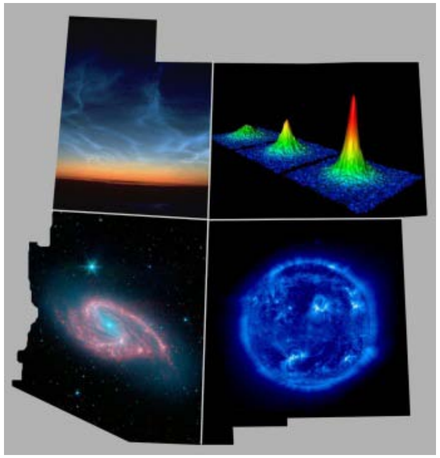
10-26-2012

Temperature-Dependent Radiation Induced Conductivity of Diverse Highly Disordered Insulating Materials

JR Dennison
Utah State Univesity

Gregory Wilson
Utah State University

Jodie C. Gillespie
Utah State University



APS Four Corner Sections Meeting

New Mexico Tech
Socorro, NM
October 26 & 27, 2012

Temperature-Dependent Radiation Induced Conductivity of Diverse Highly Disordered Insulating Materials

J.R. Dennison, Gregory Wilson and Jodie Gillespie

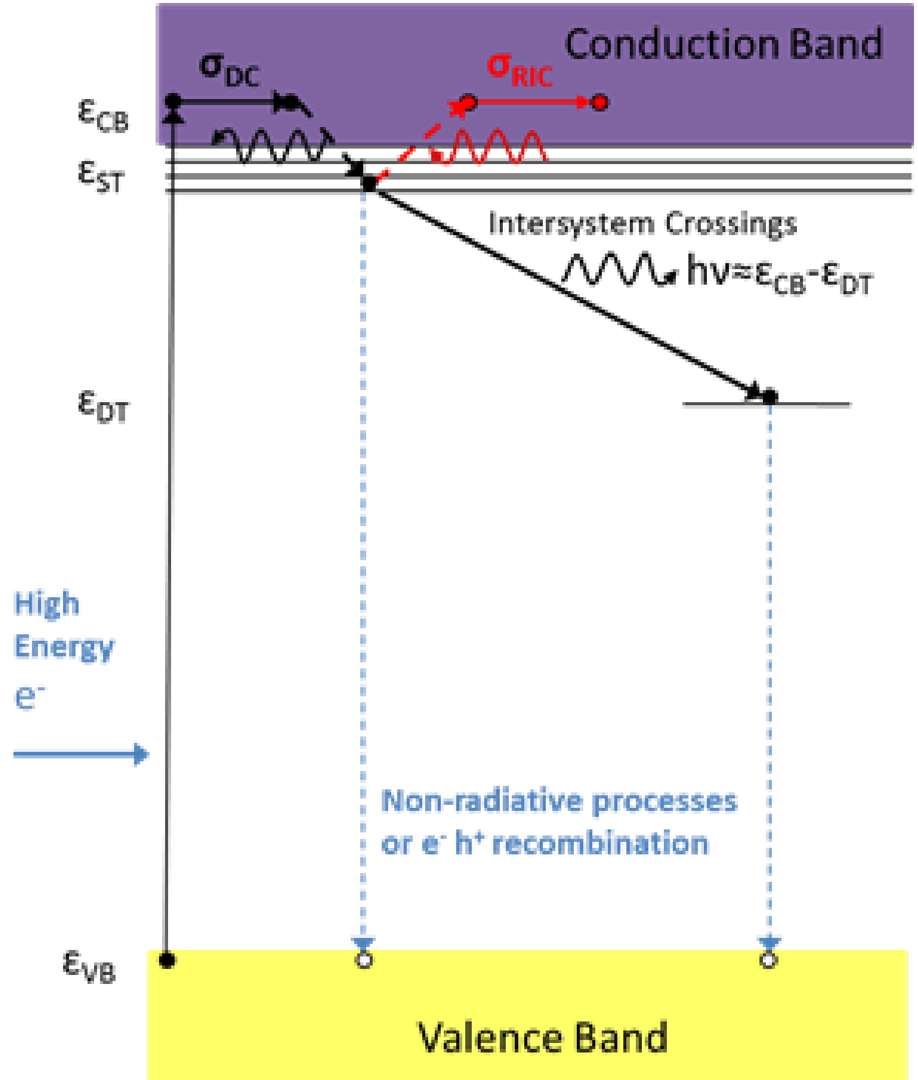
Materials Physics Group
Physics Department, Utah State University

Complementary Responses to Radiation

Modified Joblonski diagram

- VB electrons excited into CB by the high energy incident electron radiation.
- They relax into shallow trap (ST) states, then thermalize into lower available long-lived ST.
- Three paths are possible:

(i) relaxation to deep traps (DT), with concomitant photon emission;
(ii) radiation induced conductivity (RIC), with thermal re-excitation into the CB; or
(iii) non-radiative transitions or e^--h^+ recombination into VB holes.



What Is Radiation Induced Conductivity (RIC)?

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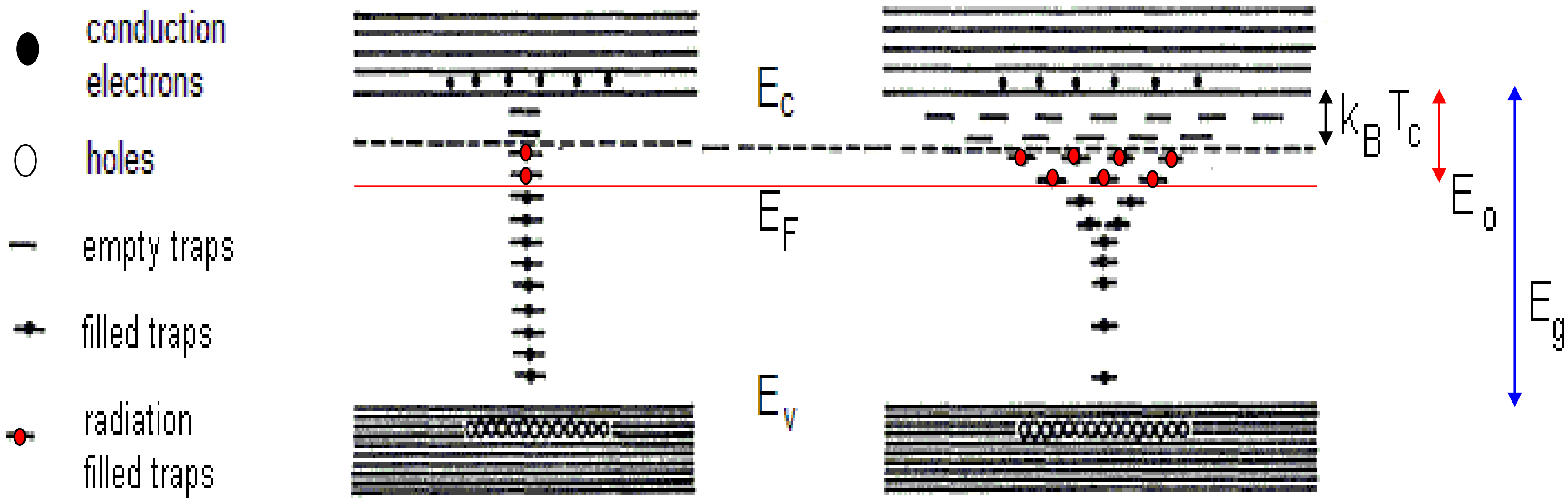


Uniform Trap Density

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

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

Exponential Trap Density

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

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

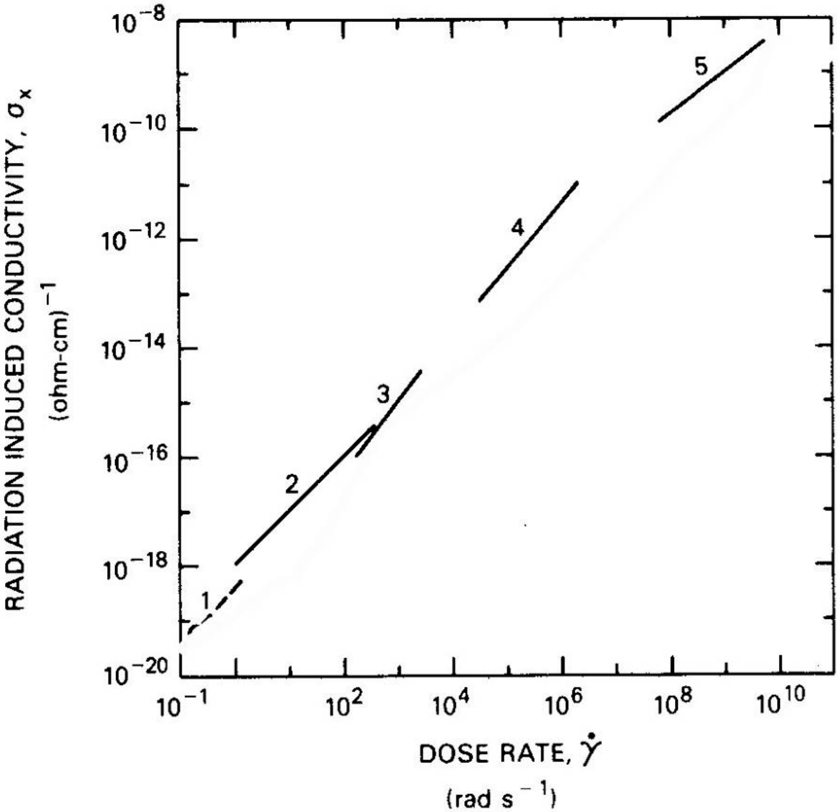
$$\sigma_{RIC}(T,D) = k_{RIC}(T)\cdot D^{\Delta(T)}$$

RIC Depends on Power Deposited

- The RIC versus radiation dose rate for polyethylene terephthalate (Mylar) [Campbell].

- The exponential fit over 10 orders of magnitude for five different studies implies that RIC is largely independent of the beam energy and type of radiation used.

- Only the amount of energy being deposited determines the magnitude of RIC.



Curve Segment	Type of Radiation	Energy	Dose Rate	Mode
1	X-rays	250 keV	0.13 rad/s	steady state
2	X-rays	15 to 30 keV	1 to 400 rad/s	steady state
3	γ-rays	1.17 and 1.33 MeV	200 to 3500 rad/s	steady state
4	pulse reactor neutrons and γ-rays	mixed	6.5×10^4 to 3.8×10^6 R/s	13 ms pulses
5	electrons	30 MeV	5×10^7 to 7×10^9 rad/s	4.5 μs pulses

Dose Rate

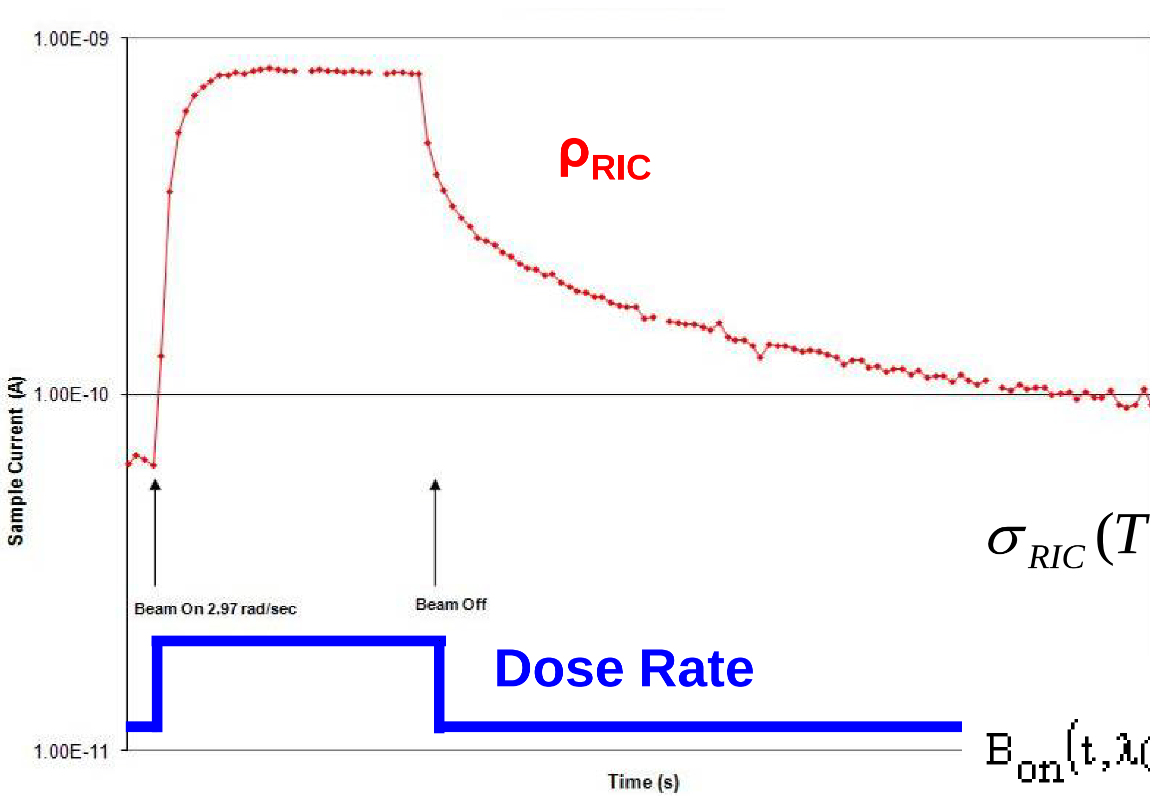
DOSE RATE is the deposited power per unit mass is:

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

which is proportional to incident electron absorption:

- **Incident areal power density, *$(J_b \cdot E_b)/q_e$***
- **Energy-dependant correction for unabsorbed quasielastic backscattered electrons, *$[1-\eta(E_b)]$***
- **For biased samples, or when excess charge is stored in the trap states, a surface voltage *V_s* *results and E_b is replaced everywhere by the landing energy, $[E_b - q_e \cdot V_s]$***
- **Absorbing mass, *$m_{absorb} = \rho_m \cdot$ (Beam Area · Penetration Depth)***
- **Only a fraction of the incident power, *$[L / R(E_b)]$*, when range exceeds sample thickness**

RIC Is Time Dependant

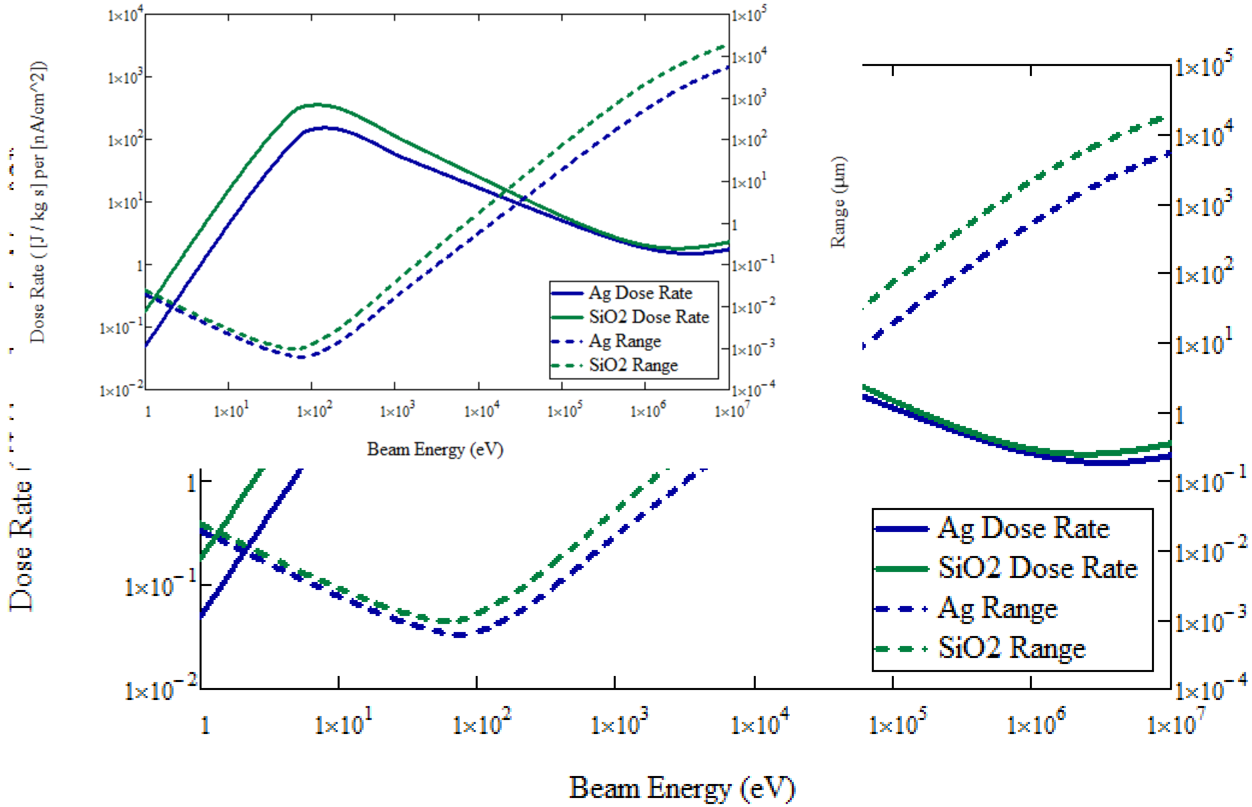


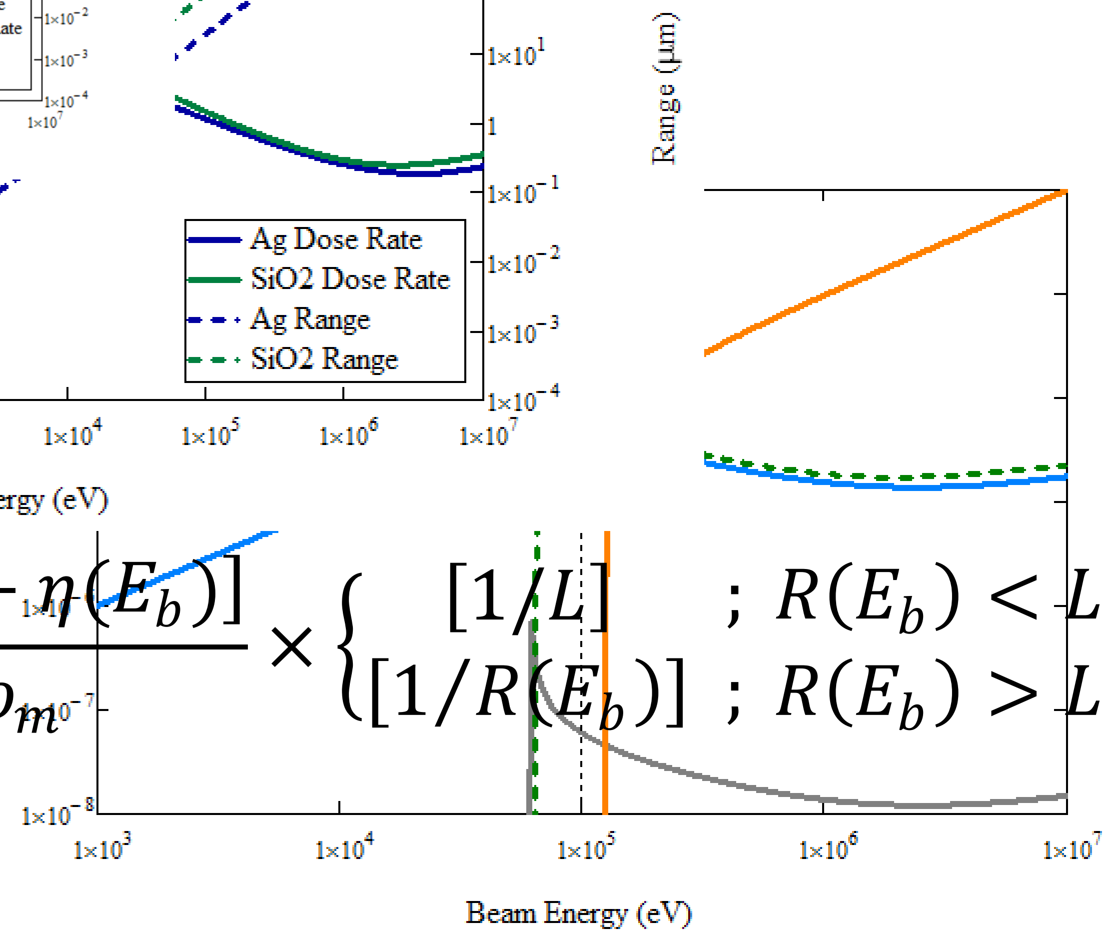
$$\sigma_{RIC}(T,D) = k_{RIC}(T)\cdot D^{\Delta(T)}$$

$$B_{on}(t,\lambda(D,T)) = 1 - e^{-(t-t_{on})\cdot\lambda(D,T)}$$

$$B_{off}(t,T,k(T)) = \frac{1}{1 + k(T)\cdot\frac{t - t_{off}}{T}}$$

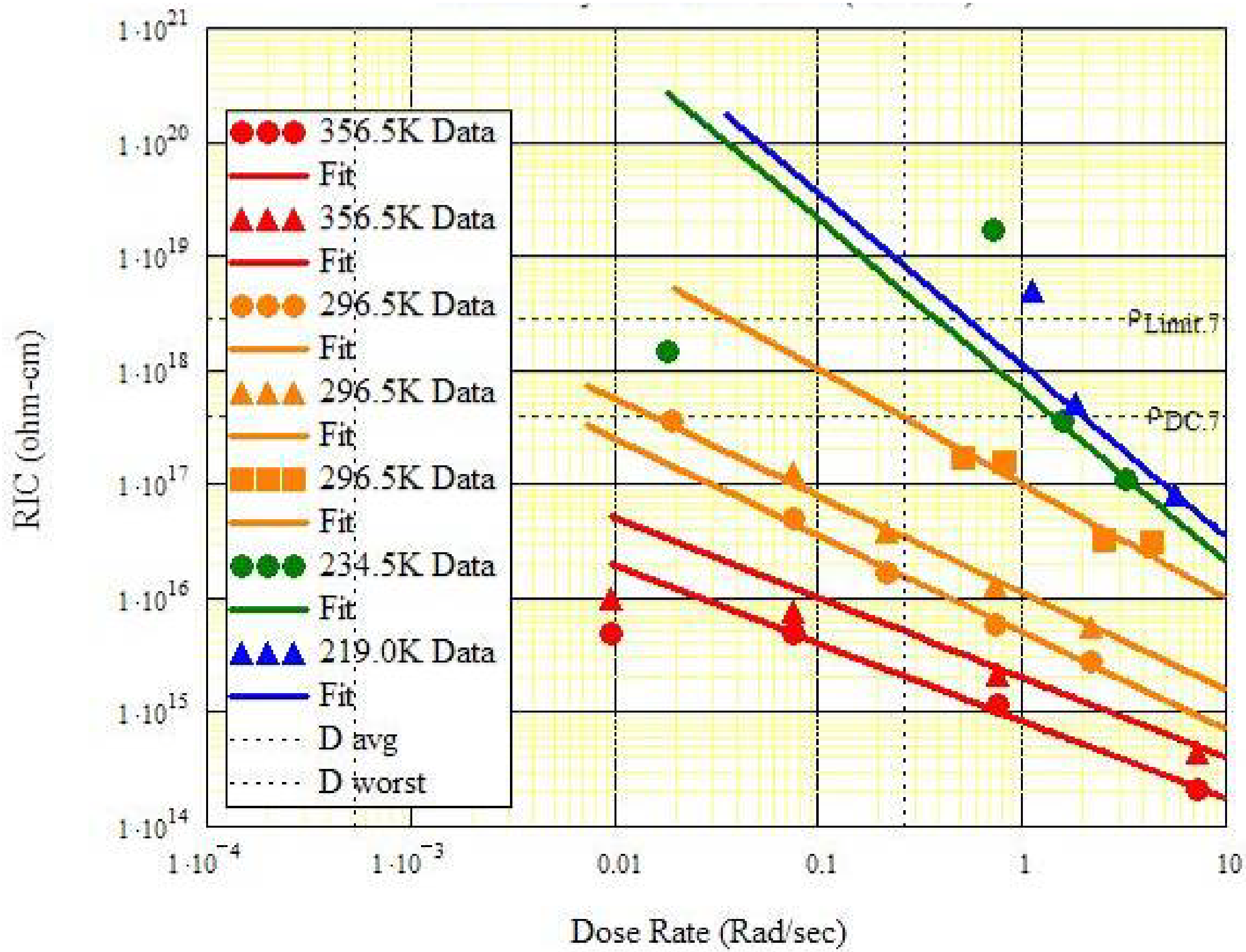
RIC Is Depth Dependant





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

RIC Dependence on Temperature

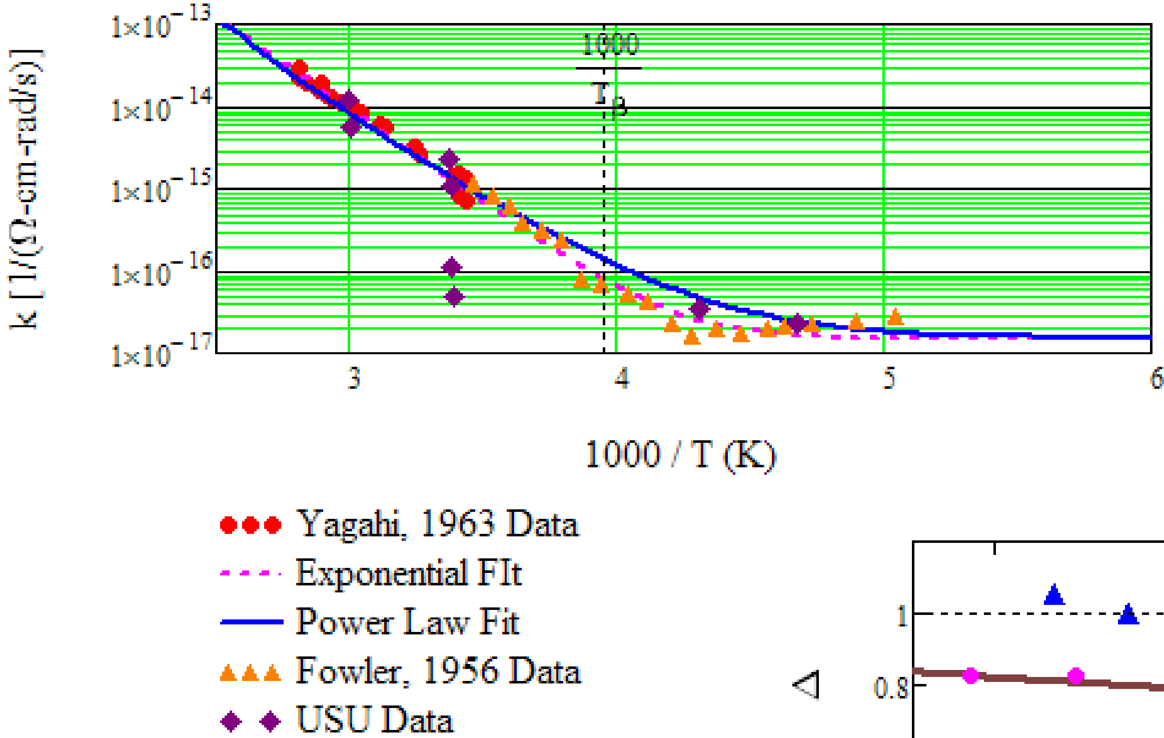


Kapton^{TM} (polyimide)

Family of curves of ρ_{RIC} vs dose rate at various temperatures. Fits are simple power law fits.

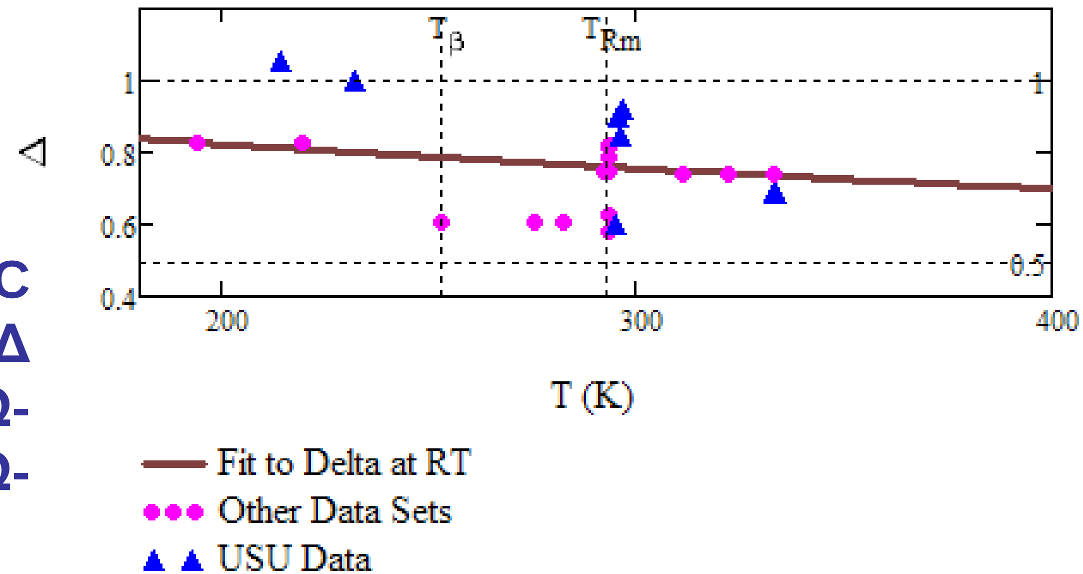
$$\sigma_{RIC}(T,D) = k_{RIC}(T)\cdot D^{\Delta(T)}$$

RIC Dependence on Temperature



Kapton™ (polyimide)

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



T dependence of RIC coefficients k (Left) and Δ (Right) with k_o= 1.5·10^{-16} (Ω-cm-Rad/s)$^{-1}$, k_1= 7.0·10^{-29} (Ω-cm-Rad/s)$^{-1}$ and T_c = 230 K.

RIC Dependence on Temperature

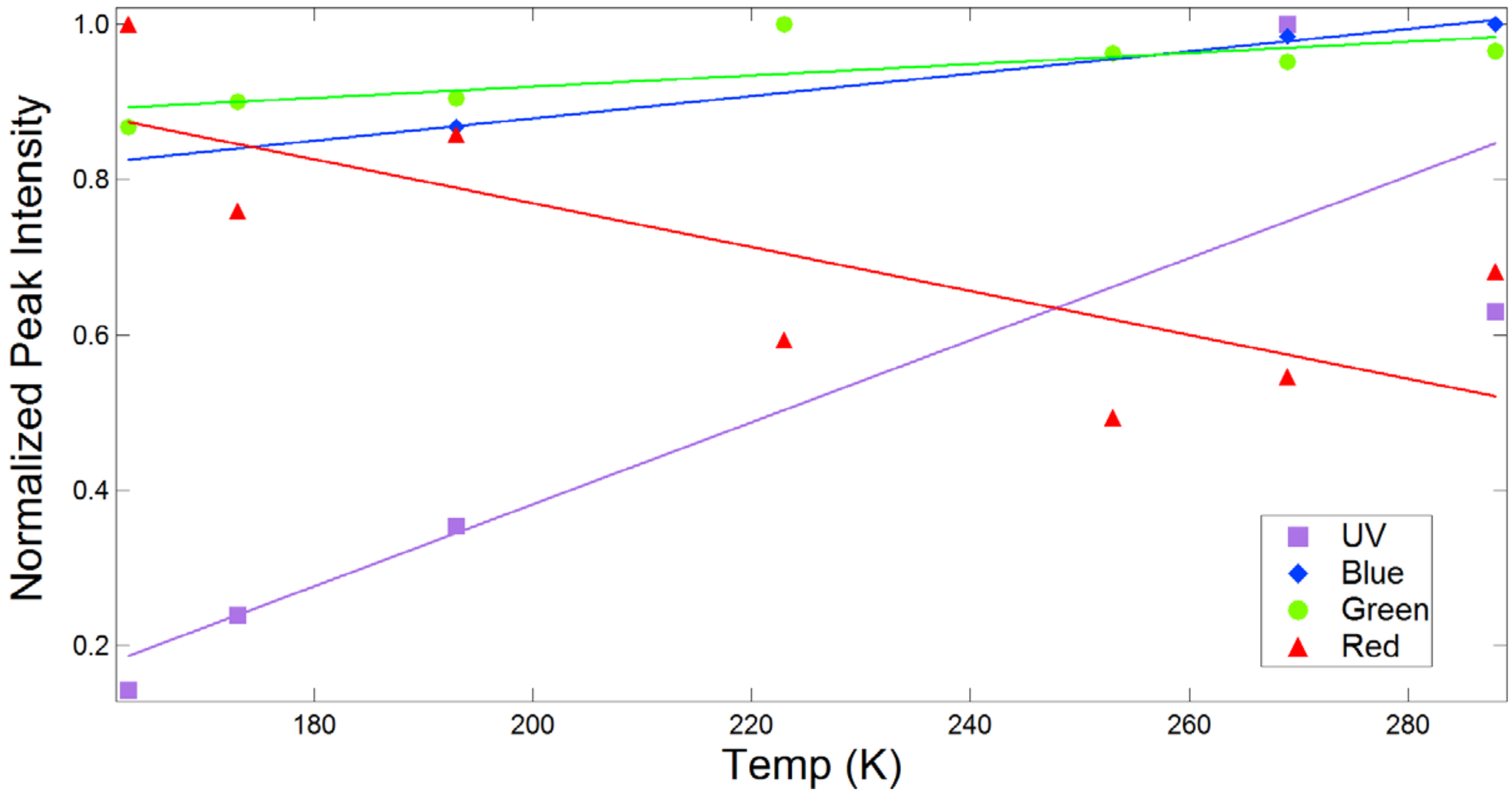
Luminescent intensity, I_γ, scales with incident current density J_b, beam energy E_b, temperature T, and photon wavelength λ as

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

which is proportional to:

- **Number of electrons in ST, thermalized from CB electrons**
  - ➢ **Trapping rates proportional to number of electrons excited in to CB which is proportional to dose rate**
  - ➢ **Retention rates leads to saturation at high charge, related to dose and T-dependant $\dot{D}_{sat}$ from RIC [5]**
- **Number of available DT states, dependant on space charge and T**
- **Emitted photon absorption**
  - ➢ **Proportional to A_f , the optical absorption coefficient of the coating**
  - ➢ **Enhanced by a factor $[1 + \mathbb{R}_m(\lambda)]$, to account for reflection from the metallic layer**

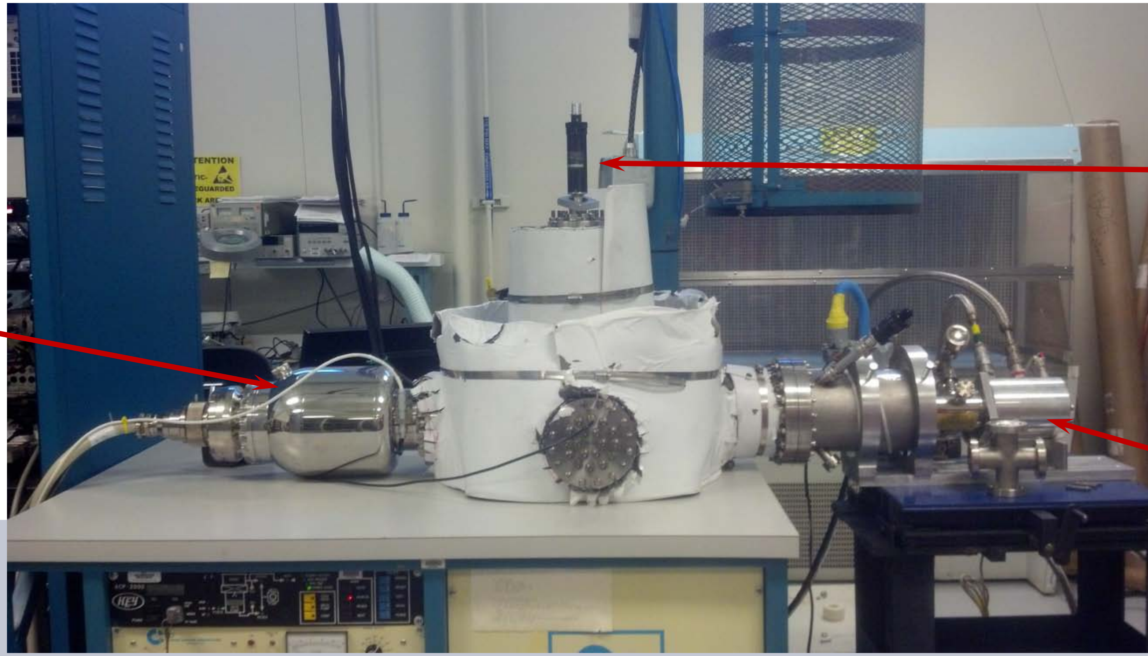
Summary of Cathodoluminescence



Peak amplitudes of four peaks as a function of sample temperature, with baseline subtracted and normalized to maximum amplitudes. This verified the T-dependent behavior observed in the SLR images.

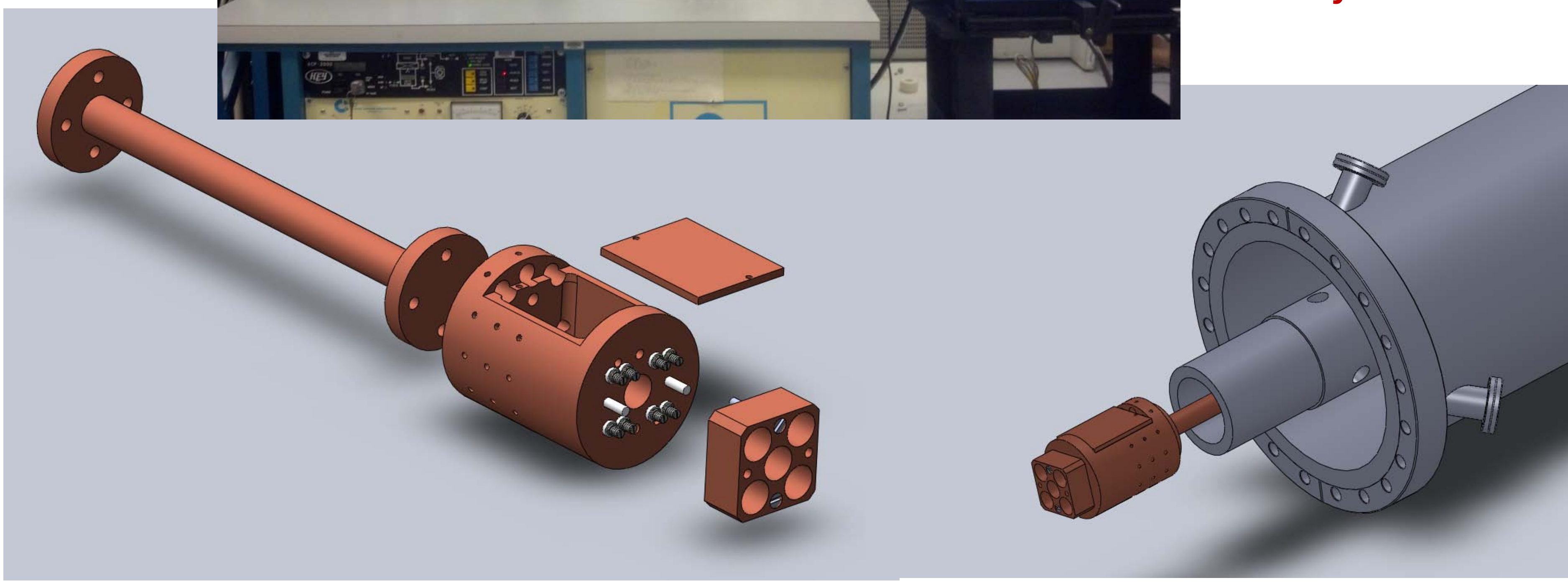
Closed-System Helium Refrigerator Sample Stage Mounting

High Energy Electron Gun

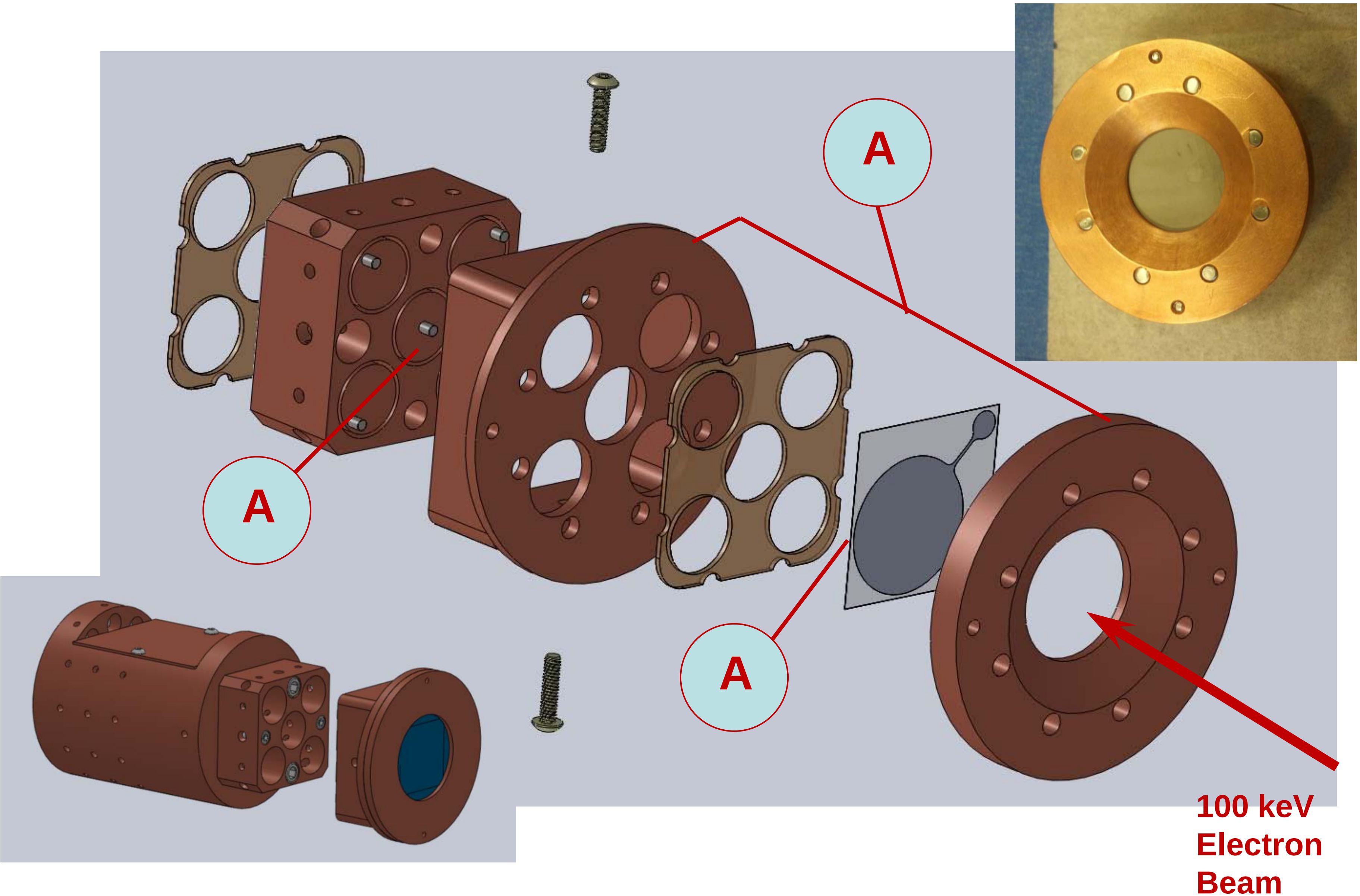


Faraday Cup Z Translation Stage

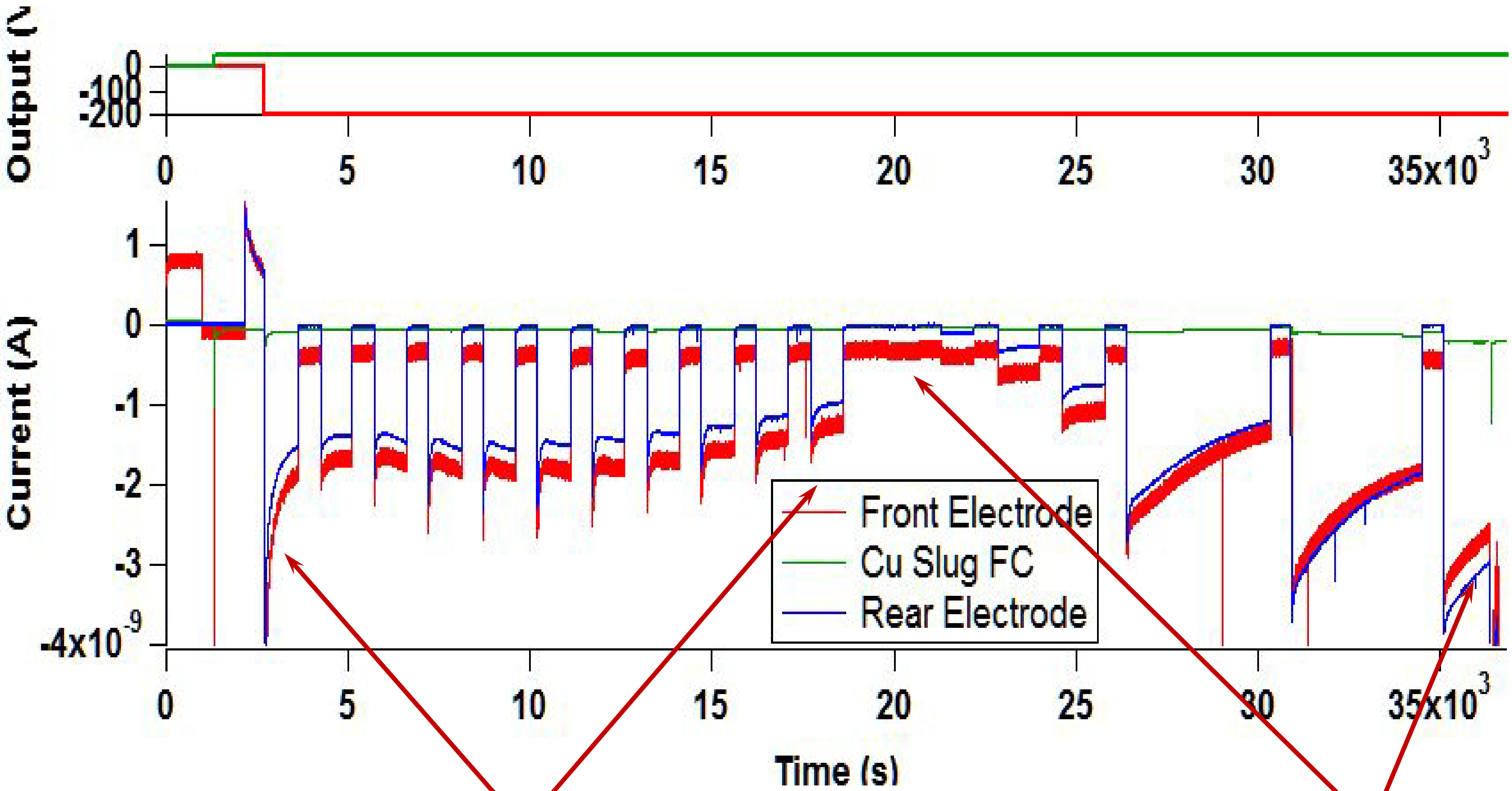
USU Closed Cycle He Cryostat



Sample Square Holder Assembly Diagram



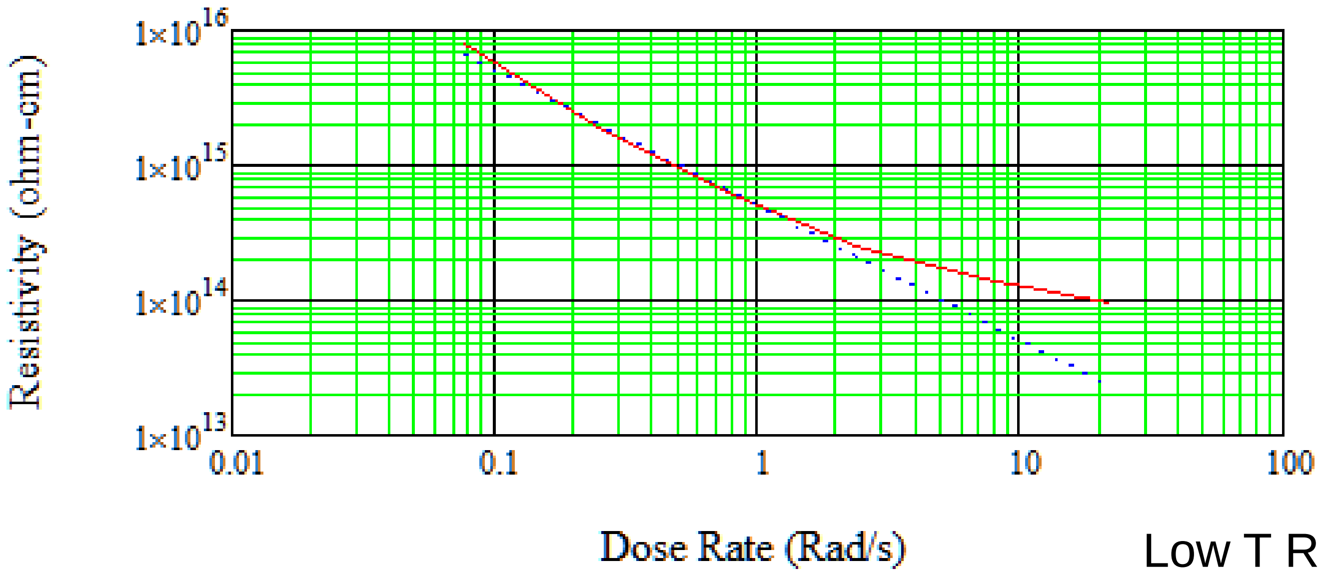
RIC Measurements



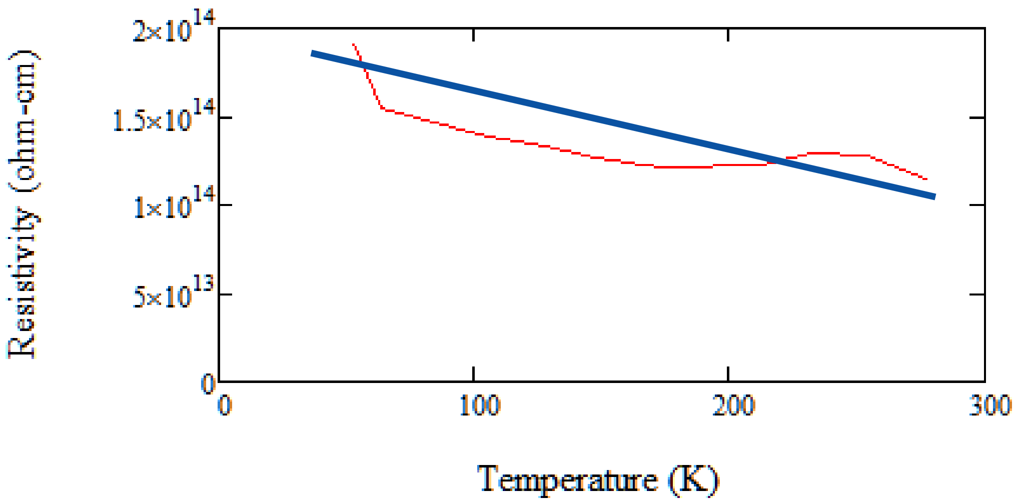
RIC current vs 295 K<T<38 K at constant Dose Rate

RIC curent vs Dose Rate at 40 K

RIC Results

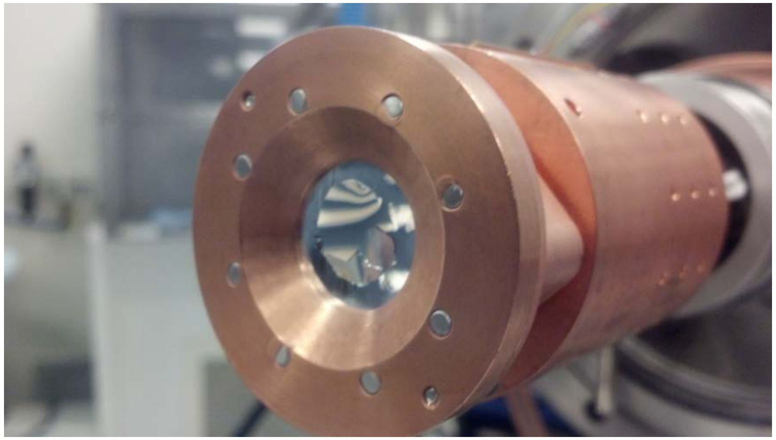


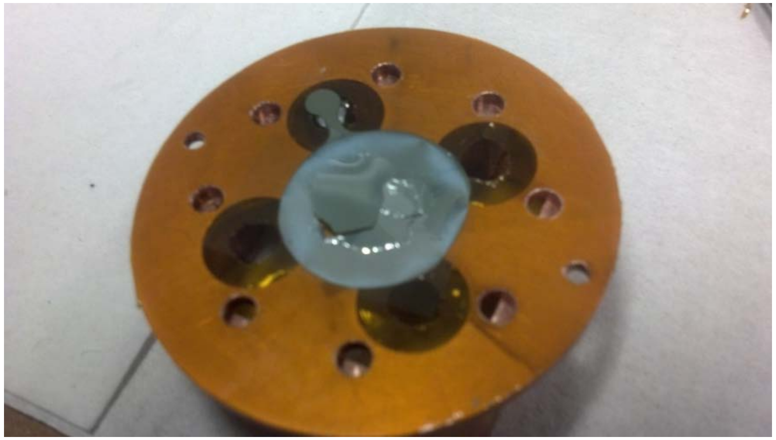
Low T RIC from data
k_p = 2E-15 mho/cm-rad-sec
Δ=1

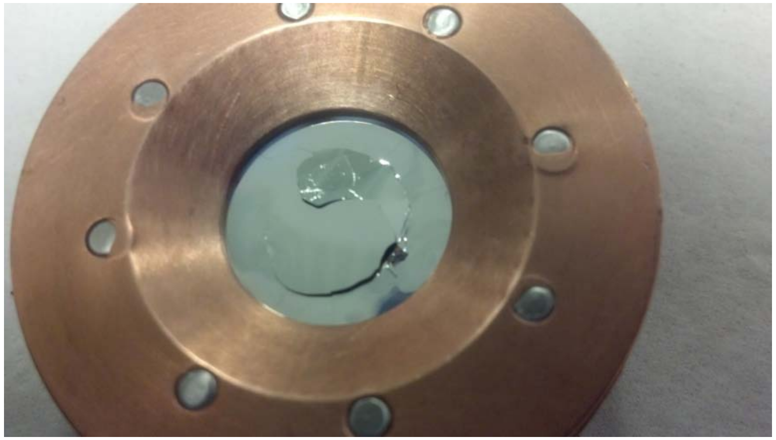


room T RIC from Culler paper
k_p = 1.7E-16 mho/cm-rad-sec
Δ=0.967

Ending with a Bang!!!







Conclusions

RIC in Thin Film Disordered SiO_2 is:

I. Proportional (nearly) to Dose Rate
II. Weakly (and roughly linearly) T-dependant
III. Complementary with cathodoluminescence
IV. RIC has rapid time dependance
V. Suggests a nearly linear density of localized states (shallow traps)

Acknowledgements

Support & Collaborations

Air Force Research Lab

NASA/JWST (GSFC)

National Research Council

B42 Amberly E. Jensen
Dependence of Electron Beam Induced Luminescence of SiO_2 Optical Coatings on Energy, Flux, Temperature and Thickness

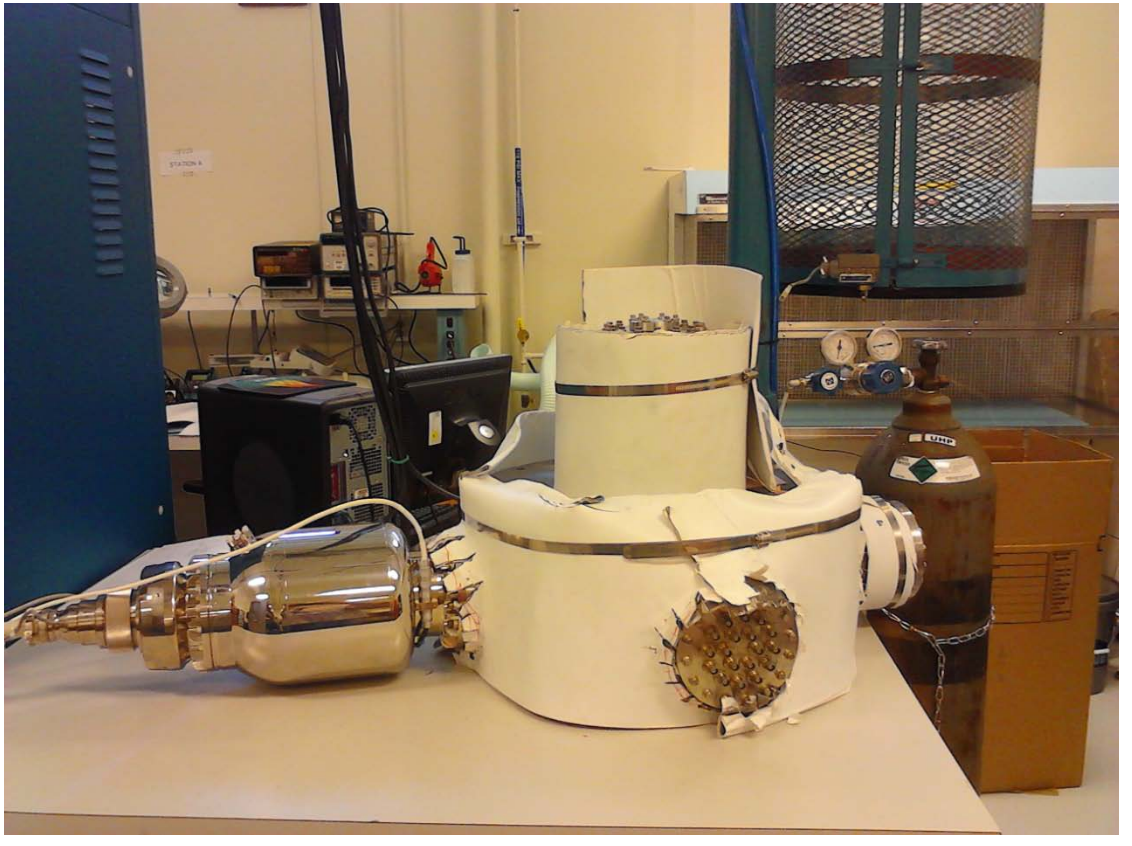
B4 4 JR Dennison
Comparison of Radiation Induced Conductivities at Low Temperature

B4 7 Greg Wilson
Power and Charge Deposition in Multilayer Dielectrics undergoing Monoenergetic Electron Bombardment

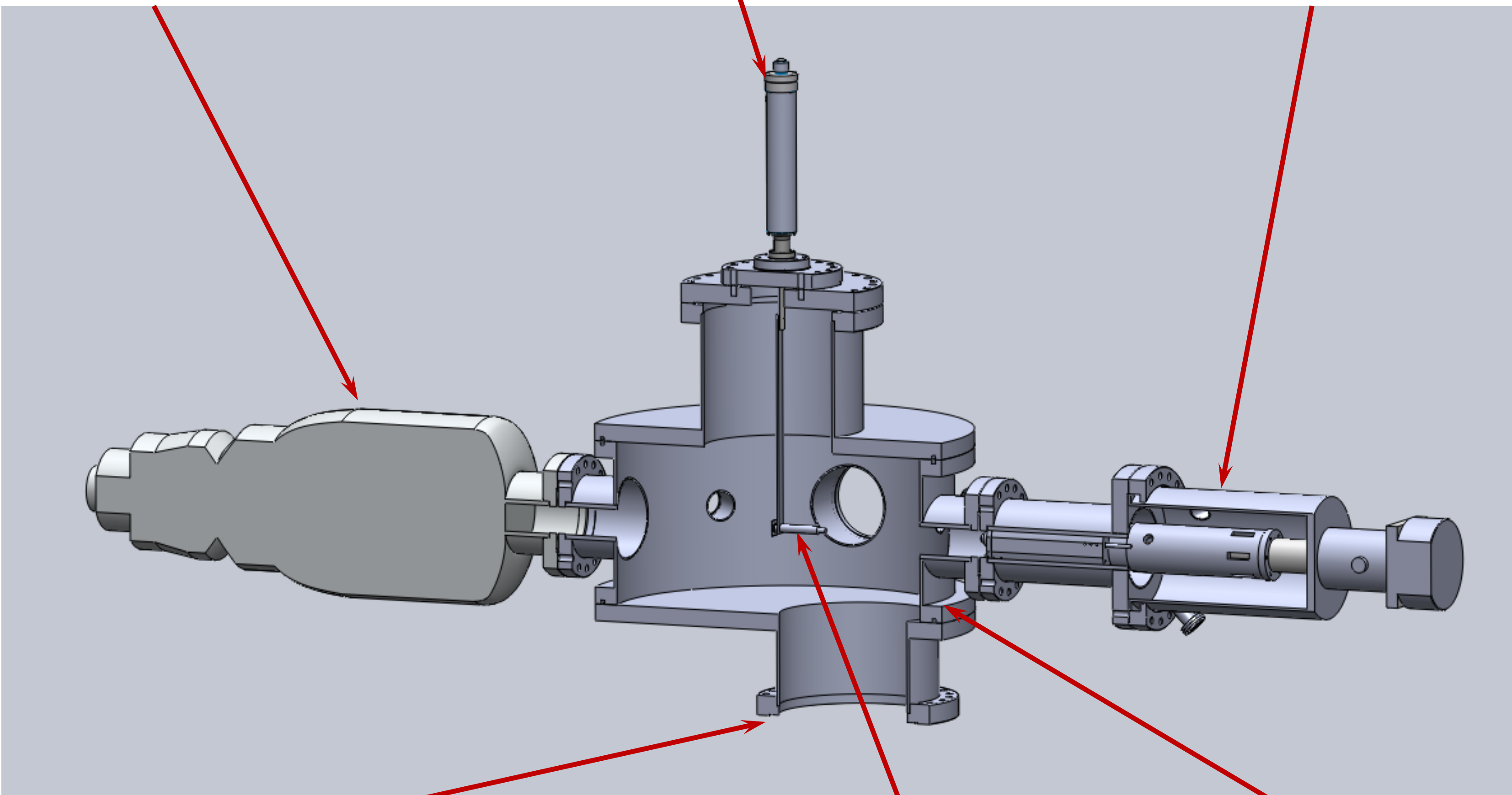
D1 40 Allen Anderson
Electrostatic Discharge Properties of Fused Silica Coatings

Supplemental Slides

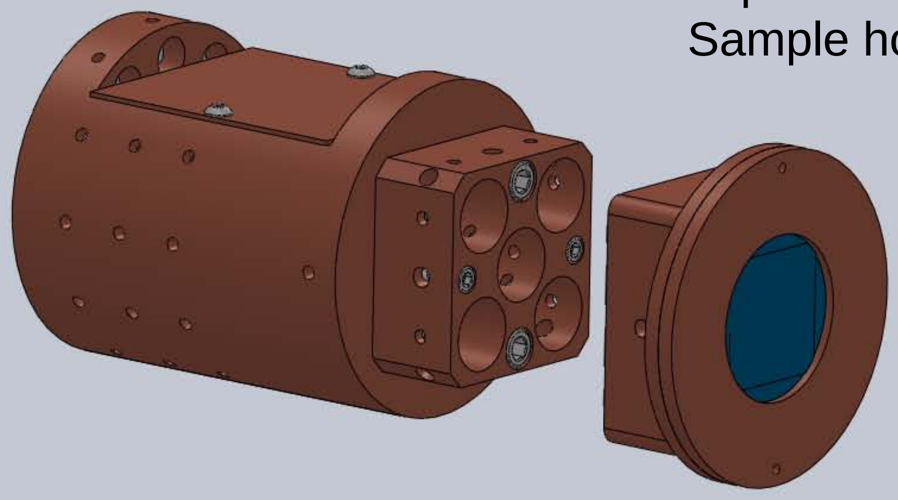
Phase VI: AFRL Bell Jar Chamber Lead Shielding



Phase VI: AFRL Bell Jar Chamber Cut Away Diagram



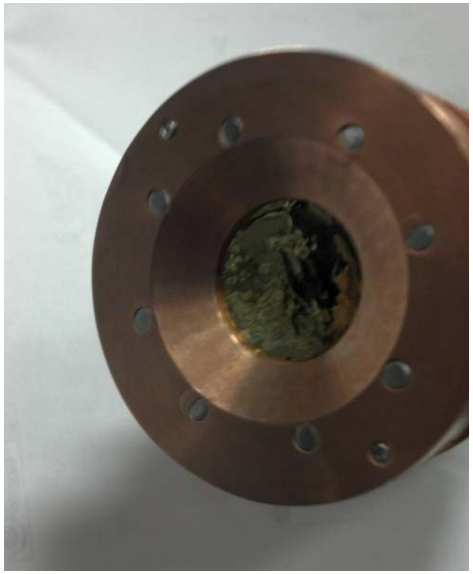
New Sample Square Holder



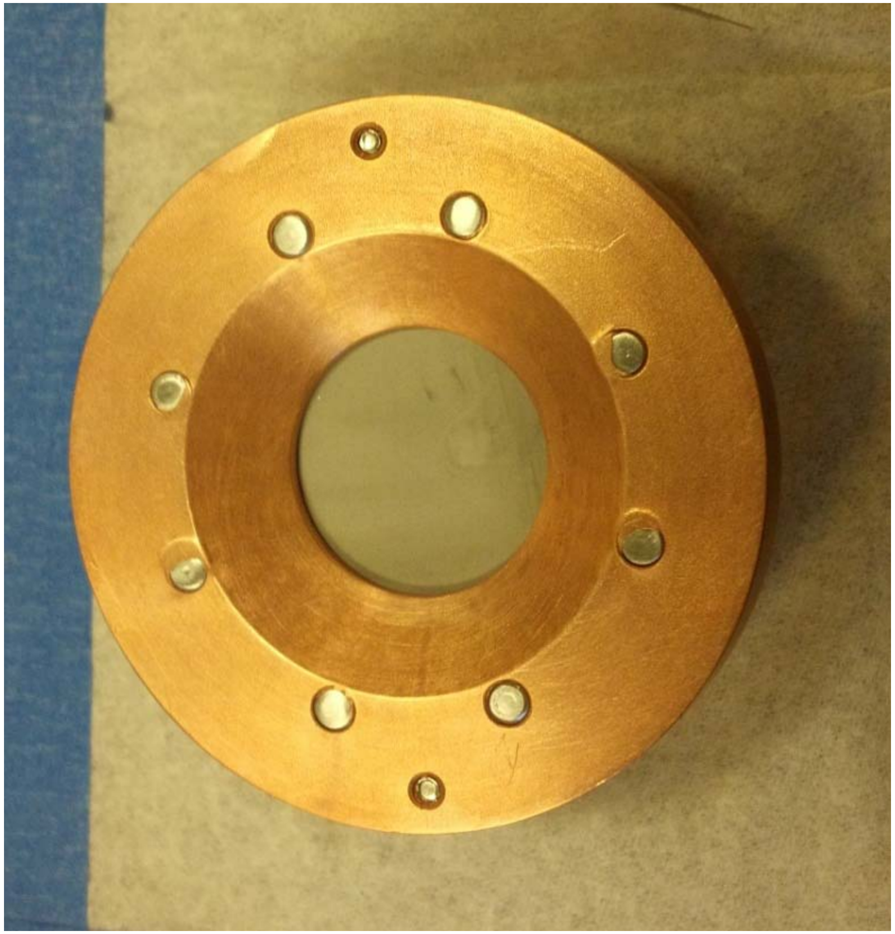
New sample holder
Slips over existing multiple
Sample holder

New Sample Square Holder

New Sample Mount- Au/Kapton Sample

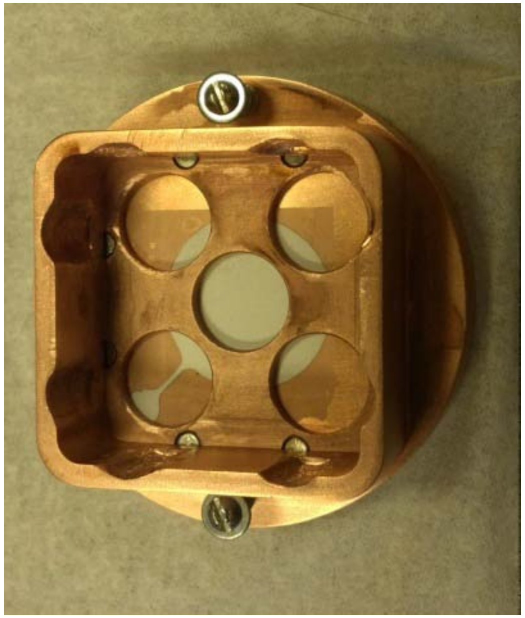


New Sample Square Holder

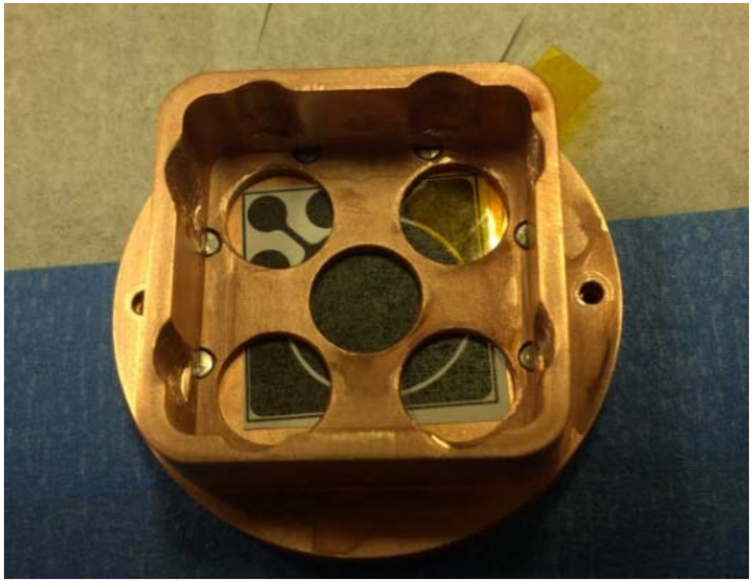


New Sample Mount- Broken Silica Sample

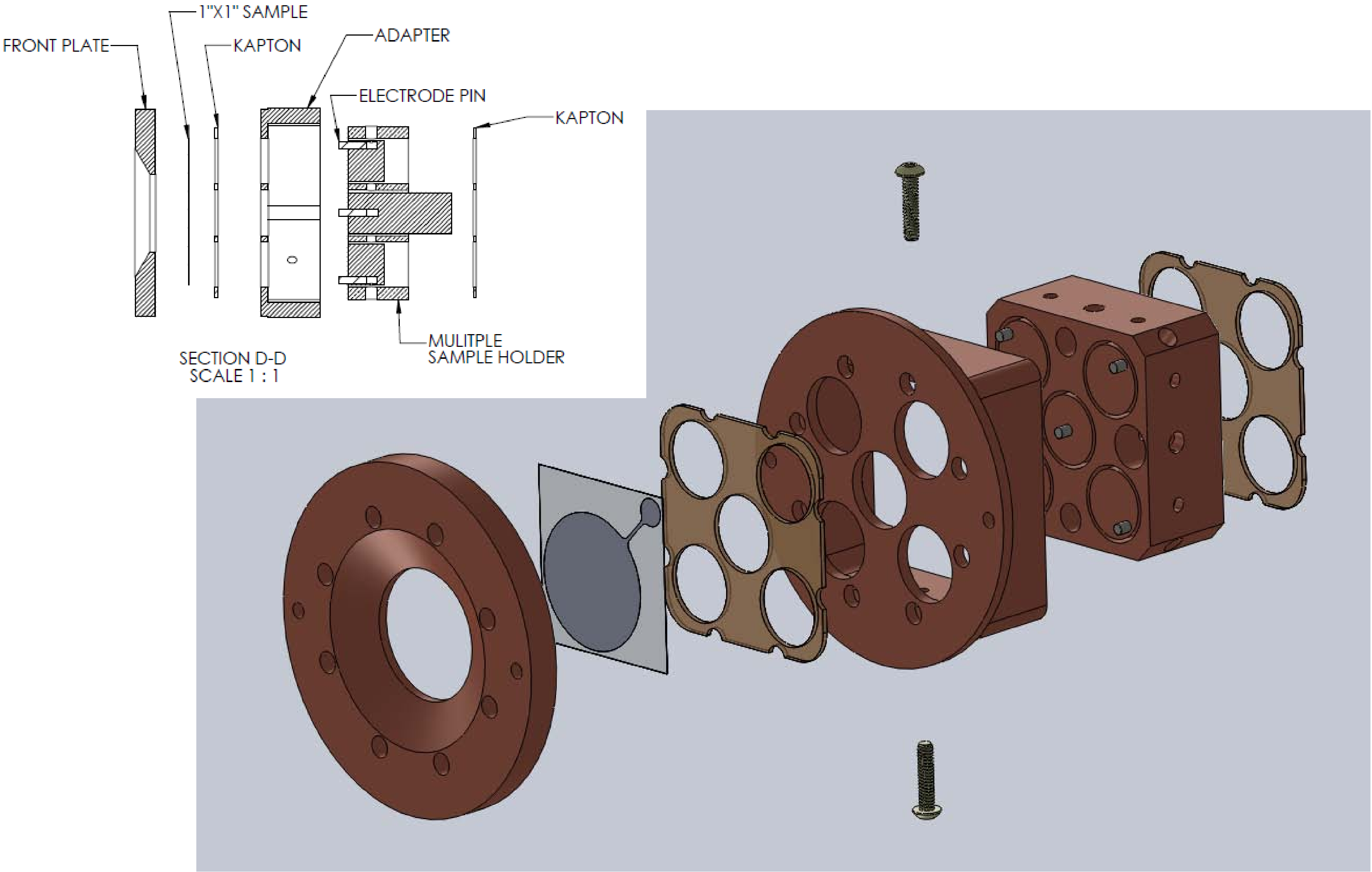
New Sample Square Holder



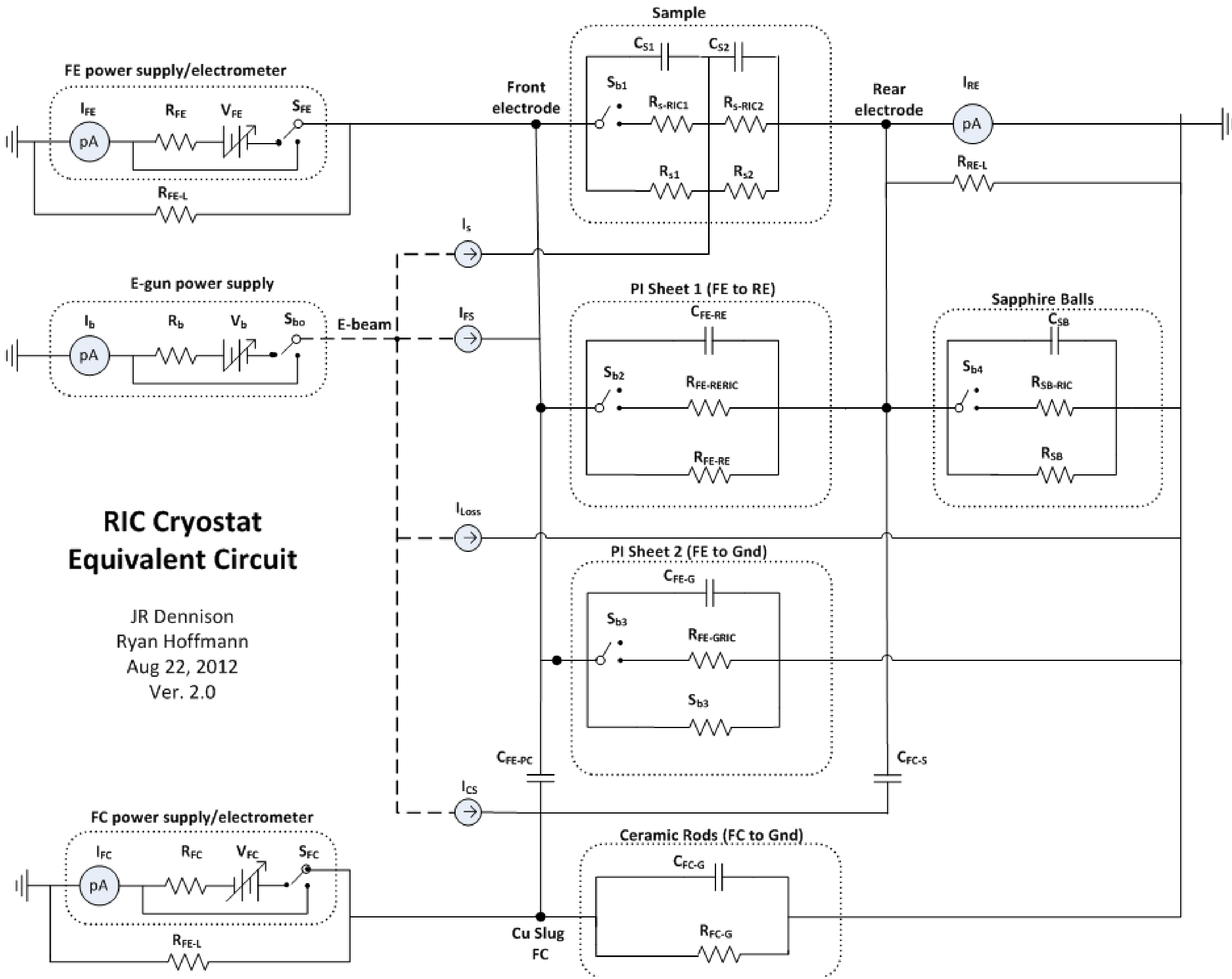
New Sample Mount Rear Views



New Sample Square Holder Assembly Diagram

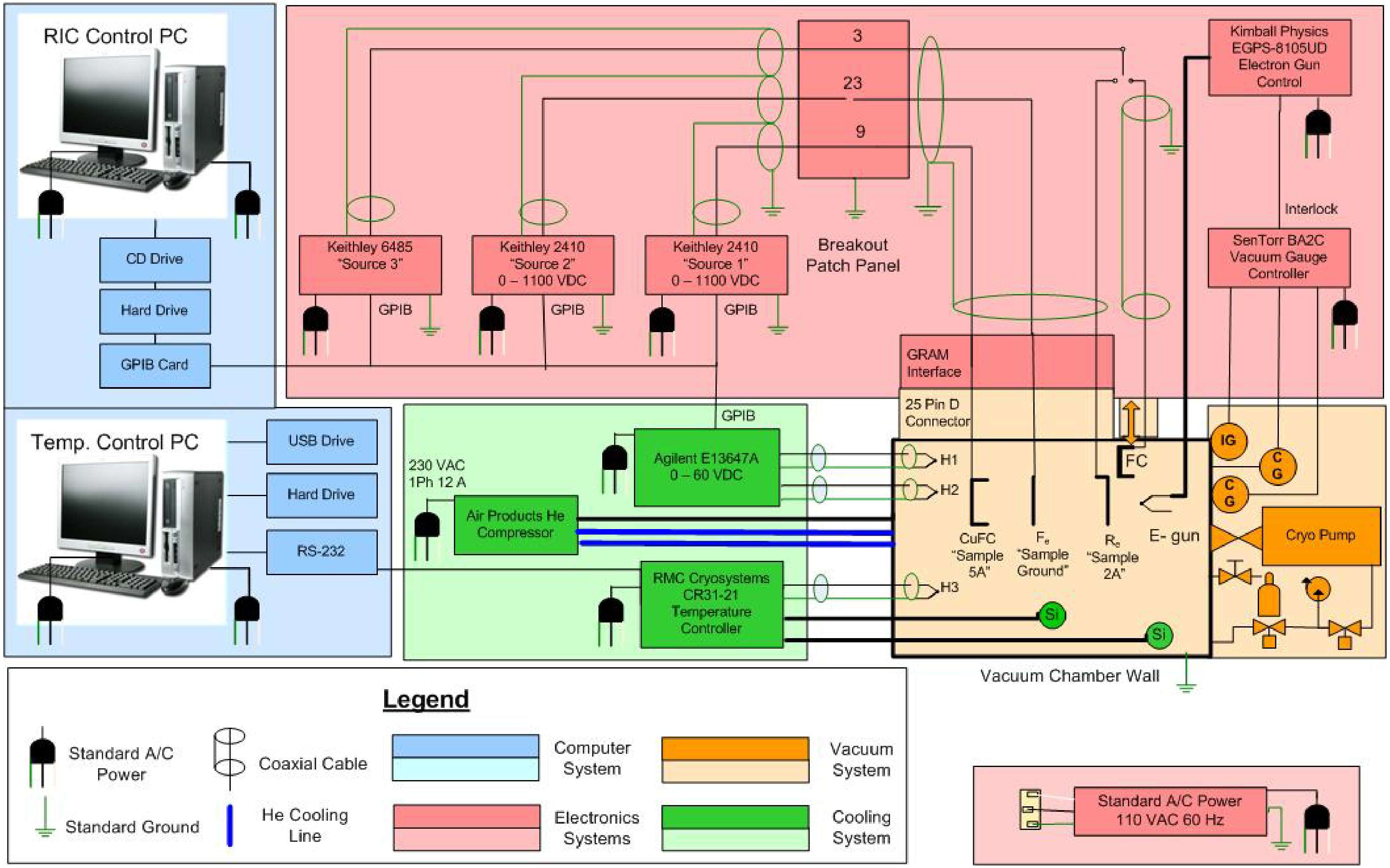


Cryostat RIC Equivalent Circuit--Full Circuit



USU/AFRL RIC Cryostat System Block Diagram

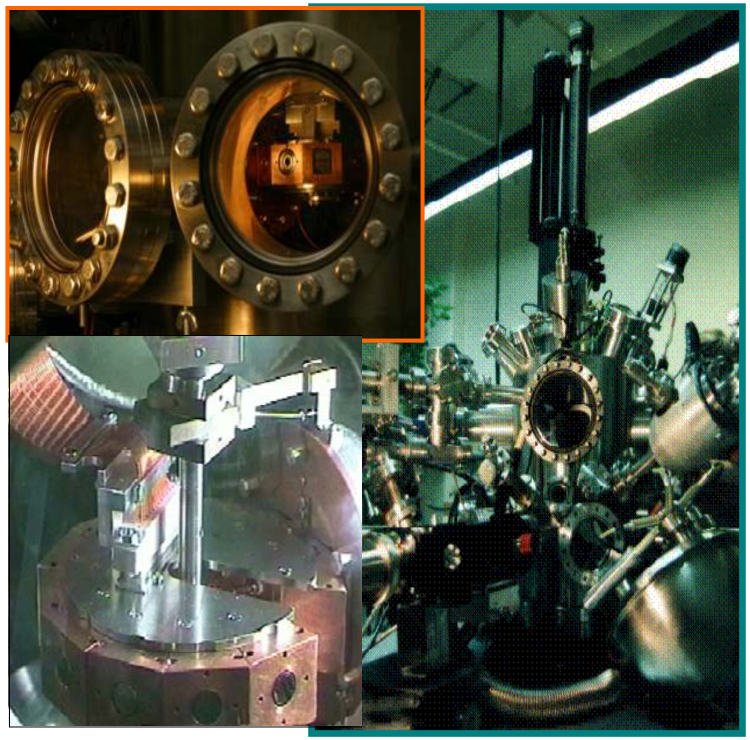
JR Dennison
Kent Hartley
Ver. 1.0 10/01/12
Ver. 1.1 10/02/12
Ver. 1.2 10/11/12

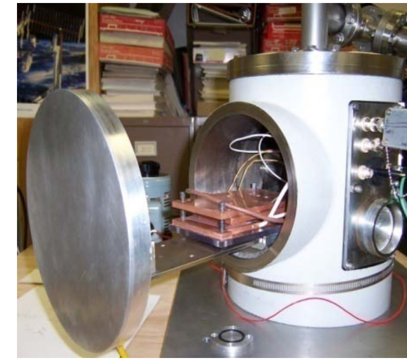


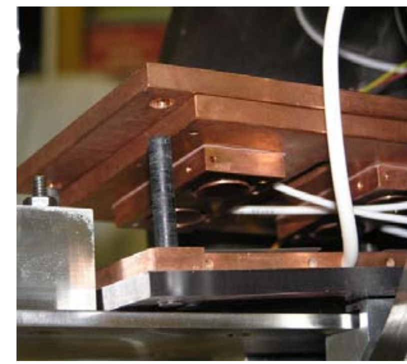
USU Experimental Capabilities

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)

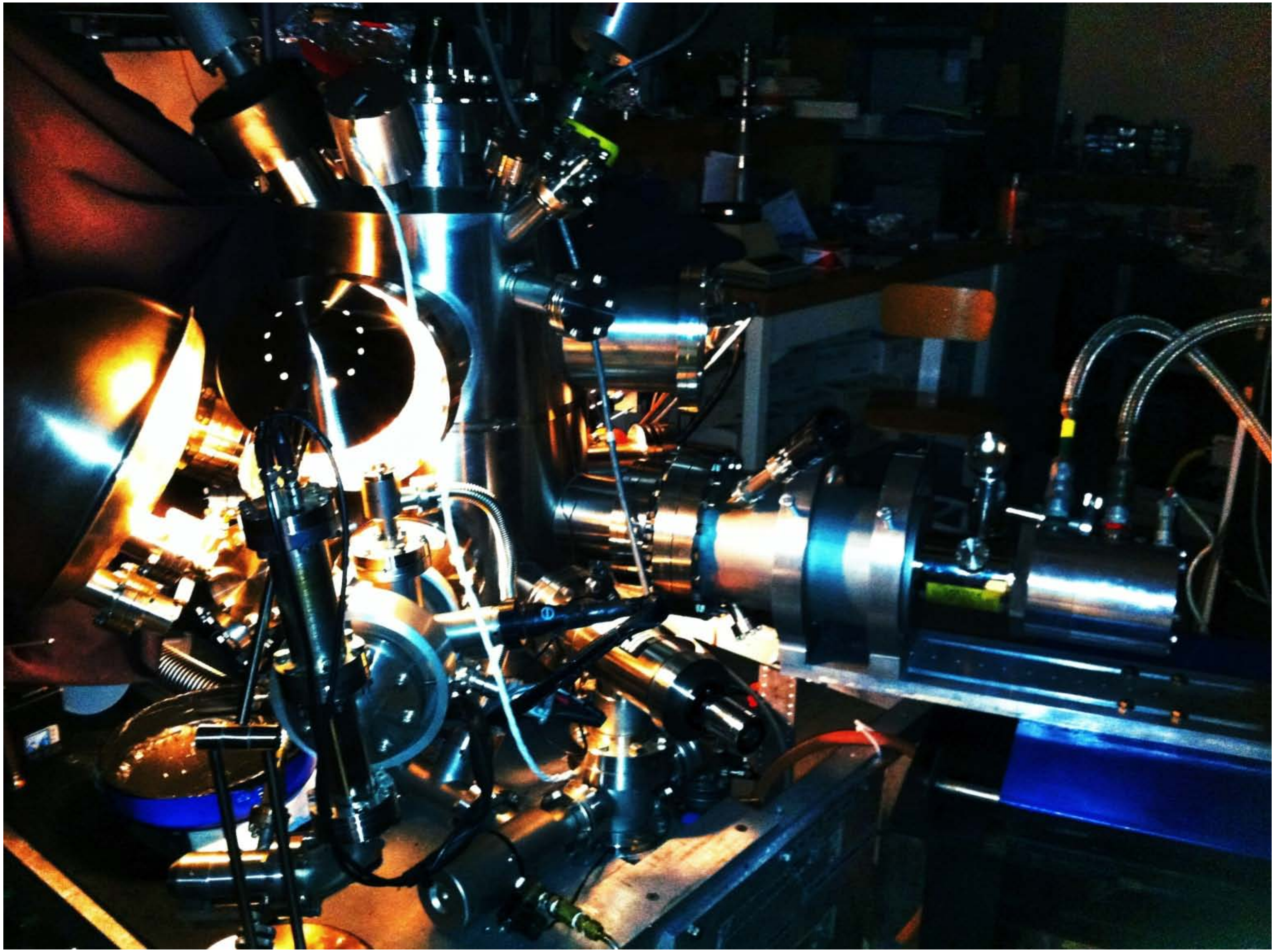






- Conductivity (<10^{-22} [ohm-cm]$^{-1}$)
- Surface Charge (<1 V to >15 kV)
- ESD (low T, long duration)
- Radiation Induced Conductivity (RIC)
- Multilayers, contamination, surface modification
- Radiation damage
- Sample Characterization

End with a Bang



Model for Luminescence Intensity in Fused Silica

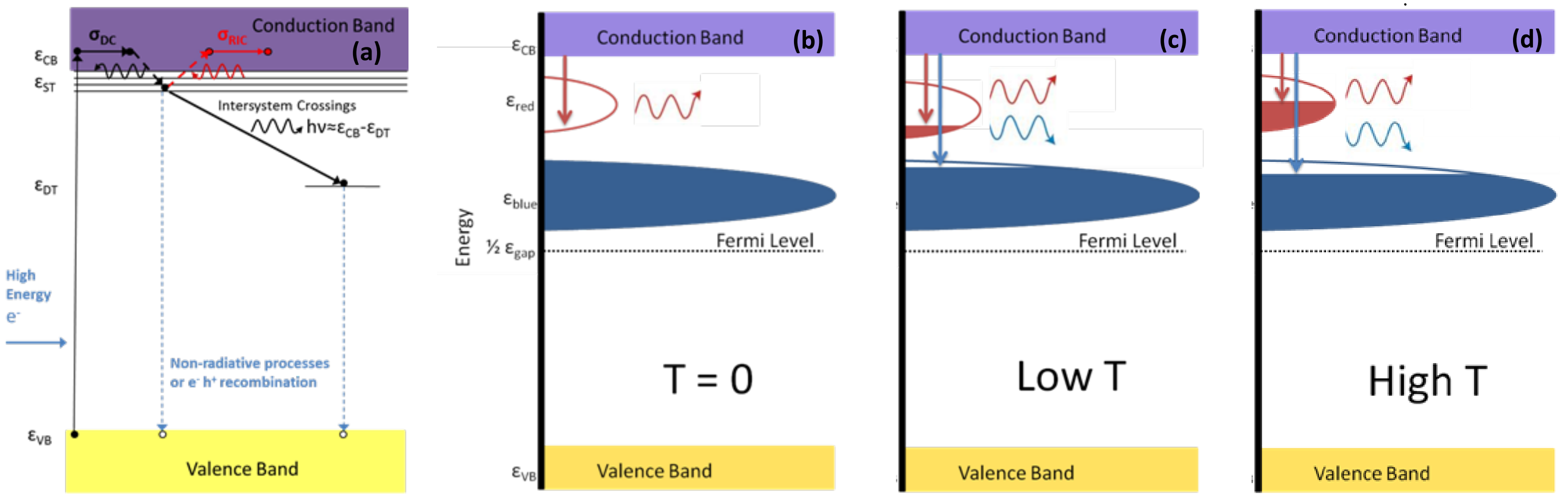


Fig. 2. Qualitative two-band model of occupied densities of state (DOS) as a function of temperature during cathodoluminescence. **(a)** Modified Joblonski diagram for electron-induced phosphorescence. Shown are the extended state valence (VB) and conduction (CB) bands, shallow trap (ST) states at ε_{ST} within ~k_BT below the CB edge, and two deep trap (DT) distributions centered at $\varepsilon_{DT}=\varepsilon_{red}$ and $\varepsilon_{DT}=\varepsilon_{blue}$. Energy depths are exaggerated for clarity. **(b)** At $T\approx 0$ 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

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

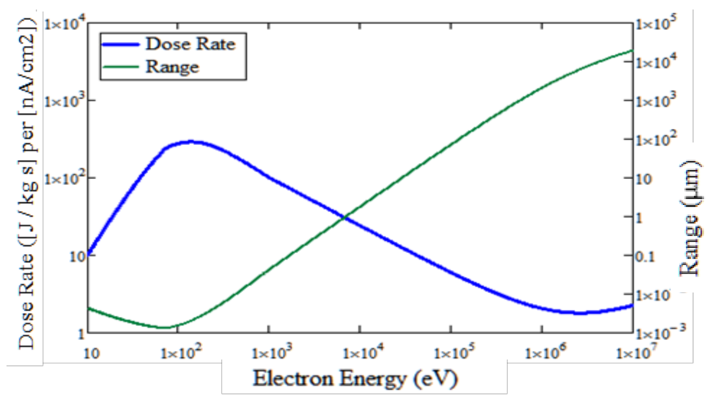


Fig. 3.Range and dose rate of disordered SiO_2 as a function of incident energy using calculation methods and the continuous slow-down approximation described in [5].

Measured Cathodoluminescence Intensity in Fused Silica

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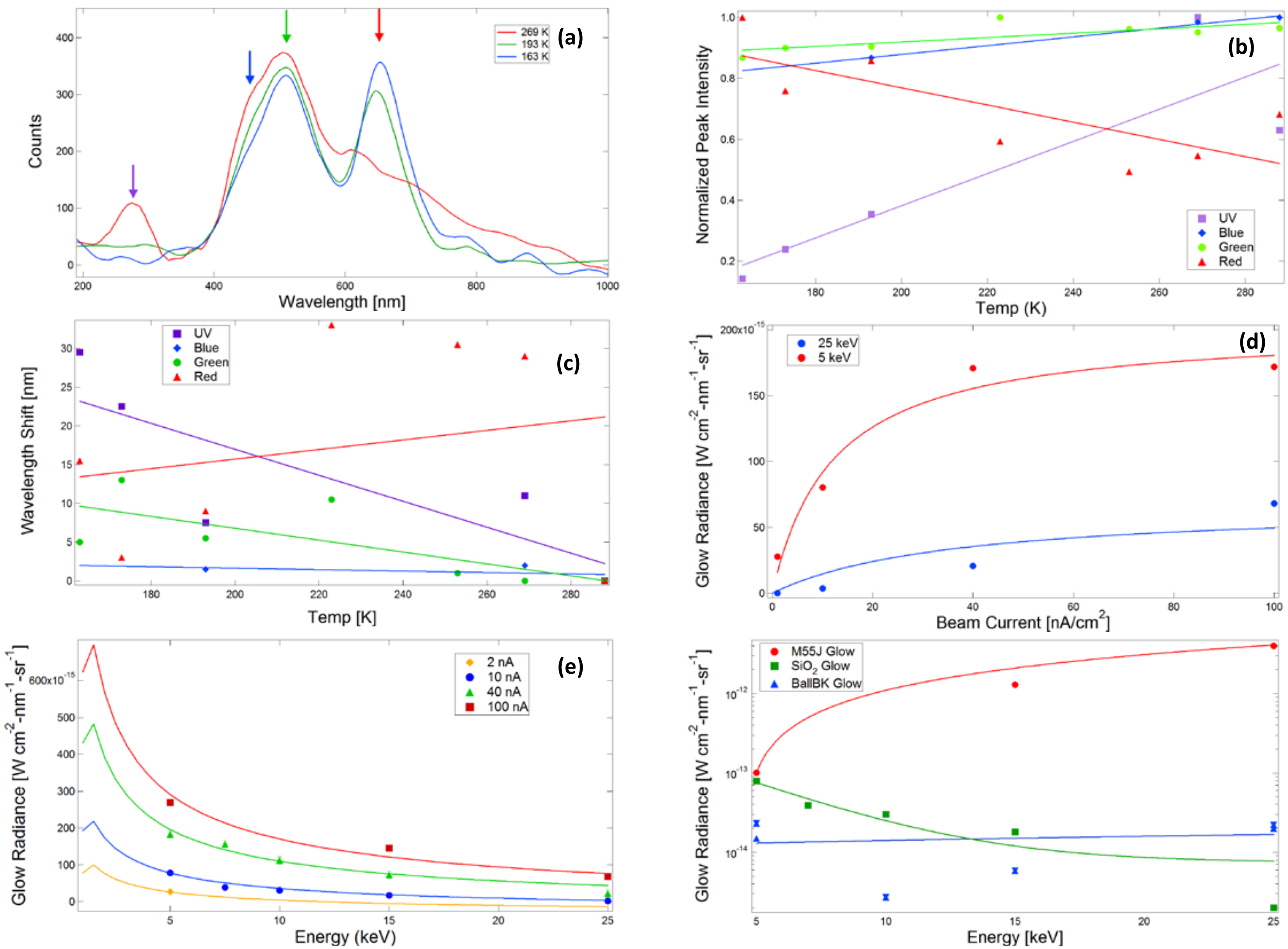
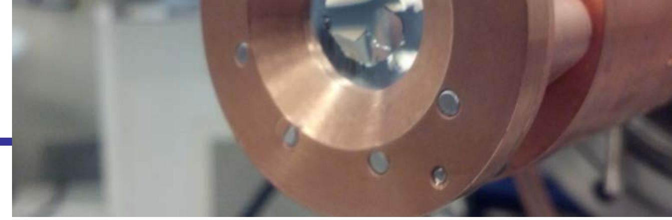
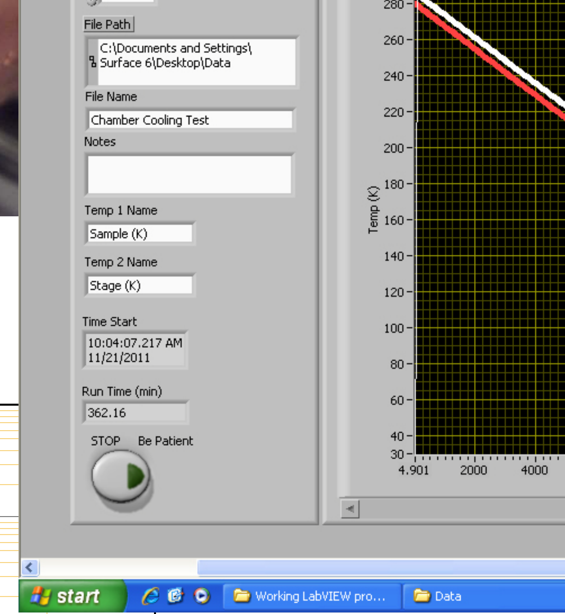


Fig. 1. Optical measurements of luminescent thin film disordered SiO_2 samples. **(a)** Three luminescence UV/VIS spectra at decreasing sample temperature. Four peaks are identified: red (~645 nm), green (~500 nm), blue (~455 nm) and UV (275 nm). **(b)** Peak amplitudes as a function of sample temperature,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




File Path
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Surface 6\Desktop\Data
File Name
Chamber Cooling Test
Notes
Temp 1 Name
Sample (K)
Temp 2 Name
Stage (K)
Time Start
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11/21/2011
Run Time (min)
362.16
STOP
Be Patient
Temp (K)
start
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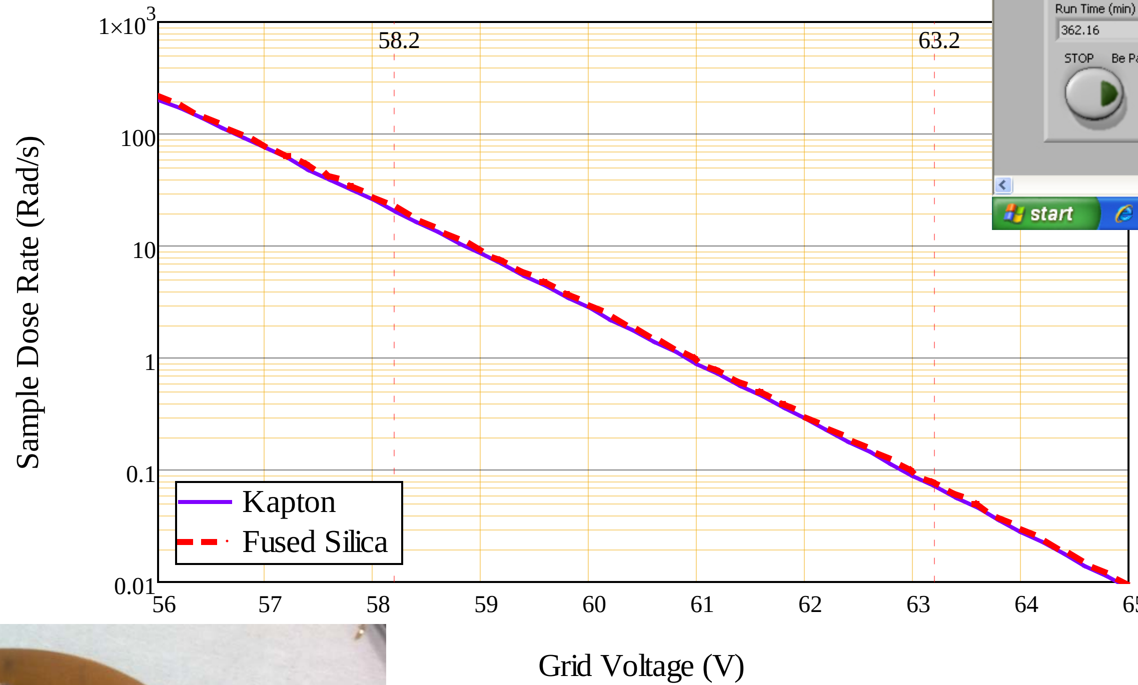
58.2
63.2
Sample Dose Rate (Rad/s)
Grid Voltage (V)
Kapton
Fused Silica
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0.01
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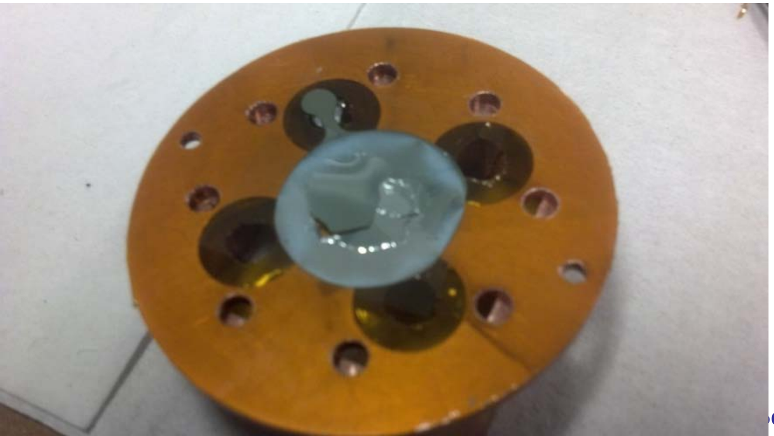
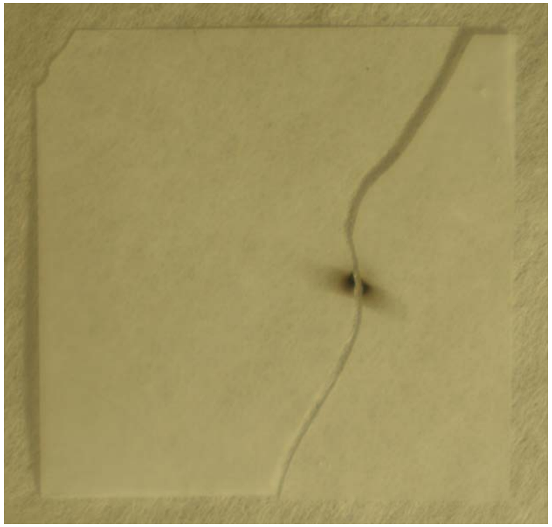
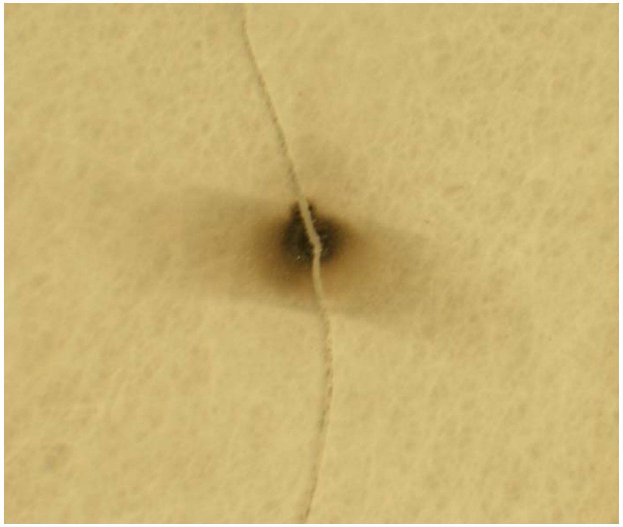
58
59
60
61
62
63
64
65



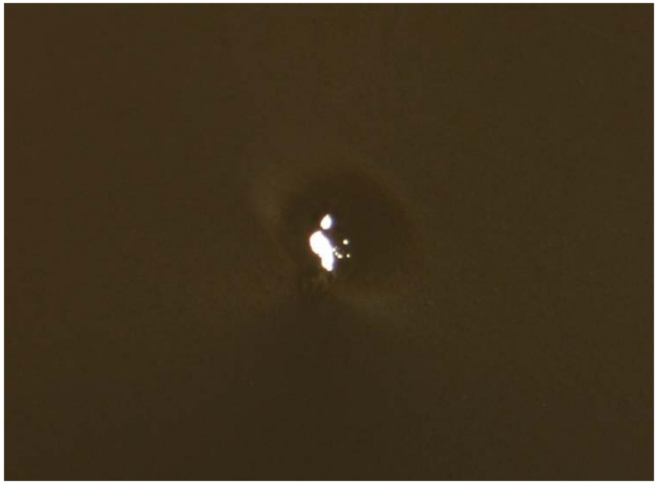
Fused Silica--Cryo ESD Breakdown Sites



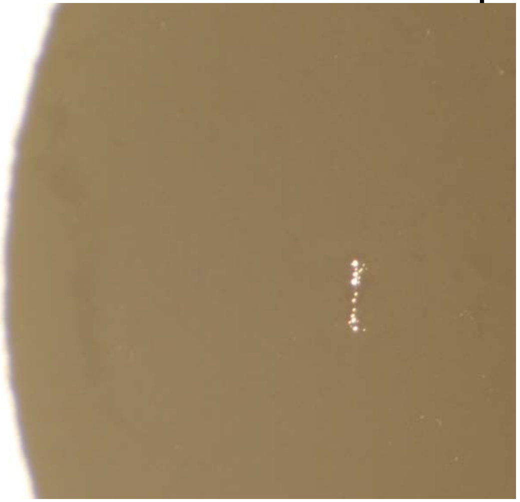
FS 4 Post-Breakdown



FS 4 Breakdown Site Close-up



Kapton Sheet Under FS 4



Kapton Pad Over FS 4

Run 10 Rear Electrode Current Analysis