + \sigma_{Diffusion}(t) + \sigma_{Dispersion}(t) + \sigma_{Transit}(t) + \sigma_{RIC}(t)$$



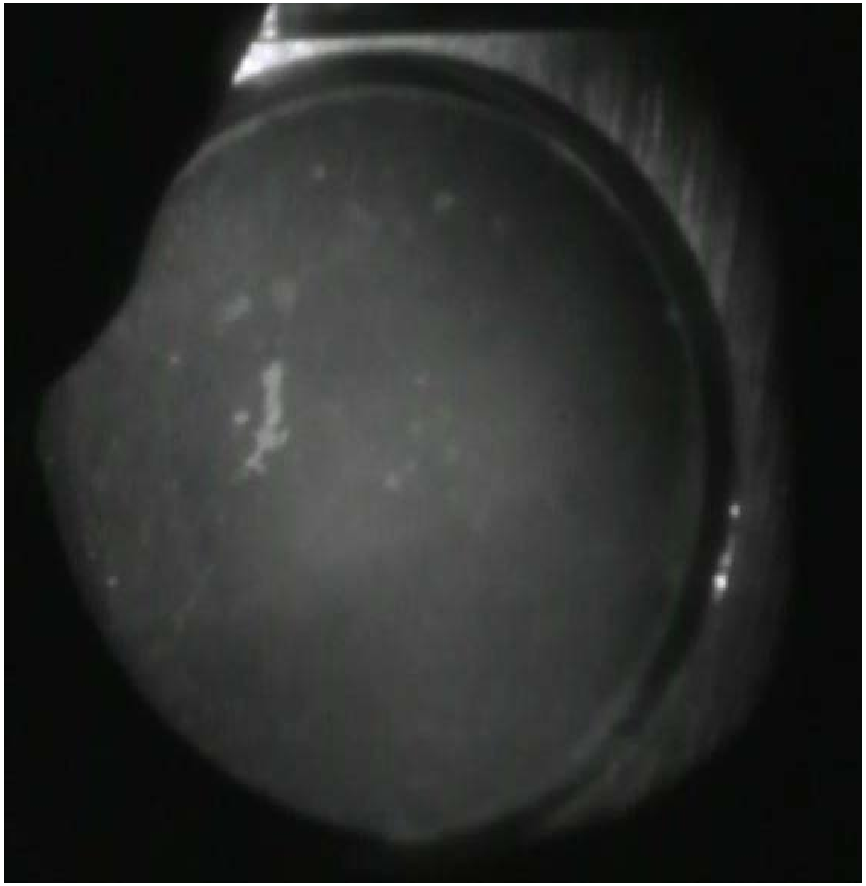
$$\sigma_{RIC}(\dot{D}) = k \cdot \left(\dot{D}\right)^{\Delta}$$



Electron-Induced Luminescence of SiO_2 Mirror

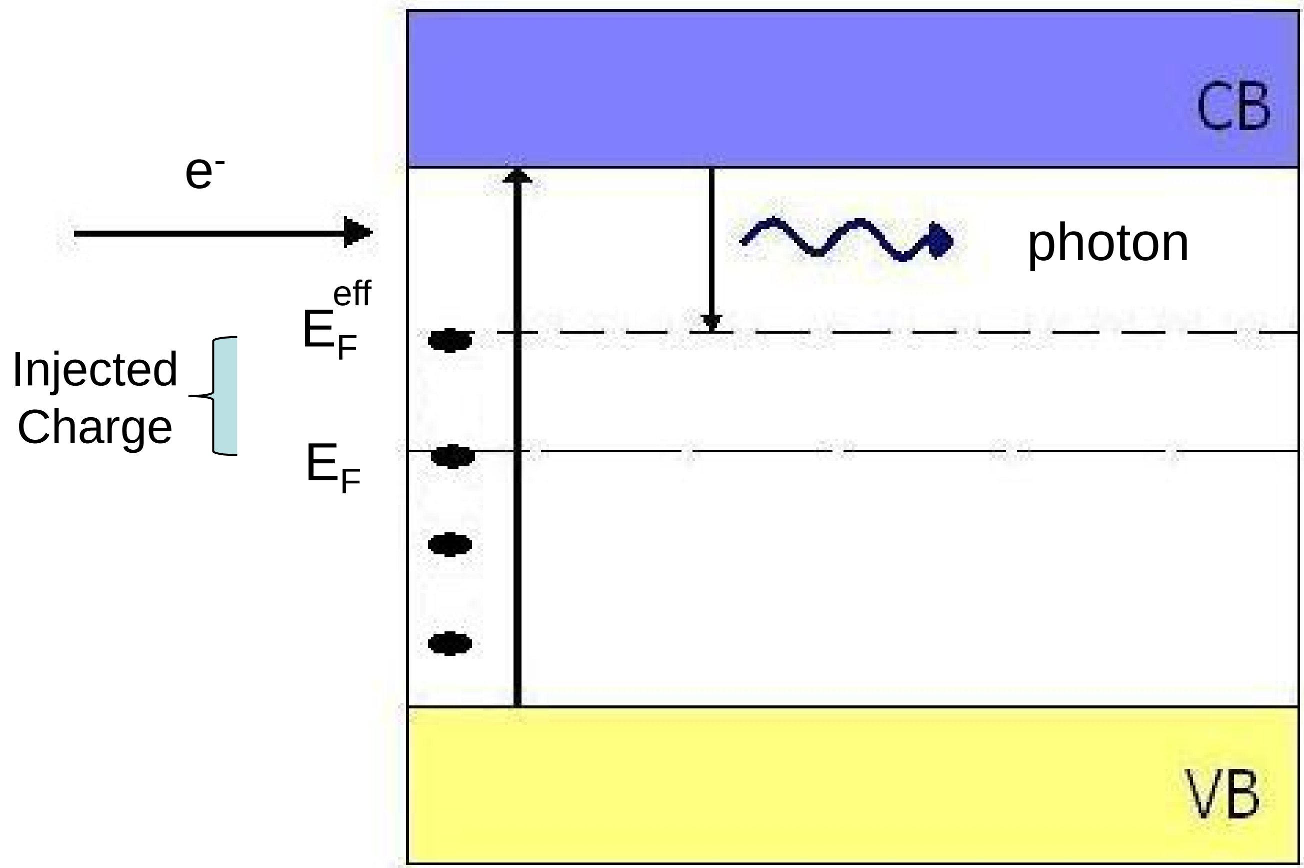


Beam off

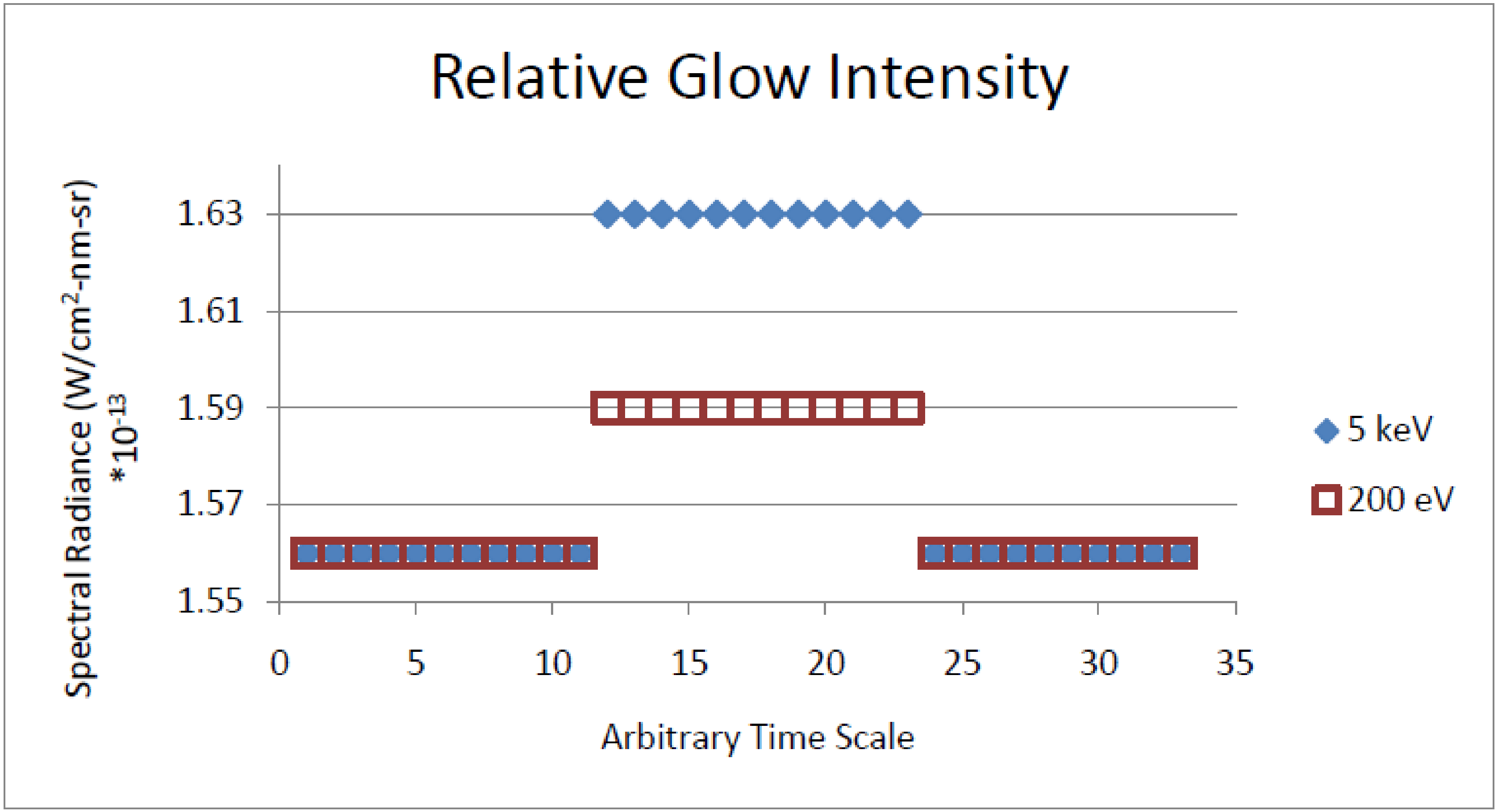


Beam on

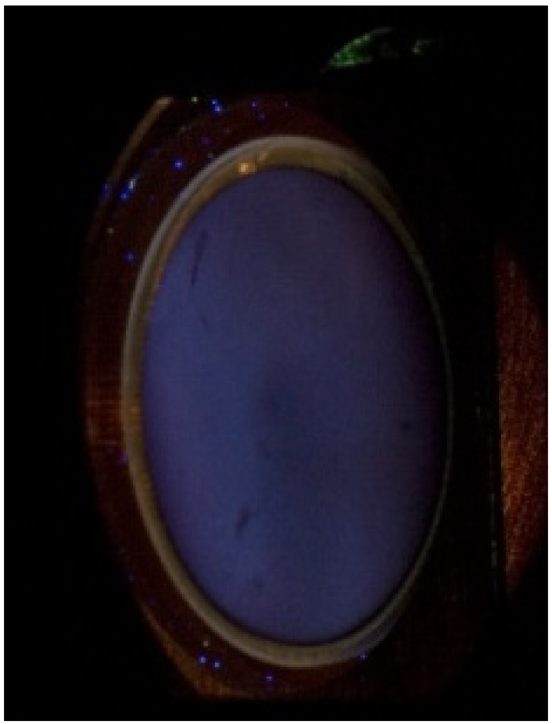
Luminescence: Excitation and Relaxation

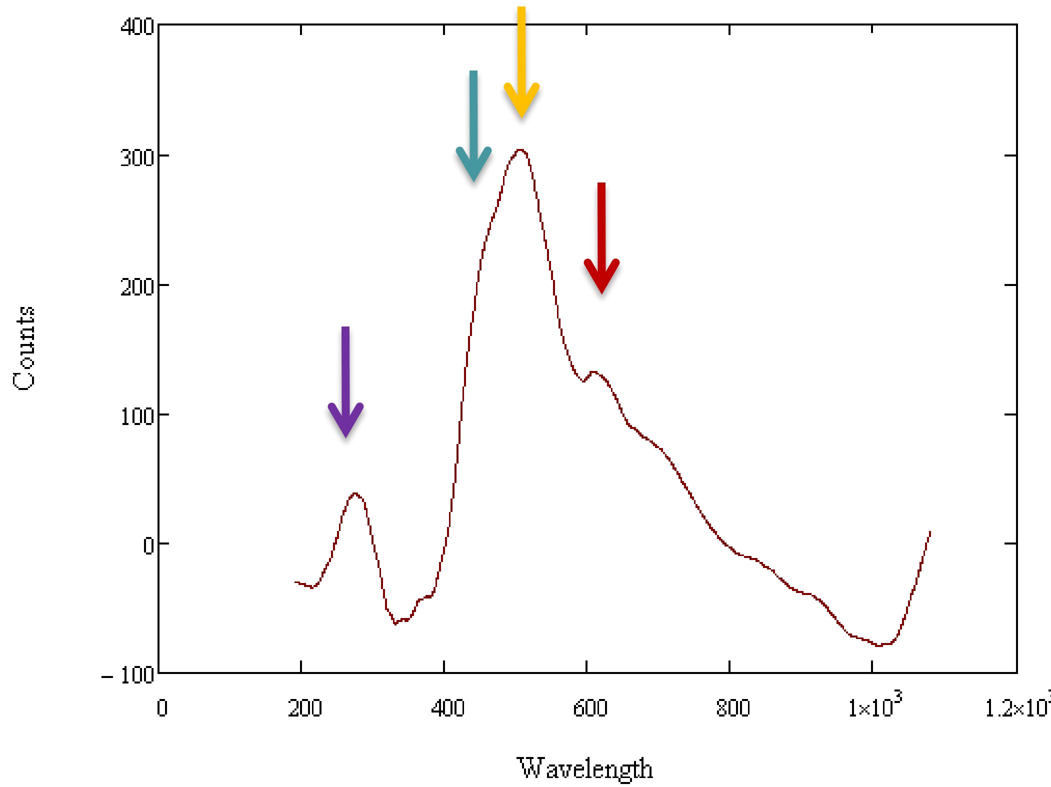


Luminescence: Effect of Beam Energy

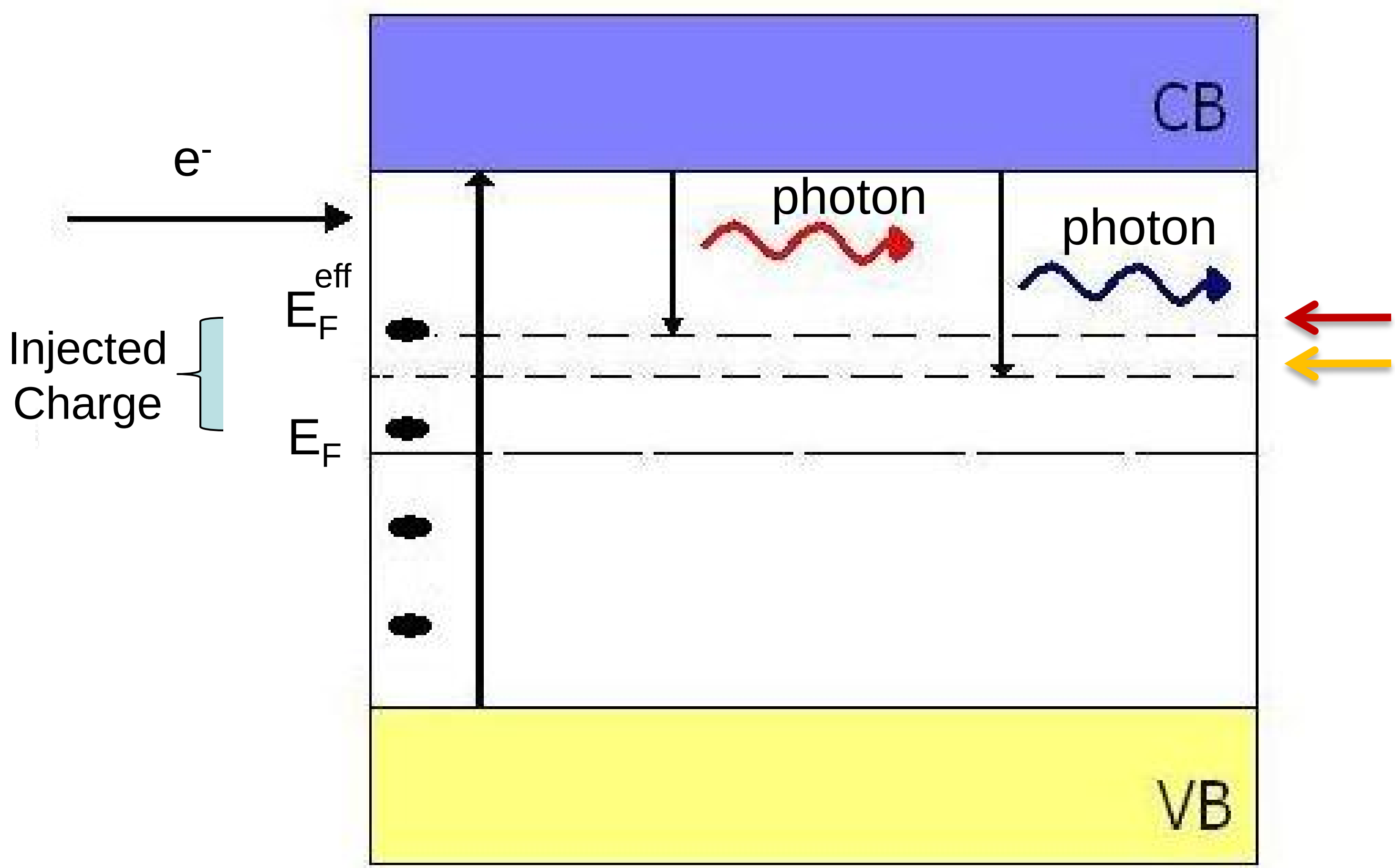


Multi-Photon Luminescence

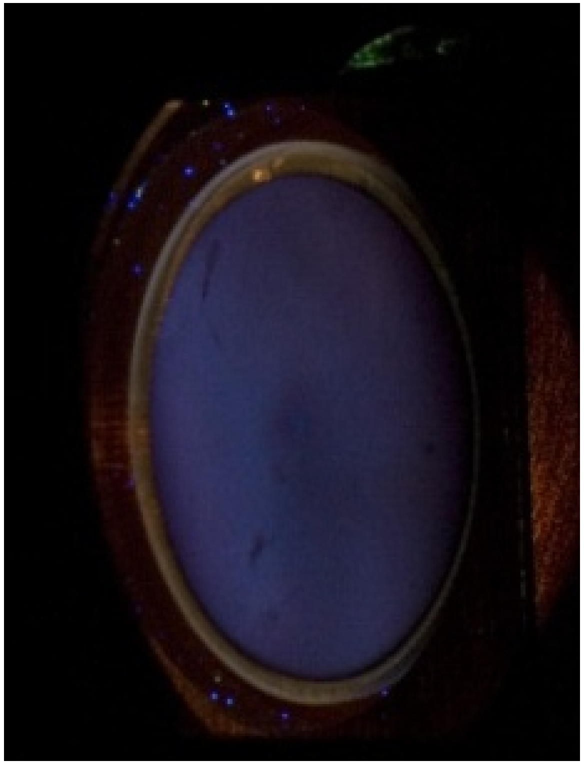




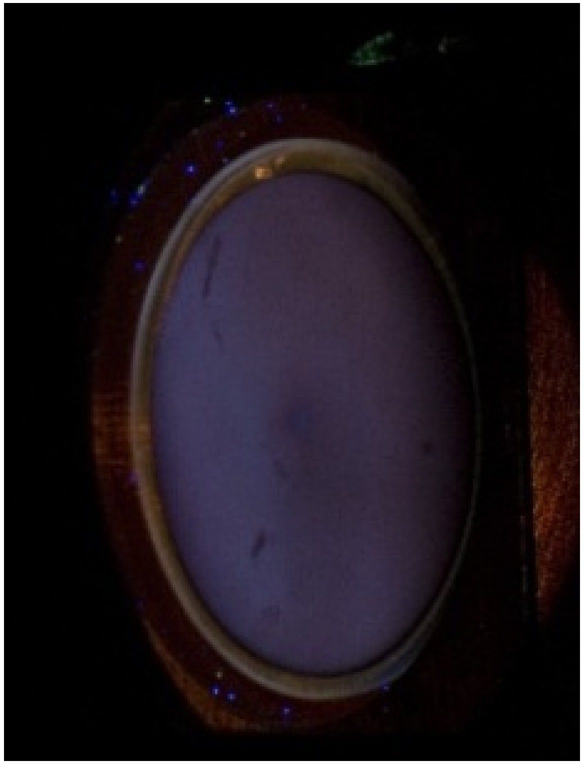
Multi-Photon Relaxation



Luminescence: Temperature Dependence



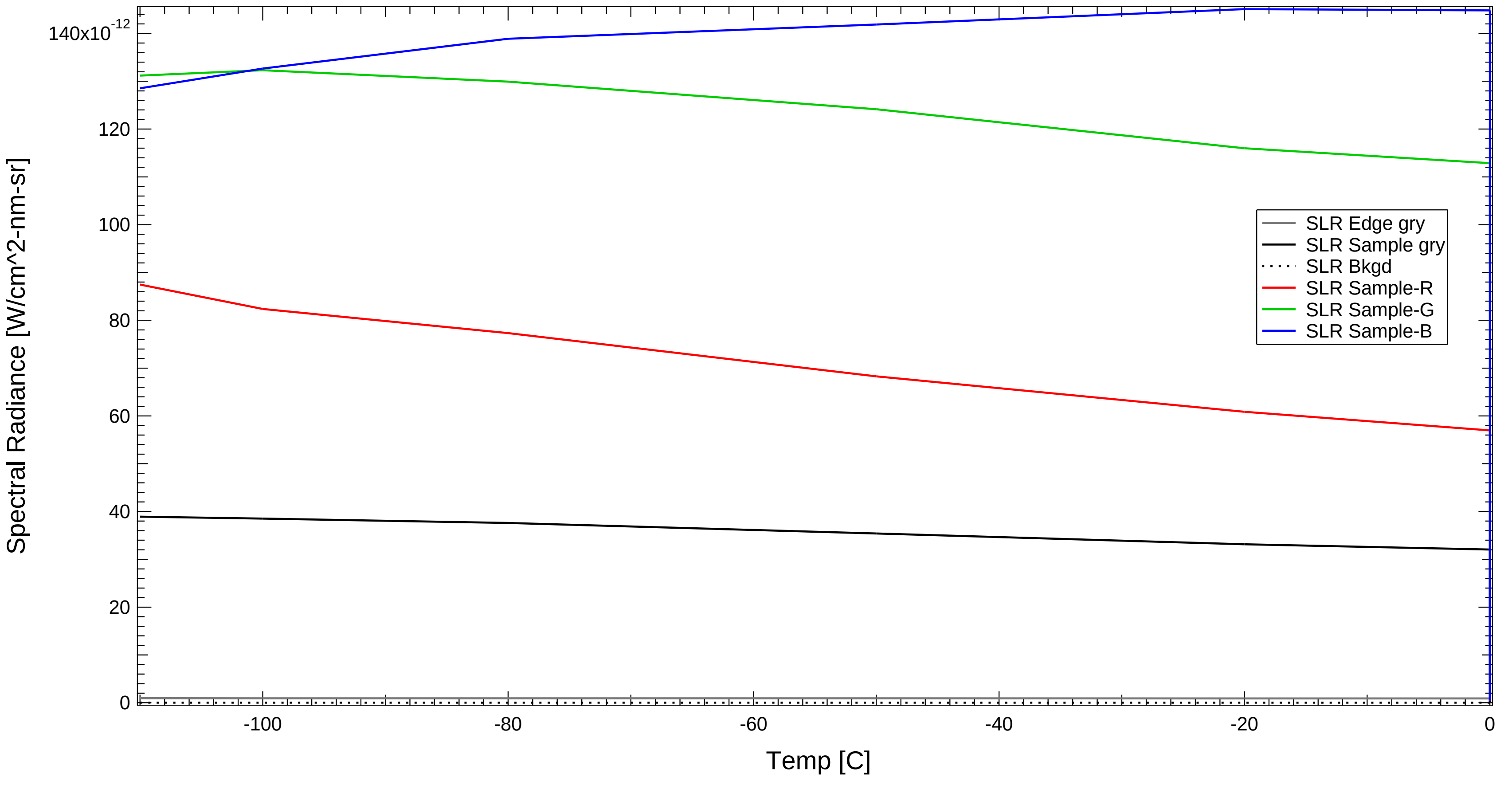
-4 C



-80 C

-110 C

SLR Spectral Radiance vs Temperature

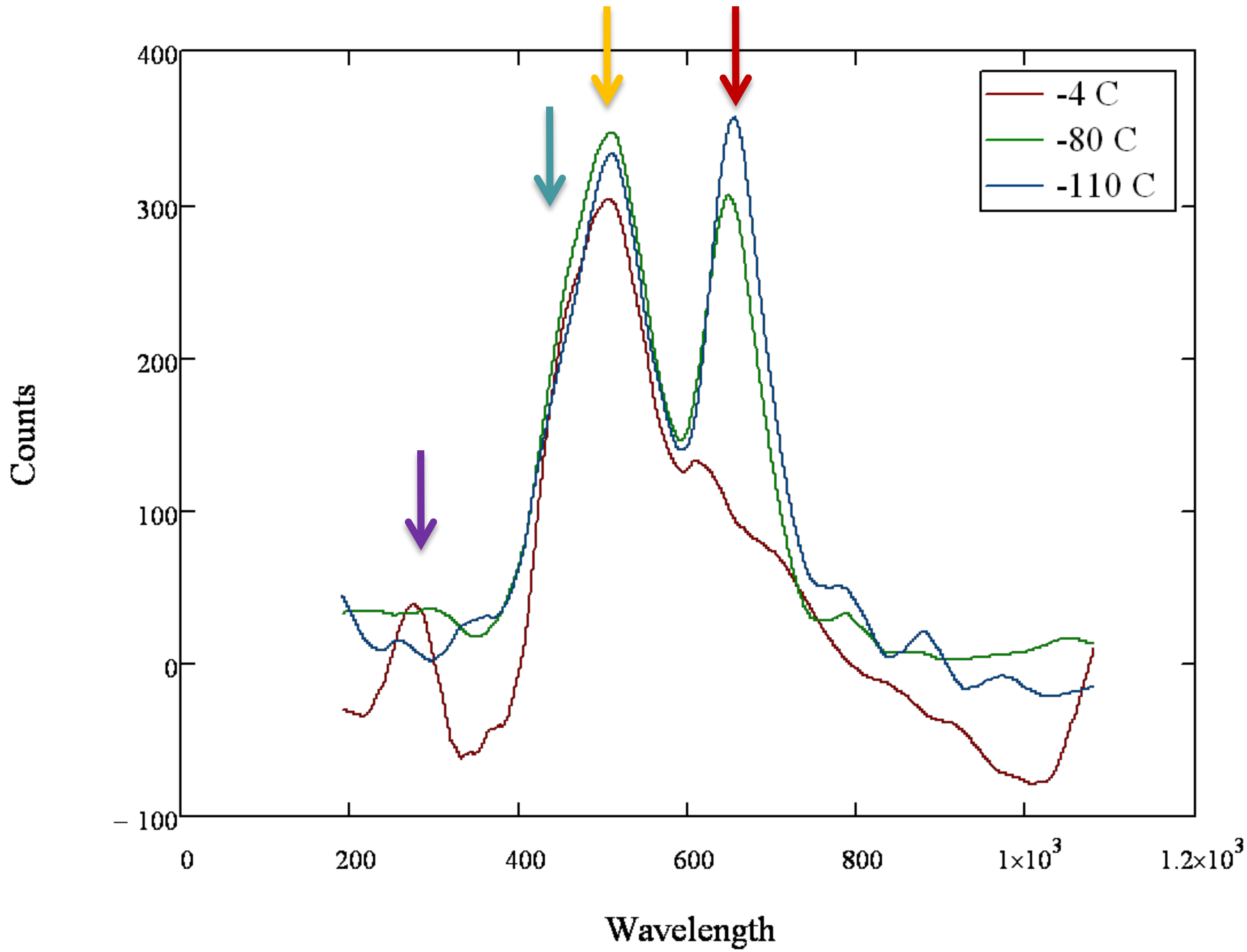


Blue increases with increasing T

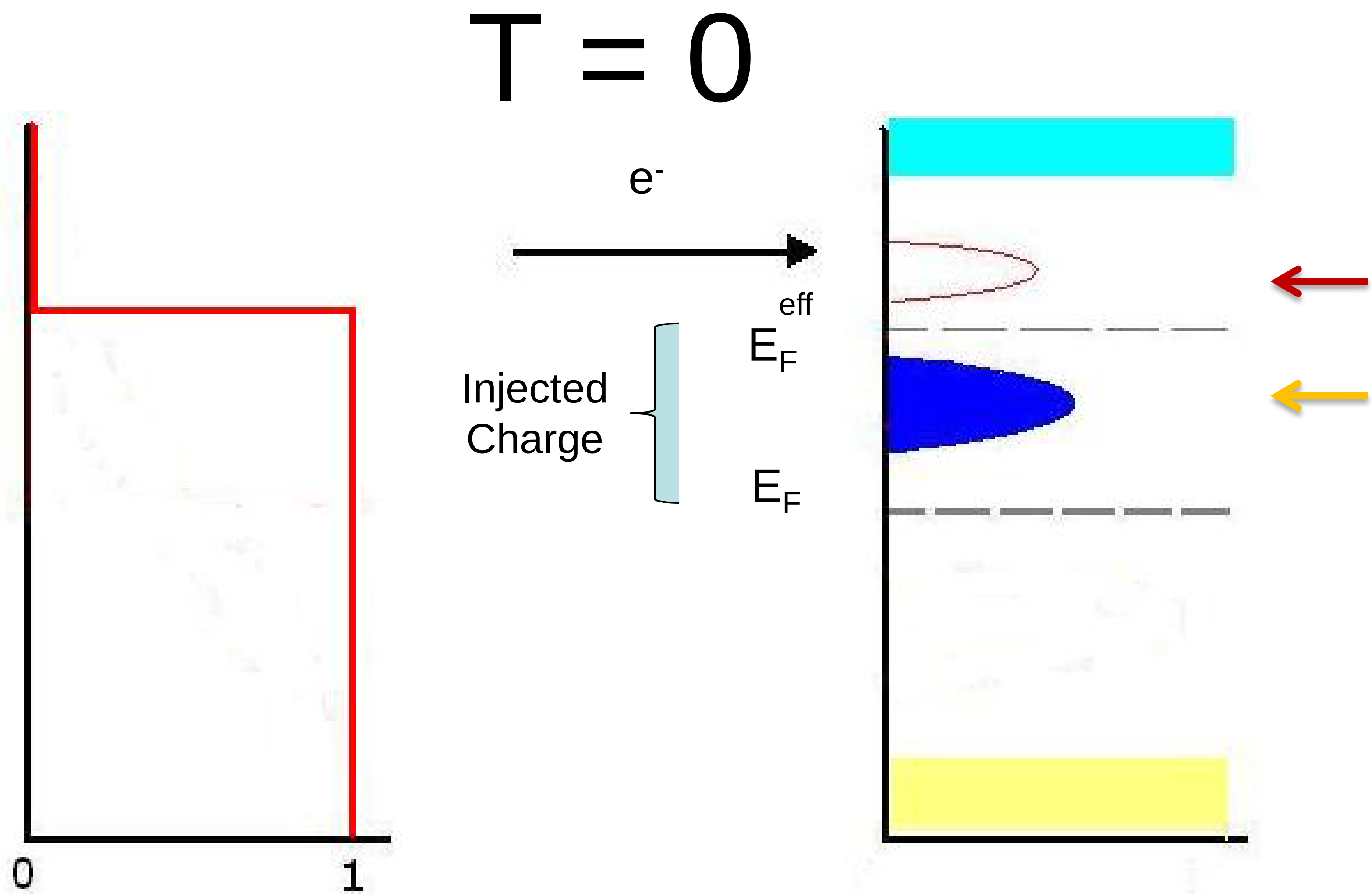
Green decreases with increasing T

Red decreases with increasing T

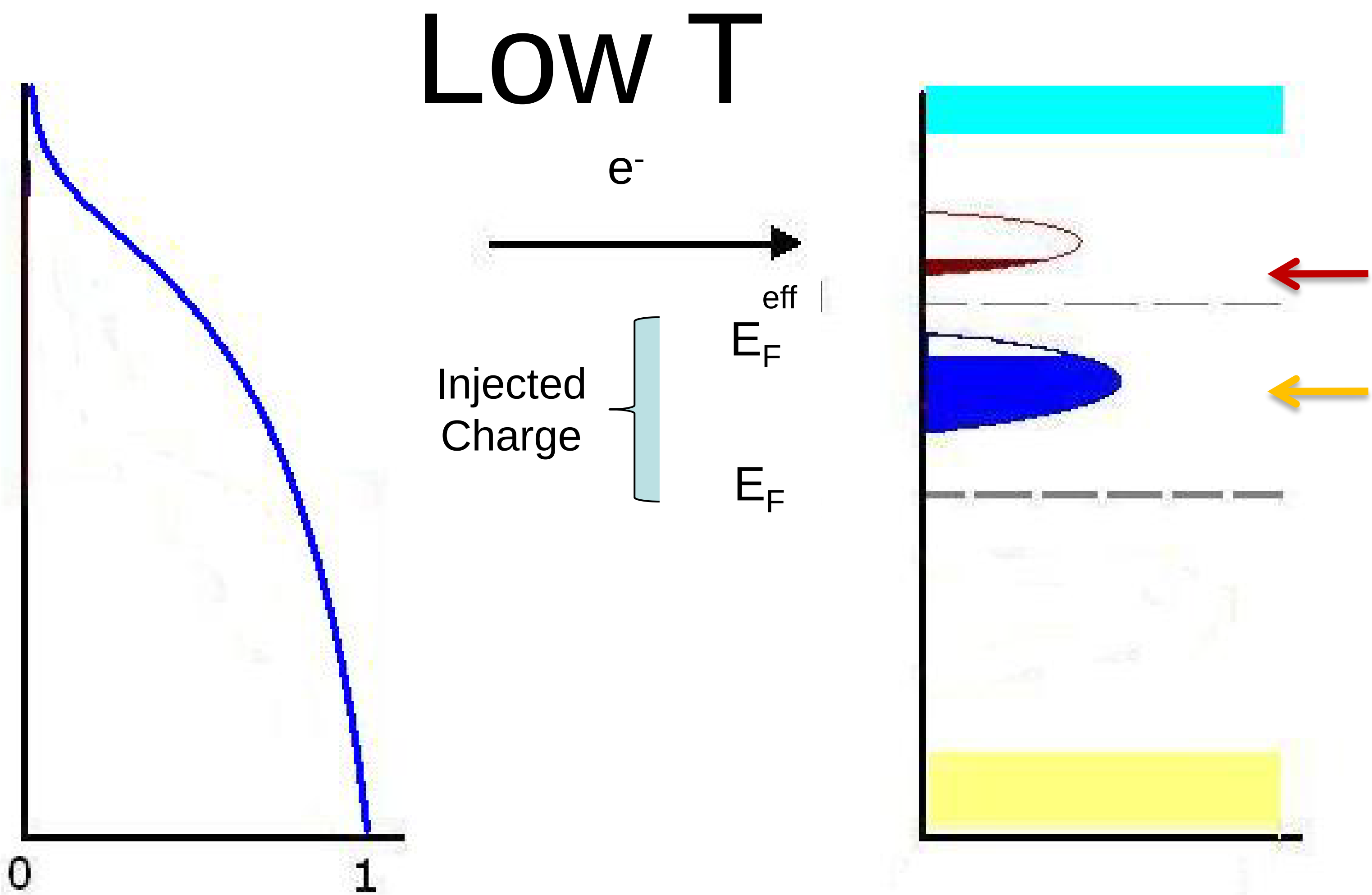
Temperature Dependent UV-Vis Spectra



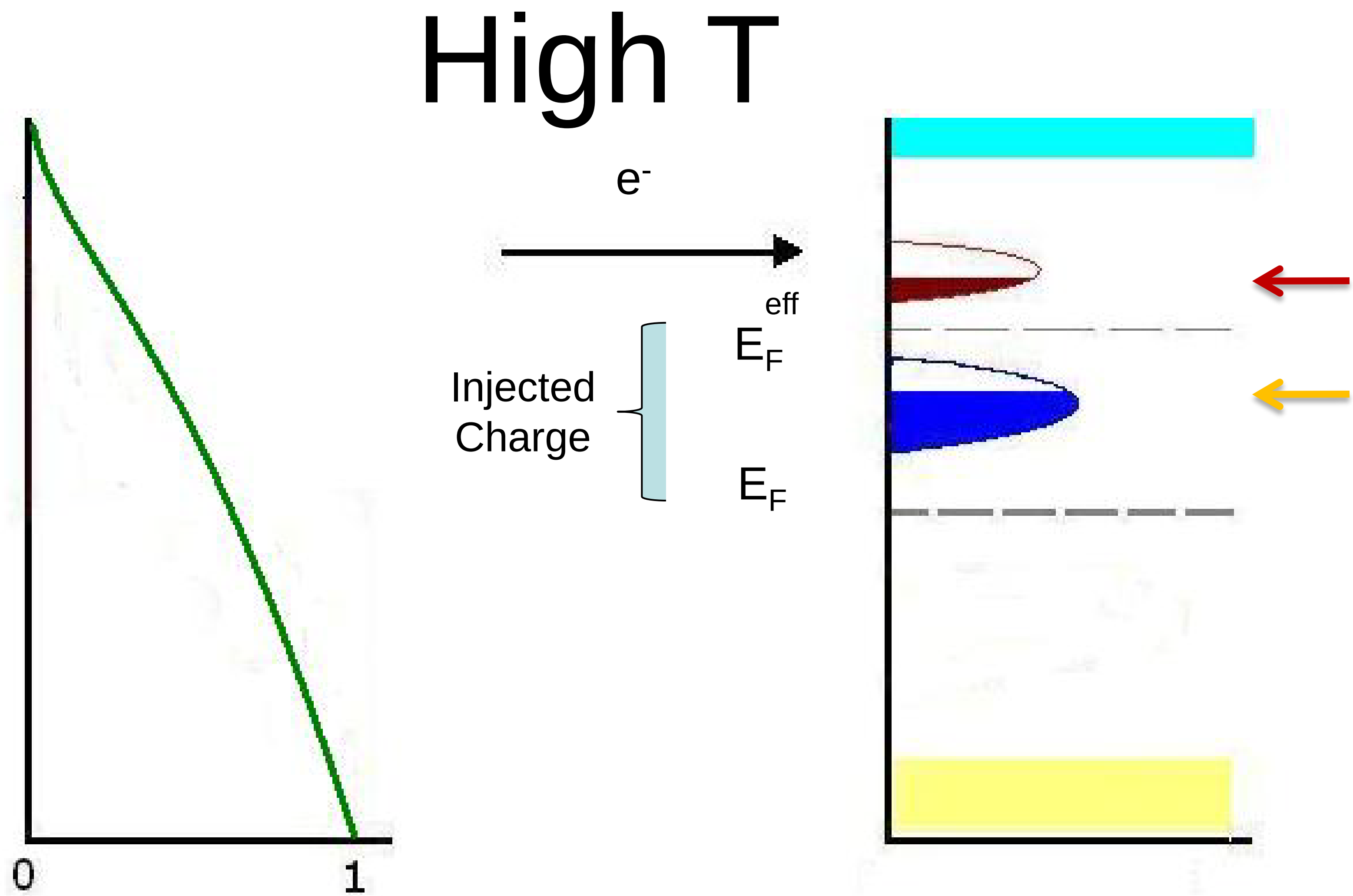
Temperature Model for Multiphonon Luminescence



Low Temperature Model



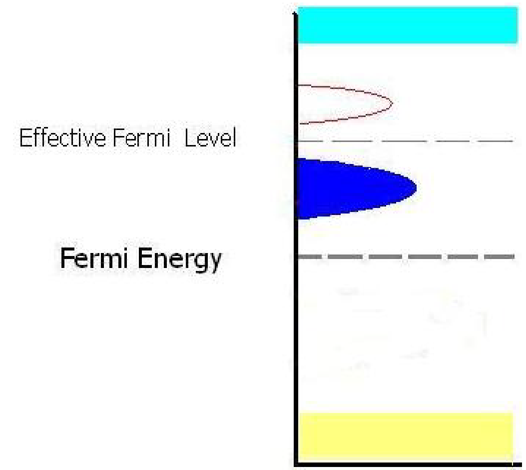
High Temperature Model



Luminescence: Conclusions

Color of Electron-Induced Luminescence

	Gaussian Energy State			
Temperature (K)		Blue	Red	
	0	→0	→max	
	Low	in between	in between	
	High	→half max	→half max	



- Identify specific defect mechanisms
- Quantify luminescence intensities, peak positions, and peak shifts with T
- Study initial time dependence as traps fill to Efeff
- Make lower T (<30 K) and higher (<400 K) T measurements

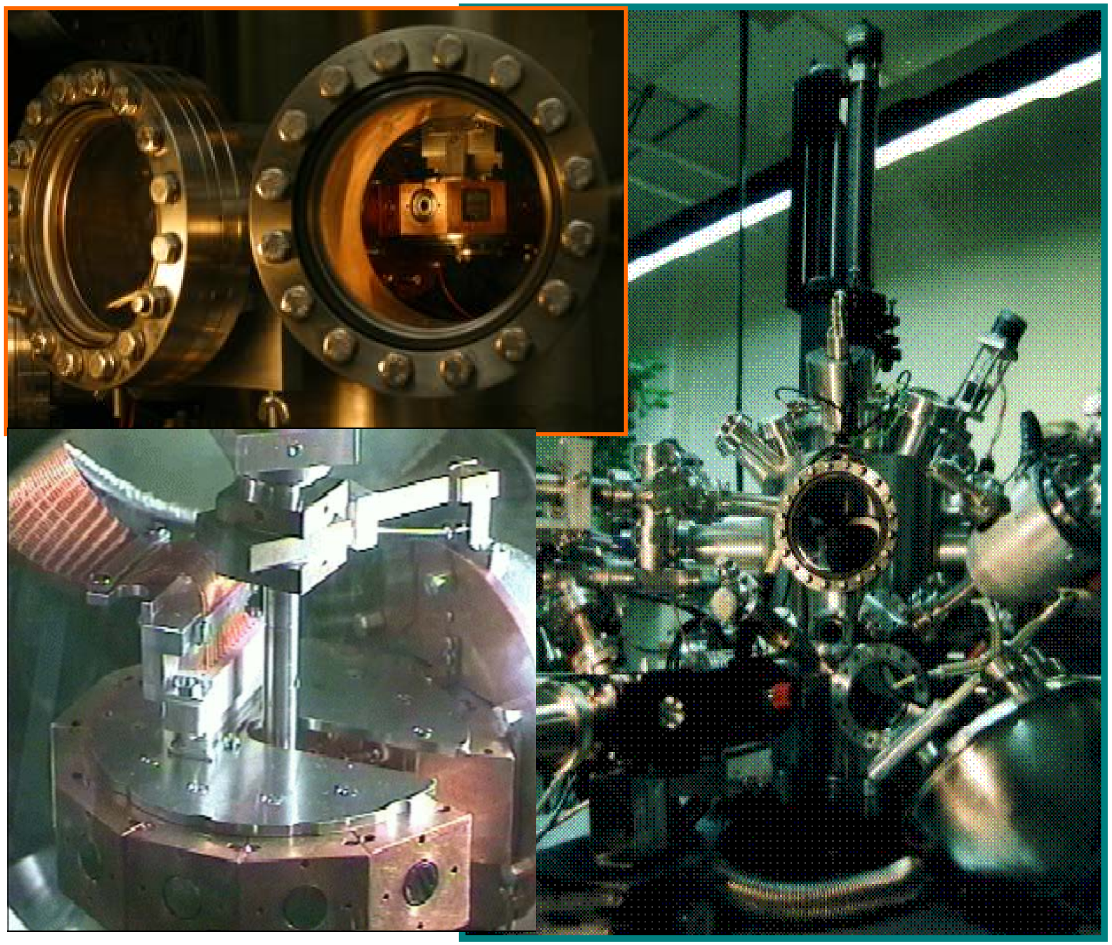
Materials Physics Group Measurement Capabilities

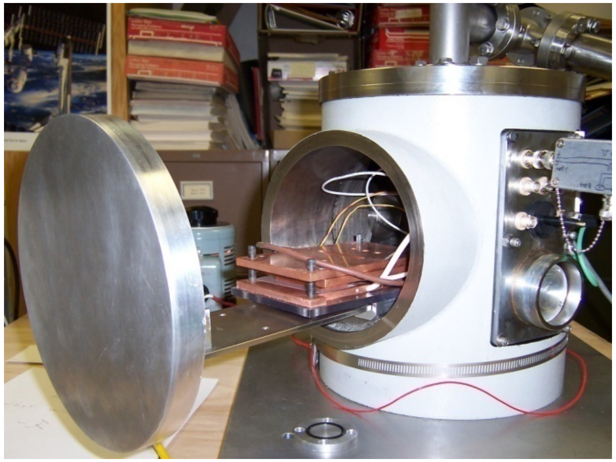
Electron Emission
Ion Yield

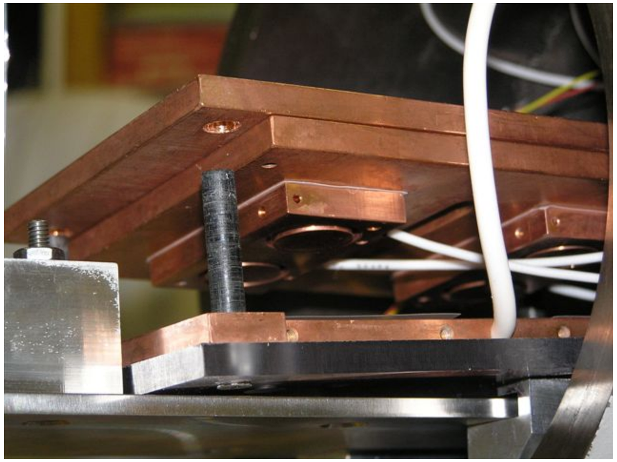
Photoyield
Luminescence

Conductivity
Electrostatic Discharge

Radiation Induced Cond.
Radiation Damage

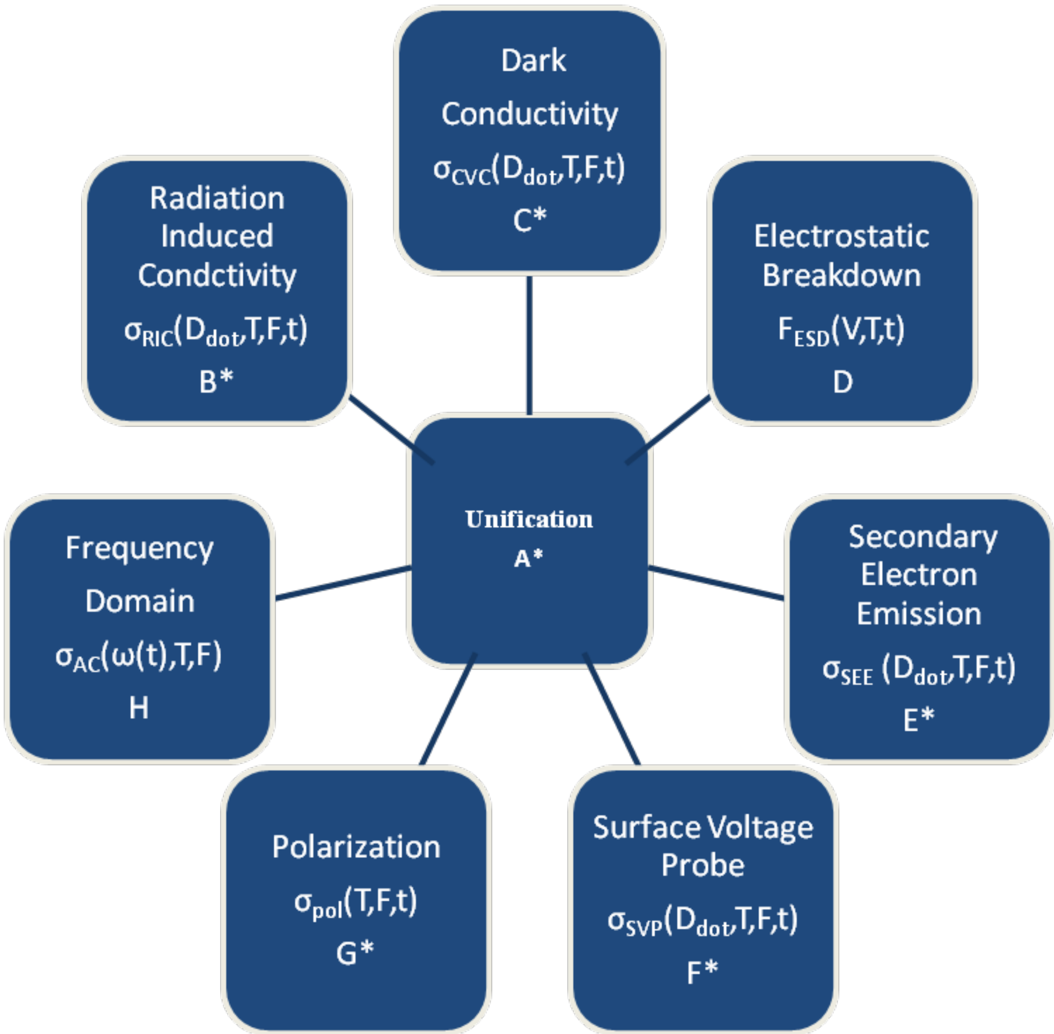






Dependence on: Press., Temp., Charge, E-field, Dose, Dose Rate

Just a drop in the bucket…



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

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

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

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

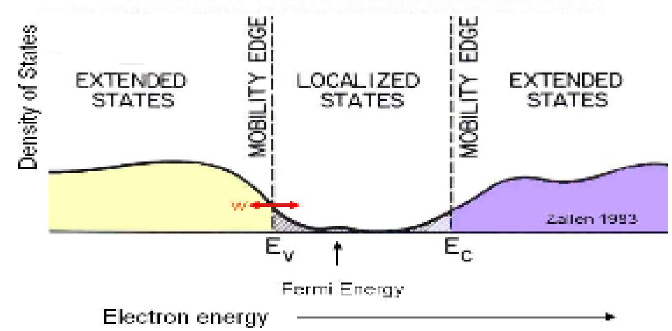
$$\alpha_{er}\, n_e(z,t)n_{tot}(z,t) + \alpha_{et}\, n_e(t)[N_t(z) - n_t(z,t)]$$

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

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

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

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



USU Physics Department Colloquium

November 15, 2011

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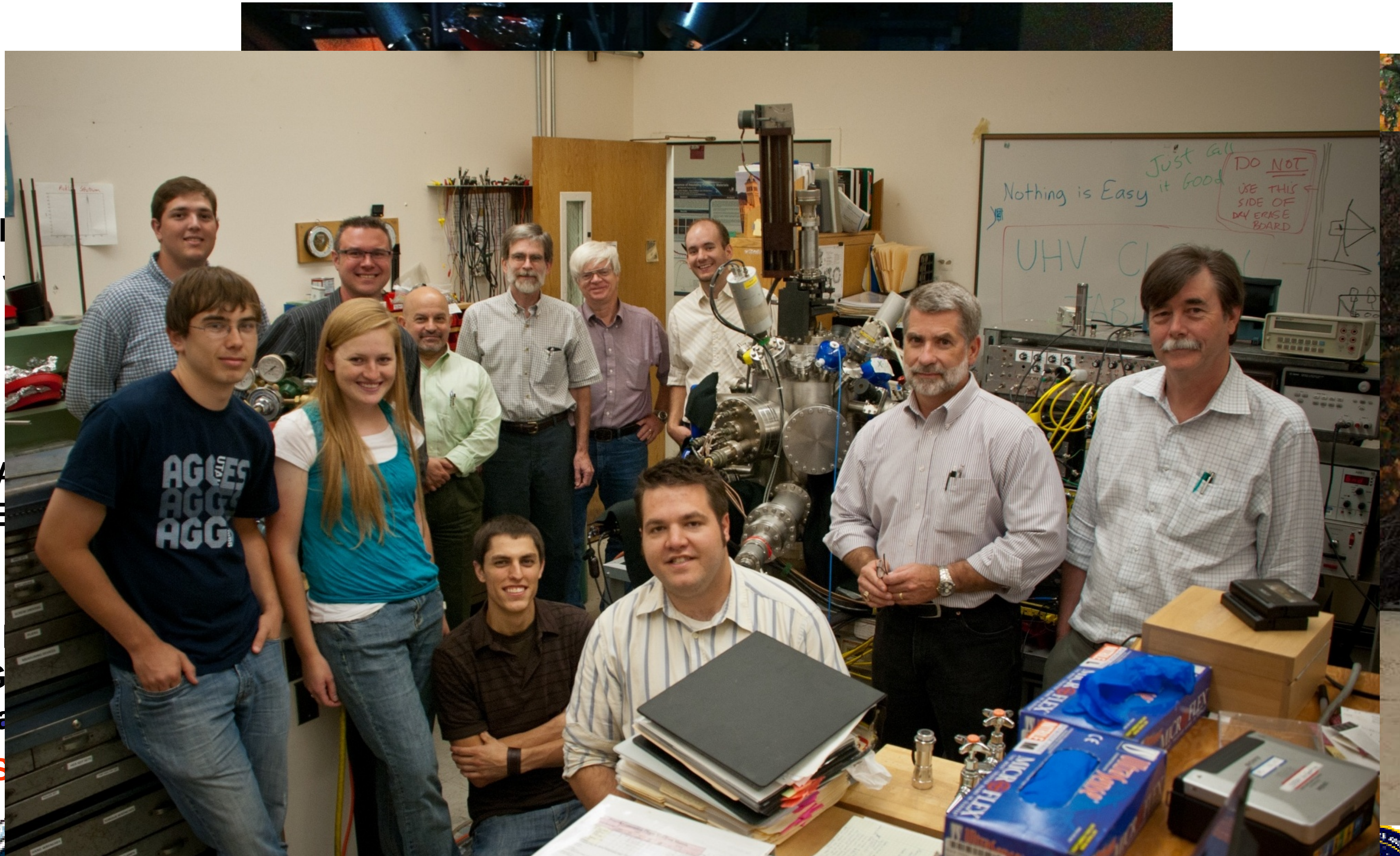

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