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Electron Yield of Challenging Materials: Low Density Polyethylene and Carbon-Composite Nanodielectrics

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Matthew Robertson, Jordan Lee and JR Dennison

Materials Physics Group
Physics Department
Utah State University
Logan, Utah USA

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Support & Collaborations

<u>***Current Funding***</u>

NASA GRC
NASA-JPL (Europa Clipper)
NASA-JPL (Europa Lander)
AFRL
Box Elder Innovations
Solar Probe Plus (Berkley Space Lab)
SpaceX
Nokomis Technologies
CoorsTek
Varex
NASA Grad Res. Fellowships
USU PDRF Fellowships
Utah NASA Space Grant Consortium
USU Space Dynamics Lab

<u>***Recent Funding***</u>

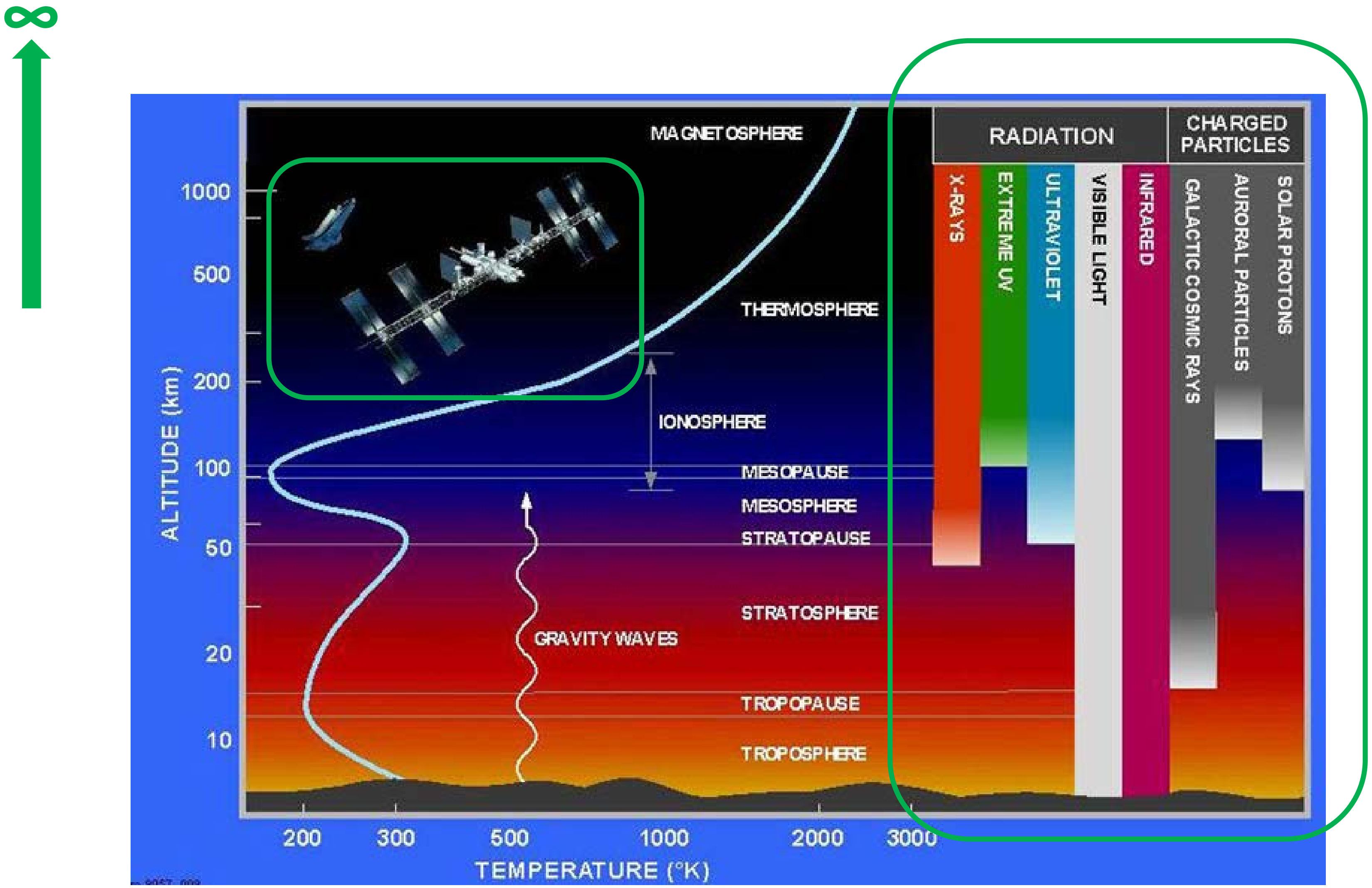
NASA SEE Program
JWST (GSFC/MSFC)
NASA MSFC
ViaSat (Comm. Sats)
Times Microwave (Comm Sats)
Lockheed Martin (Orion Space Capsule)
Solar Probe Mission (JHU/APL)
Rad. Belt Space Probe (JHU/APL)
Solar Sails (JPL)
AFRL
NSF
Boeing
Ball Aerospace
Orbital
LAM Research Corporation
AFRL/NRC Fellowship
Sienna Technologies

(Back row Left to Right) Ben Russon, Heather Zollinger, Zack Gibson, Matthew Robertson, Jordan Lee, David King

(Front row Left to Right) Justin Christensen, Alexandra Hughlett Nelson, Alex Souvall, Greg Wilson, Allen Andersen, JR Dennison, Windy Olsen

(Not pictured) Brian Wood, Vladimir Zavyalov, Jodie Gillespie, Jonh Mojica Decena, Tyler Kippen, Lisa Phillipps, Phil Lundgreen, Tanner Linton

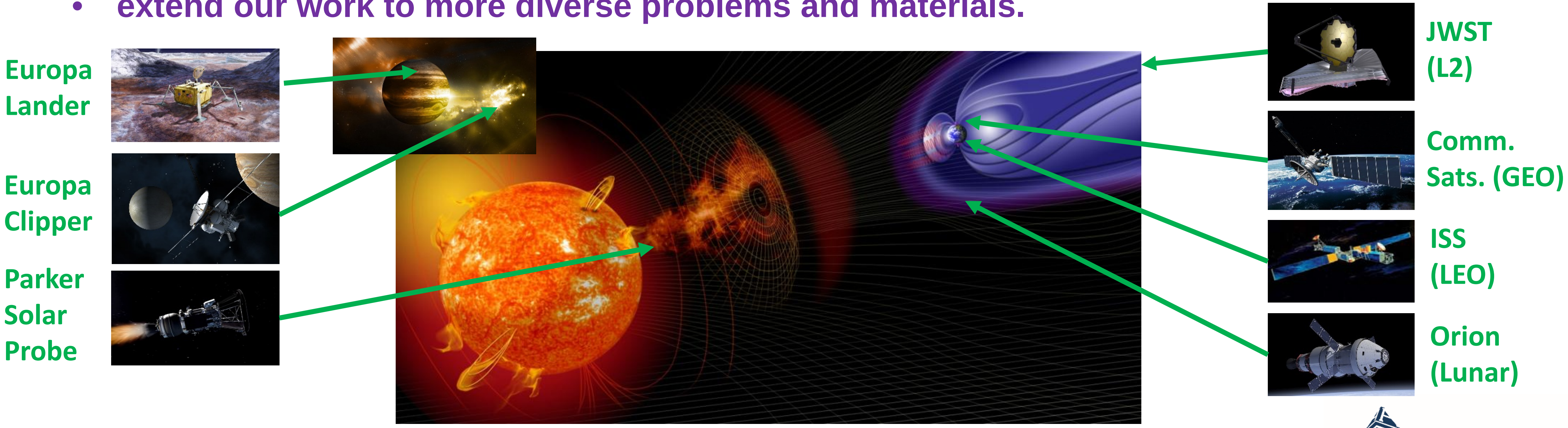
Putting MPG Work in Context



Bottom line for the *USU Materials Physics Group*:

Interactions with this harsh space environment can modify materials and cause unforeseen and detrimental effects to spacecraft. Therefore, we:

- **simulate the space environments,**
- **characterize their effects on materials properties,**
- **use these results to predict and mitigate space environment effects,**
- **work to understand the materials physics involved at the atomic scale to**
- **extend our work to more diverse problems and materials.**



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The True Bottom Line for JR:

To paraphrase Douglas Adams,

"Space is [harsh]. Really [harsh]. You just won't believe how vastly, hugely, mind-bogglingly [harsh] it is.

I mean, you may think it's a long way down the road to the chemist, but that's just peanuts to space."

D. Adams--*Hitchhiker's Guide to the Galaxy*

JR Dennison, Kent Hartley, Lisa Montierth Phillipps, Justin Dekany, James S. Dyer, and Robert H. Johnson, "Small Satellite Space Environments Effects Test Facility," *Proceedings of the 28th Annual AIAA/USU Conference on Small Satellites*, (Logan, UT, August 2-7, 2014), 7pp.

Where Materials Testing Fits into the Solution

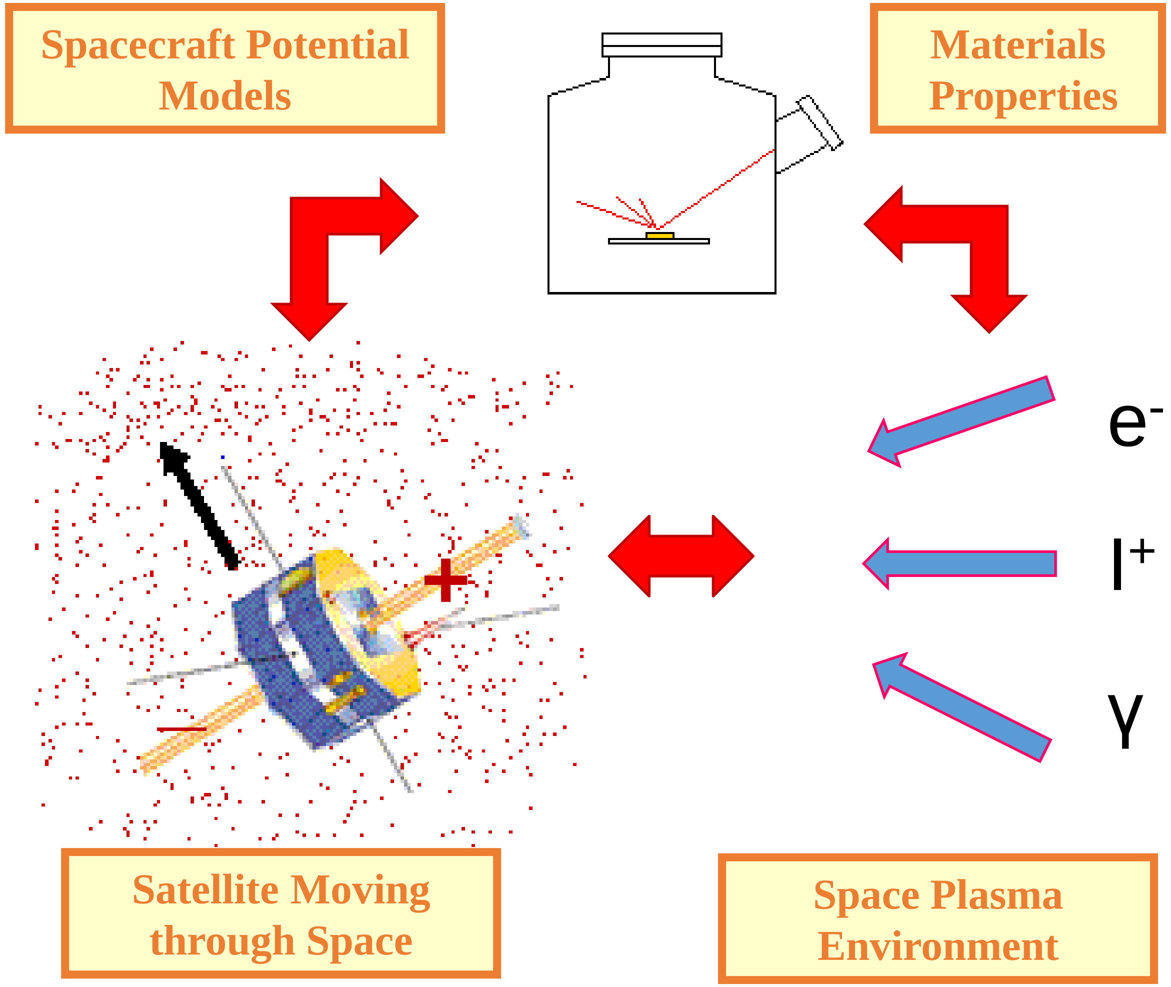
Charge Accumulation

- Electron yields
- Ion yields
- Photoyields
- Luminescence

Charge Transport

- Conductivity
- Radiation Induced Conductivity
- Permittivity
- Electrostatic breakdown
- Penetration range

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



Complex dynamic interplay between space environment, satellite motion, and materials properties

USU Materials Physics Group Capabilities

Facilities & Capabilities

Sample Characterization & Preparation
- Bulk composition (AA, IPC).
- Surface contamination (AES, AES mapping ESD).
- Surface morphology (SEM, optical microscopy).

Conduction Related Properties:
- Bulk & surface conductivity.
- High resistivity testing.
- *C*apacitance, dielectric constant, charge decay monitoring, and electrostatic discharge.

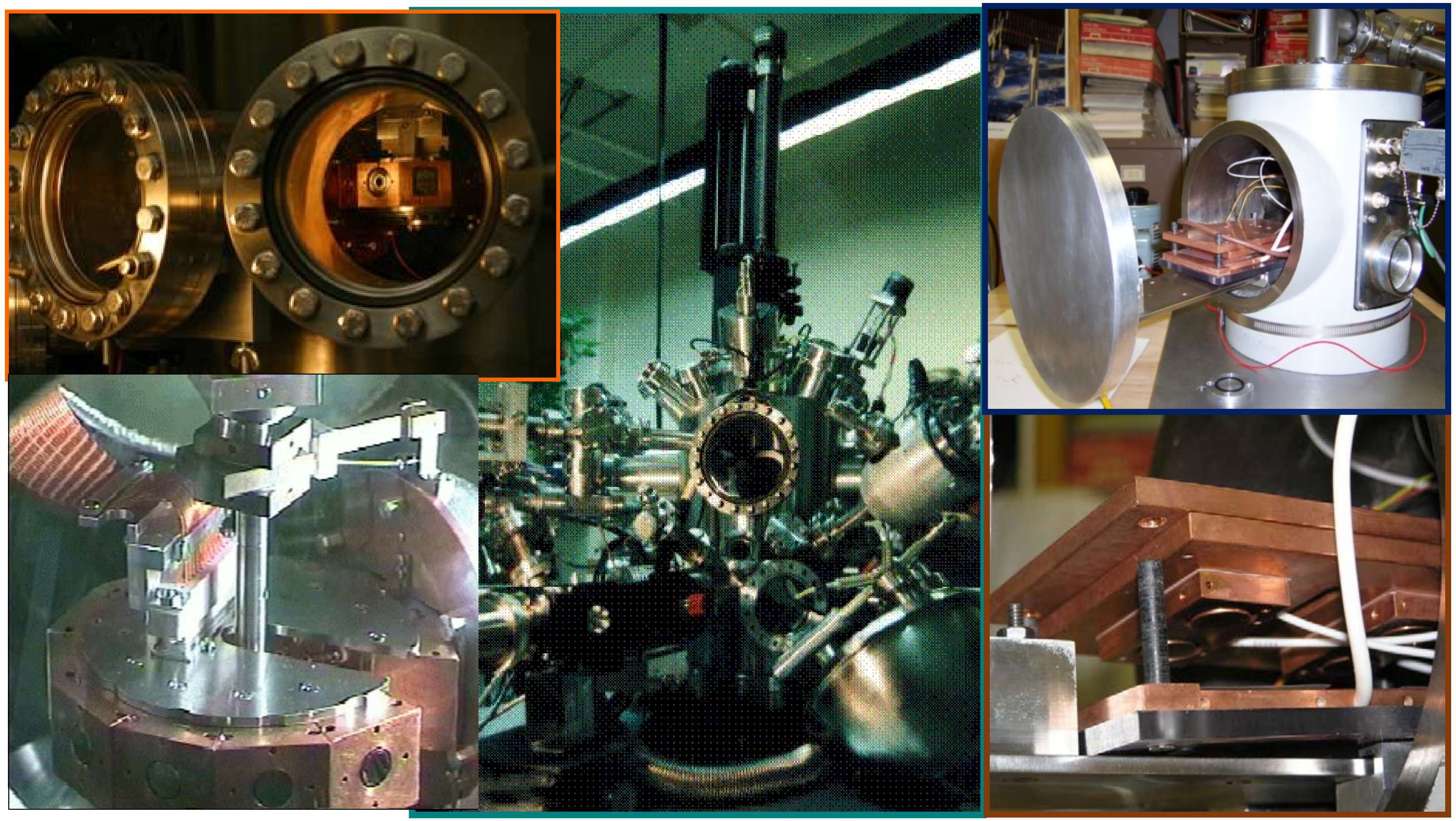
Electron Induced Emission:
- Total, secondary and backscattered yield vs. incident energy and angle.
- Energy-, angle-resolved emission spectra.
- Cathodoluminescence

Ion Induced Emission:
- Total electron and ion yield versus incident energy and angle.

Photon Induced Emission:
- Total electron yield vs photon energy.
- Energy-angle resolved photoelectron yield cross-sections.

Electron Induced Arcing:

- **Four ultrahigh vacuum chambers for electron emission tests equipped with electron, ion, and photon sources, detectors, and surface analysis capabilities.**
- **Two high vacuum chambers for resistivity tests.**
- **High vacuum chamber for electrostatic breakdown tests.**
- **Ultrahigh vacuum chamber for pulsed electro acoustic measurements of internal charge distributions.**



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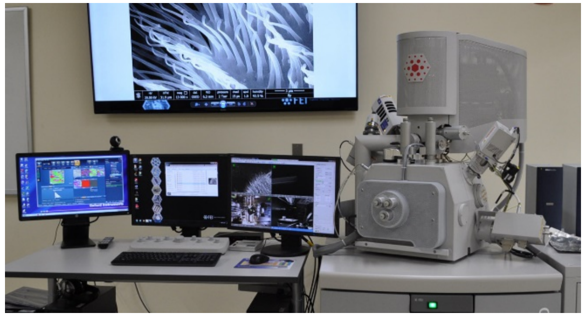
Myriad of Applications

Spacecraft Charging

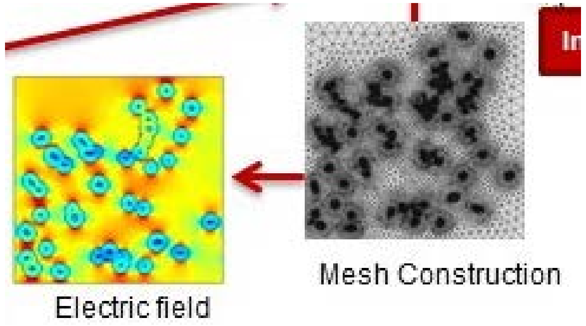
Particle Accelerators

HVDC Transmission

Electron Microscopy

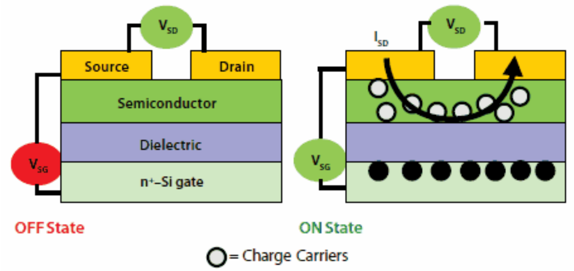


Nanodielectrics

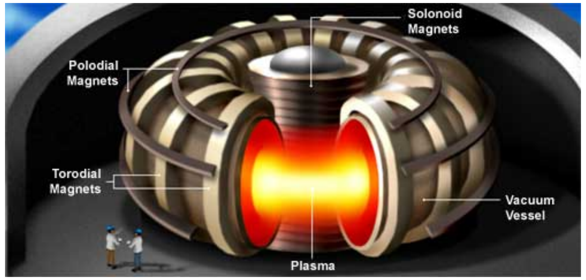


High Voltage Switching & Devices

Dielectric Layers

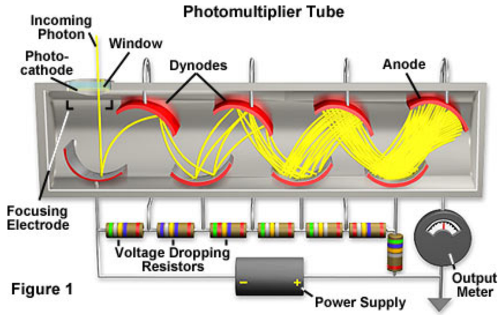


Plasma Devices

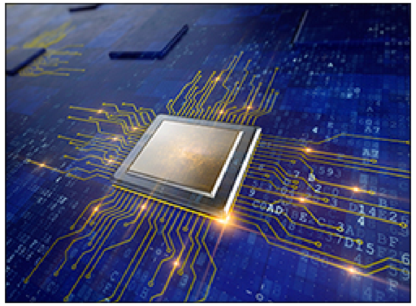


Klystron, Multipactors

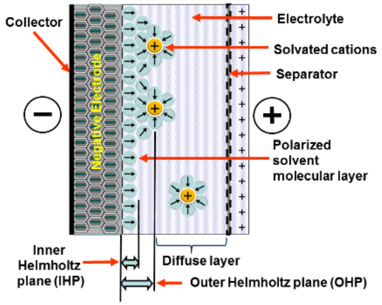
Photomultipliers



Microelectronics



Supercapacitors



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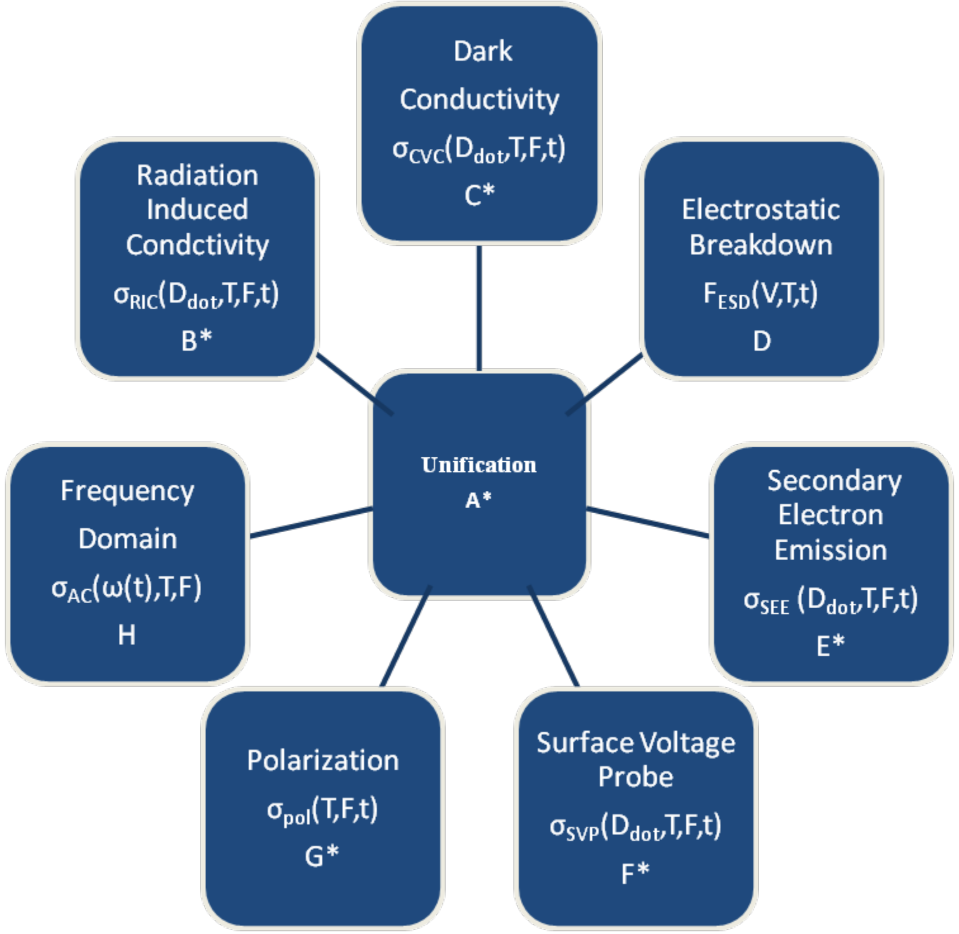
A Materials Physics Approach to the Problem

Measurements with many methods…



Interrelated through a…

Complete set of dynamic transport equations

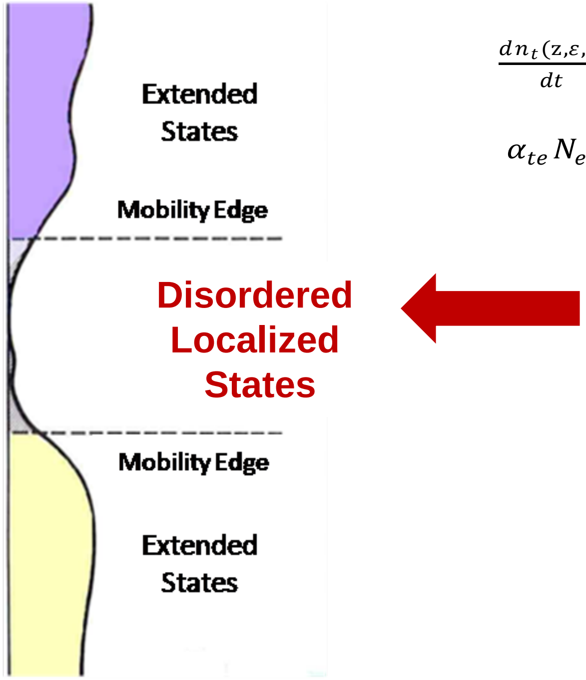
$$J = q_e n_e(z,t)\mu_e F(z,t) + q_e D \frac{dn_{tot}(z,t)}{dz}$$

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

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

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

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



…written it terms of spatial and energy distribution of electron trap states

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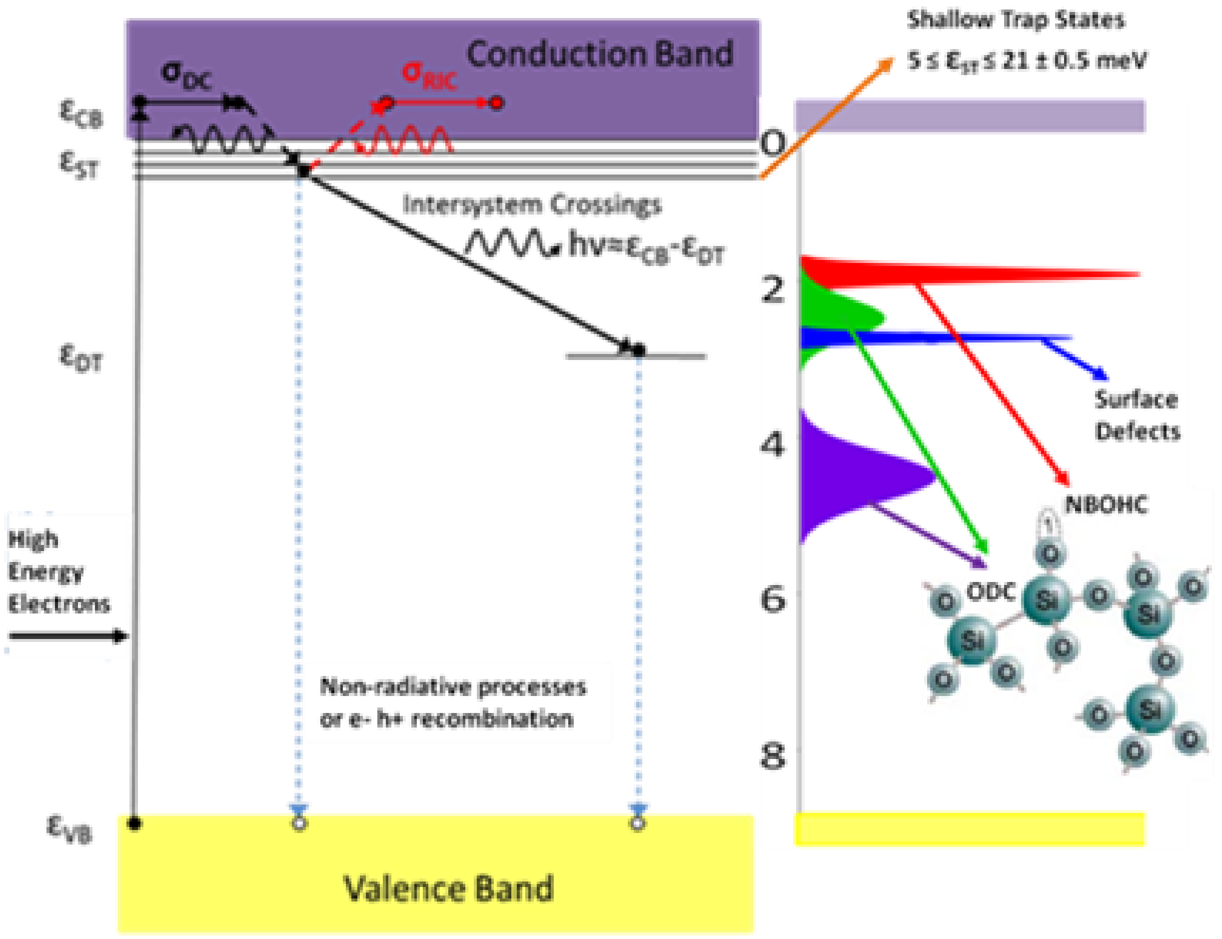
Putting the Pieces Together

Focus on DOS:

- Synthesis of results from different studies and techniques

- Development of overarching theoretical models allow extension of measurements made over limited ranges of environmental parameters to make predictions for broader ranges encountered in space.



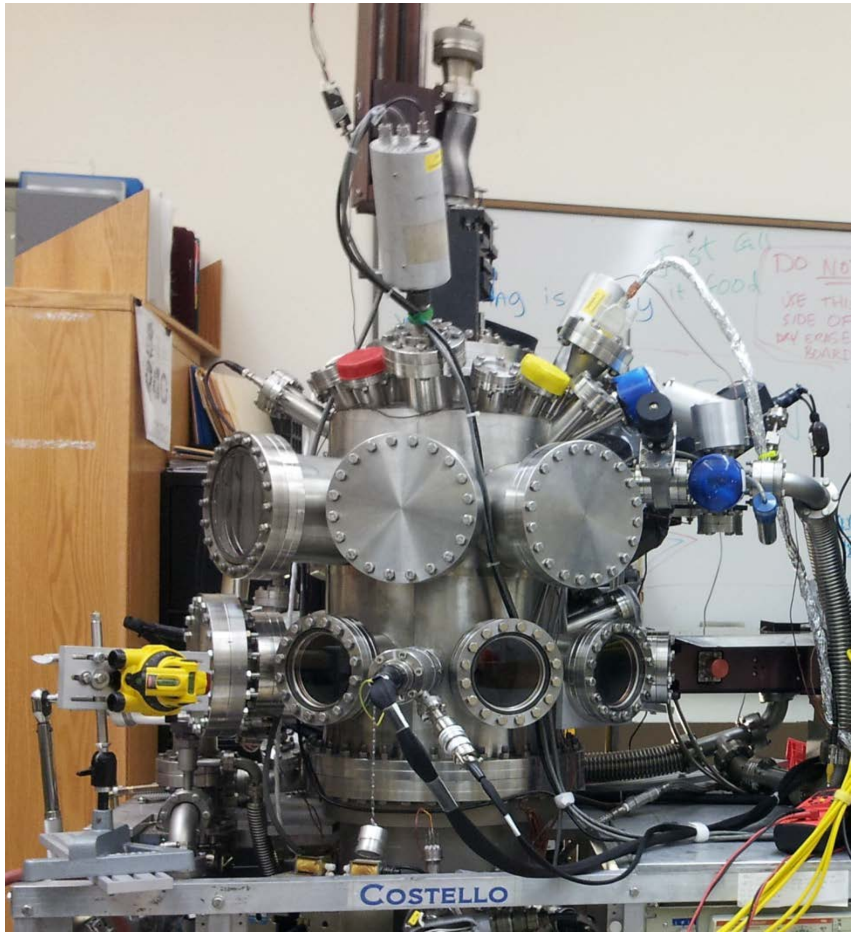
Band	Peak	Peak	FWHM	Defect	Ref.
Red	1.93±0.01 eV	663±3 nm	42 nm	NBOHC	[16,20,23]
Green	2.48±0.03	506±7	68	ODC	[17,23]
Blue	2.76±0.03	450±5	11	Surface	[18-20,23]
UV	4.97	275	50	ODC	[17-20,23]

Electron Yield Tests

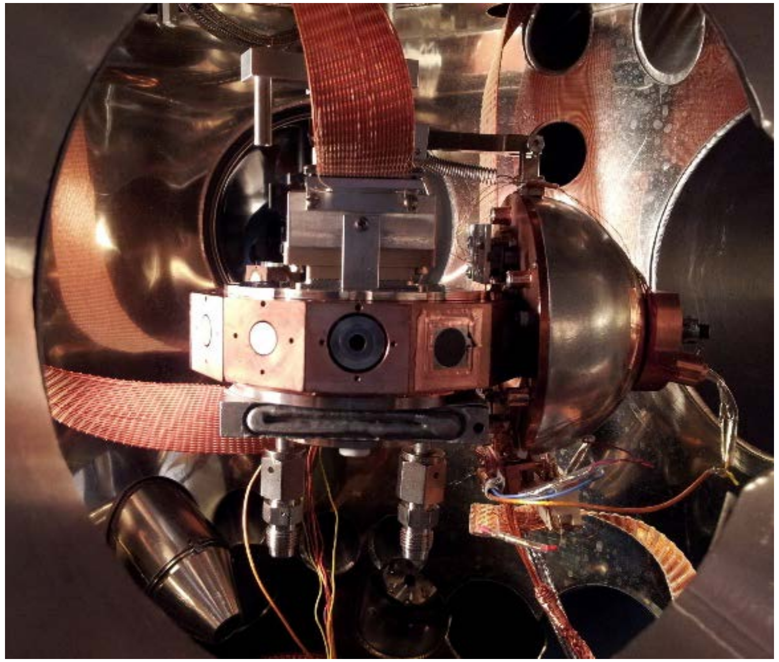
EET Chamber

Animated Video of Chamber

Measuring Pulsed / DC Yields



- Pressures from 10^{-7} Torr – 10^{-9} Torr
- Temperature range of 40 – 400 K
- Electron energies from 20 eV – 30,000 eV
- The hemispherical grid retarding field analyzer (HGRFA) measures the electron yield of different materials.



Conductors

No difference between Pulsed and DC measurements

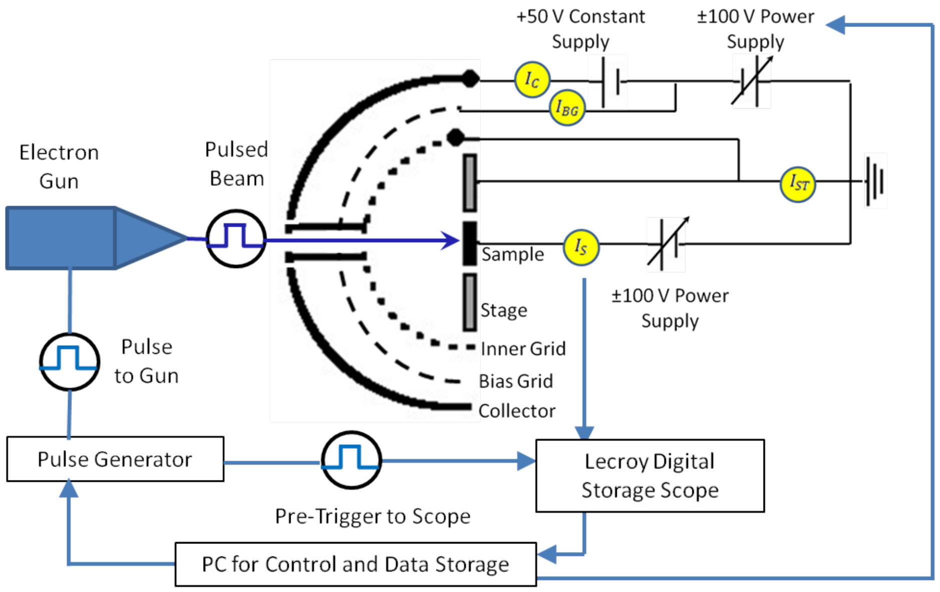
Insulators

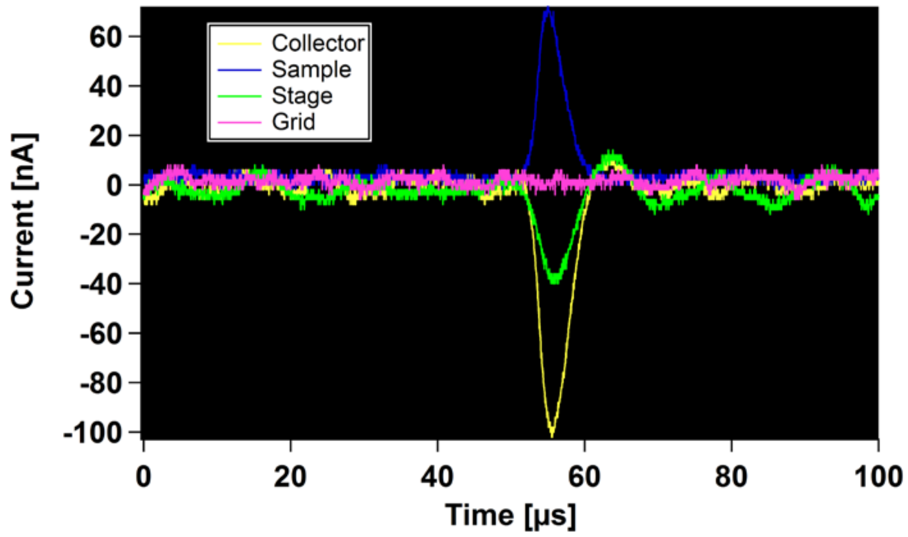
Embedded charge

Difference between Pulsed and DC measurements

Flooding (UV LED & Flood Gun)

Pulsed Backscattered and Secondary Yield Measurements





Charges

$$Q_{incident} = Q_{sample} + Q_{collector} + Q_{Grid} + Q_{stage}$$
$$Q_{emitted} = Q_{collector} + Q_{Grid} + Q_{stage}$$

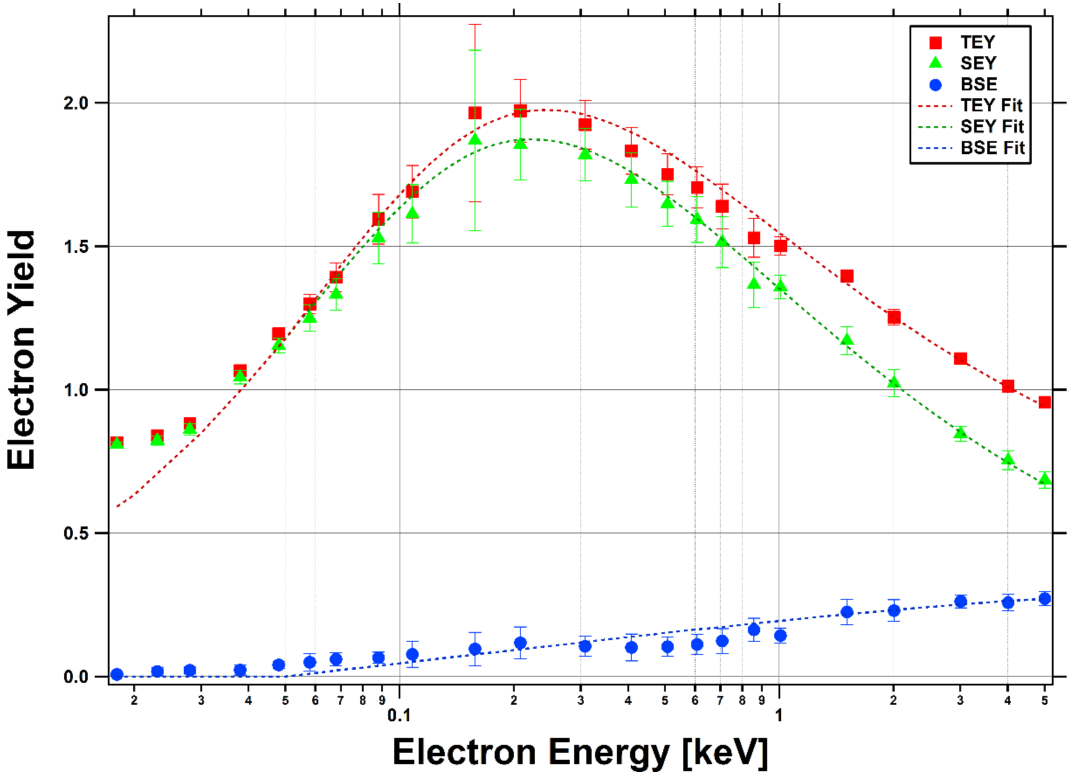
Currents

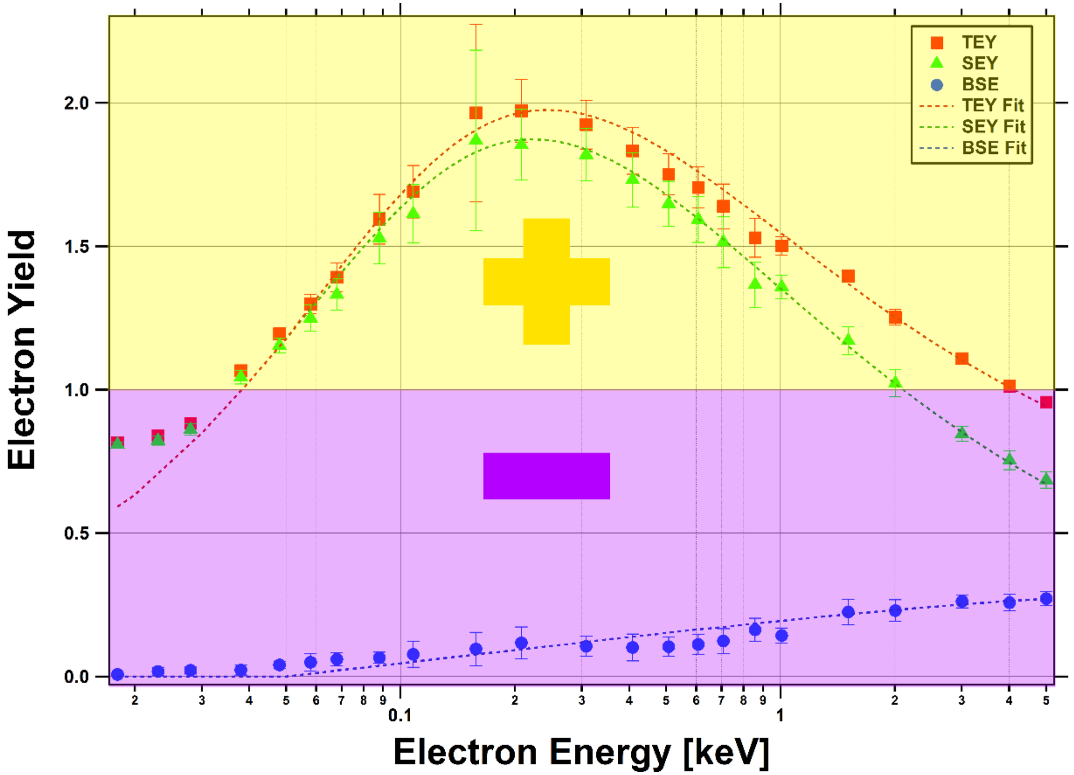
$$(TEY)\ \sigma = \frac{Q_{emit}}{Q_{incident}} = \frac{\int [I_{collector} + I_{grid} + I_{stage}]\ dt}{\int [I_{sample} + I_{collector} + I_{grid} + I_{stage}] dt}$$

$$(BSEY)\ \eta = \frac{Q_{emit}}{Q_{incident}} = \frac{C \int I_{collector}\ dt}{\int [I_{sample}+I_{collector}+I_{grid}+I_{stage}]\ dt}$$

$$(SEY)\ \delta = \sigma - \eta$$

Tungsten Pulsed Yield





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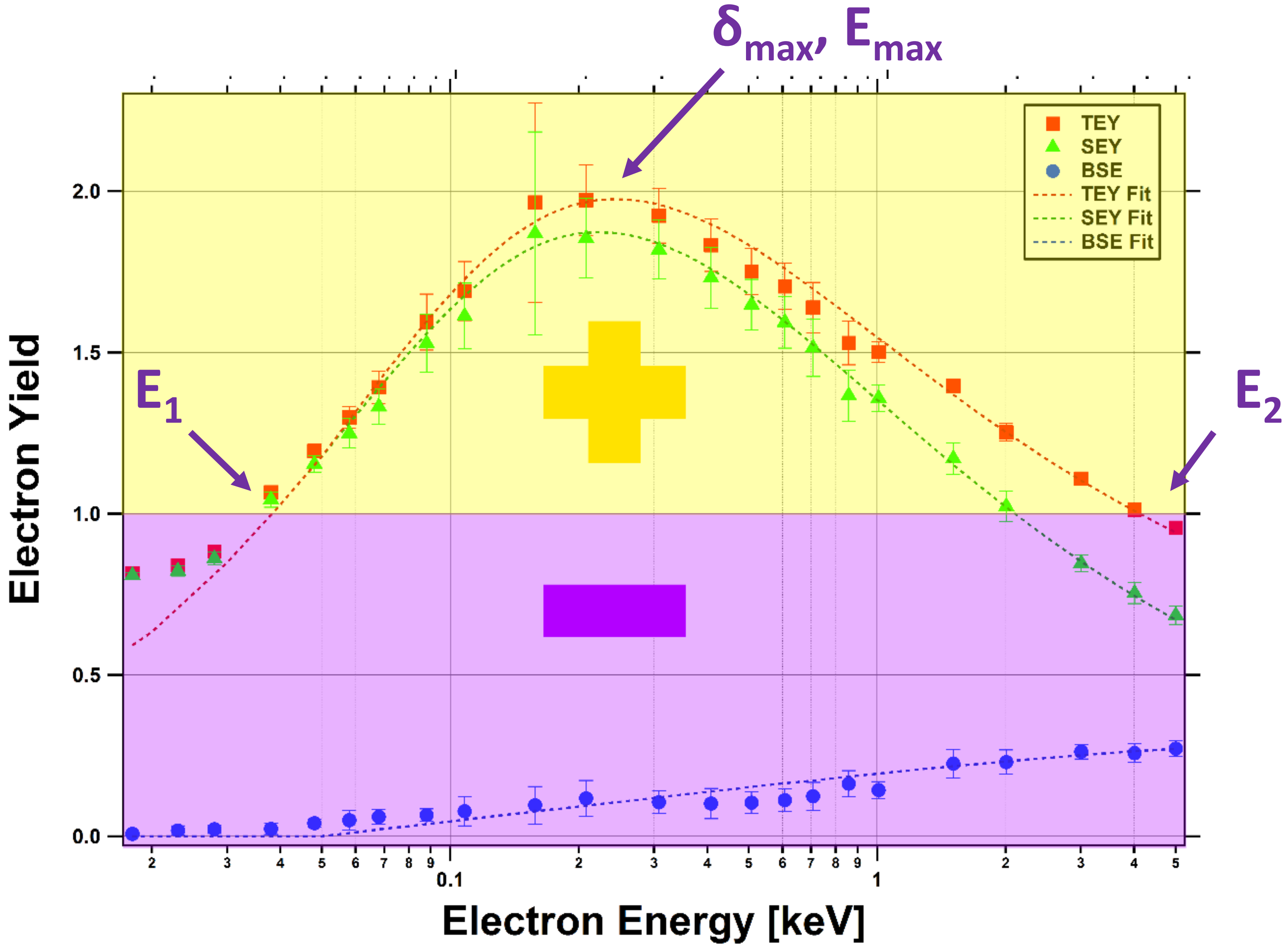
Tungsten Pulsed Yield



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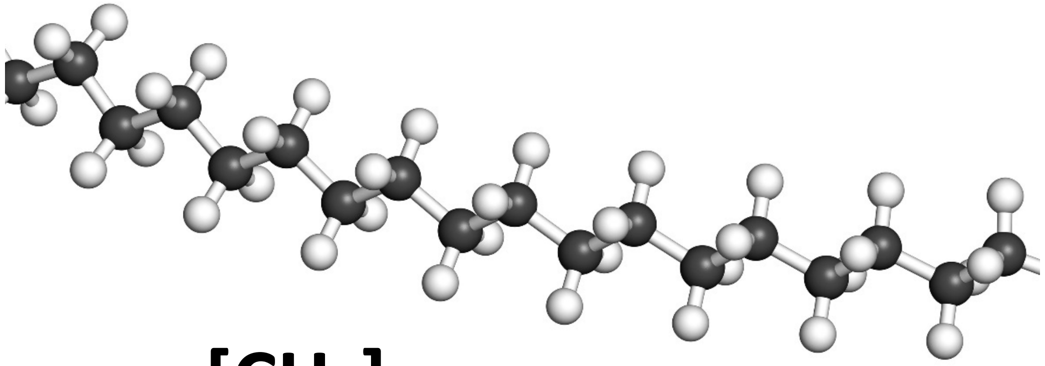
LDPE

- High material resilience
- High chemical resistance
  - Acids
  - Bases
- Range of uses
  - Industrial packaging
  - Laboratory bottles
  - Insulator for electrical equipment on satellites



$-[CH_2]_n-$

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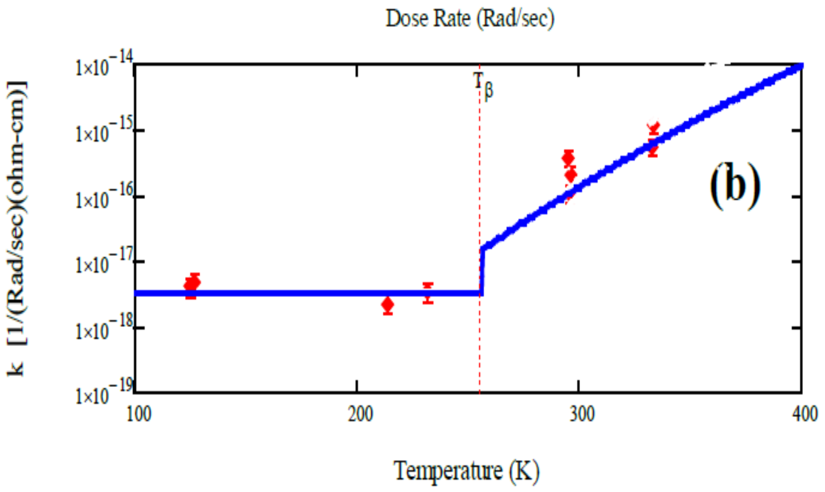
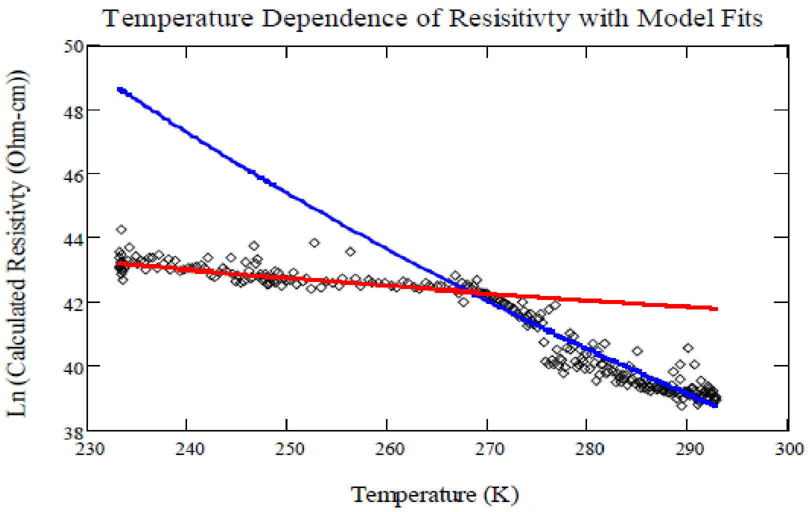
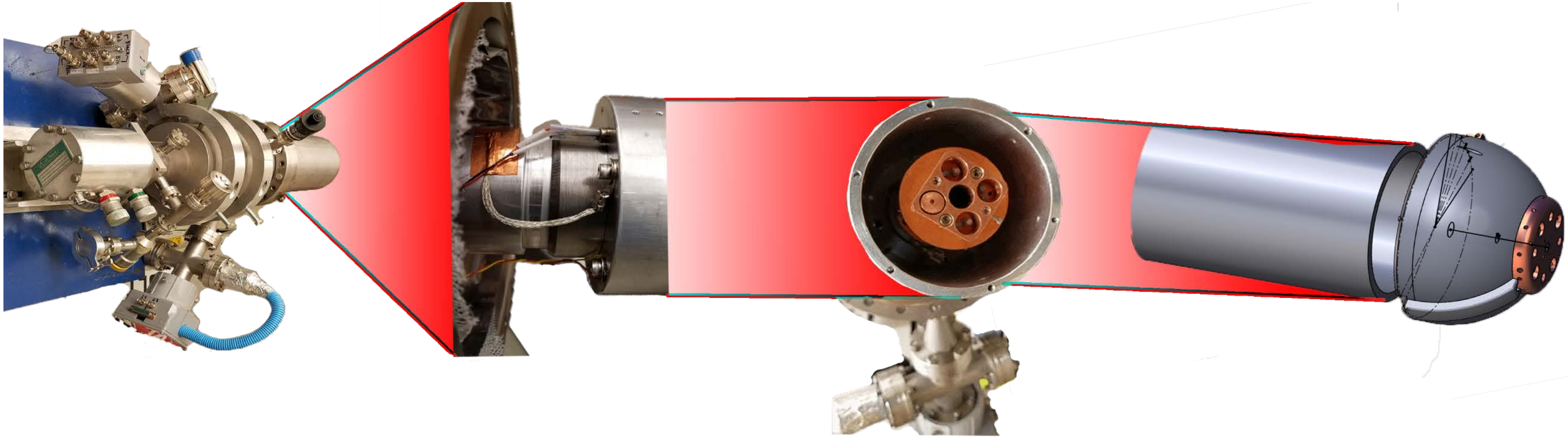
LDPE (Graph)

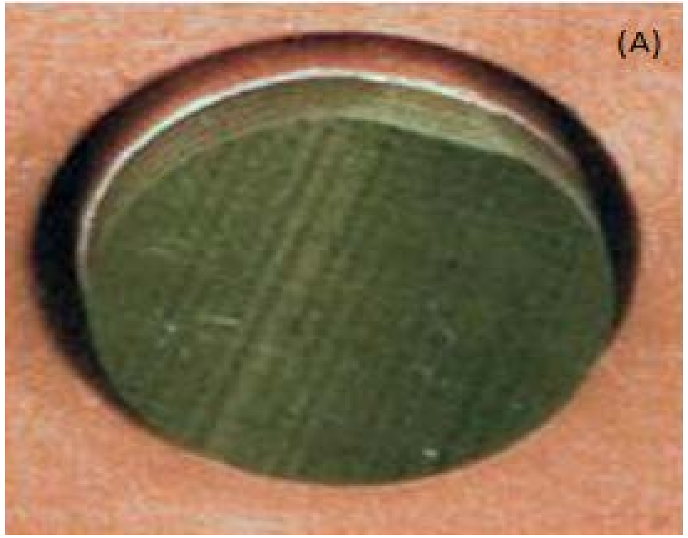
Next step for LDPE



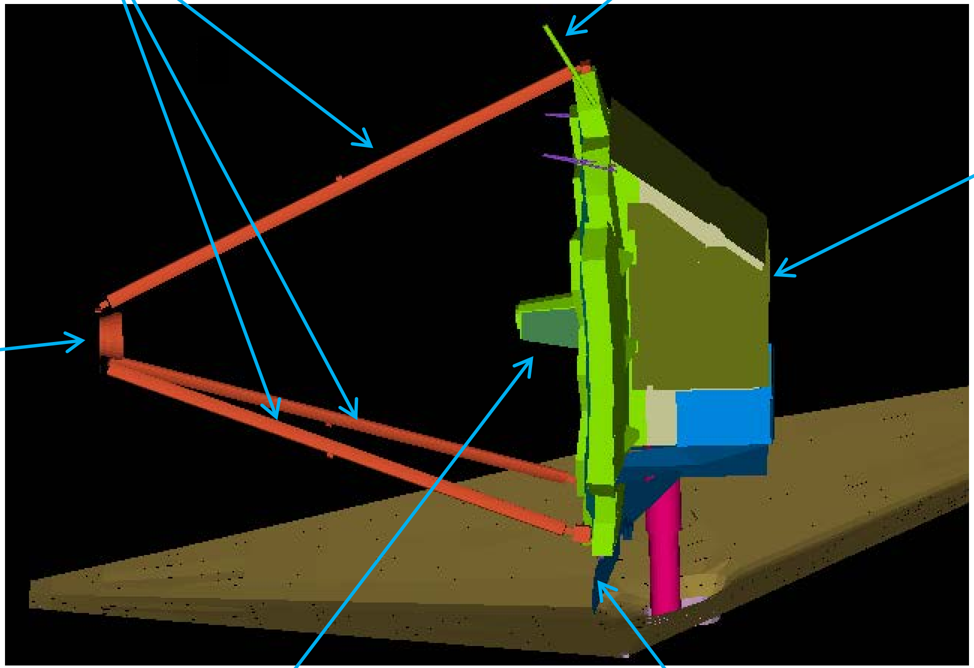




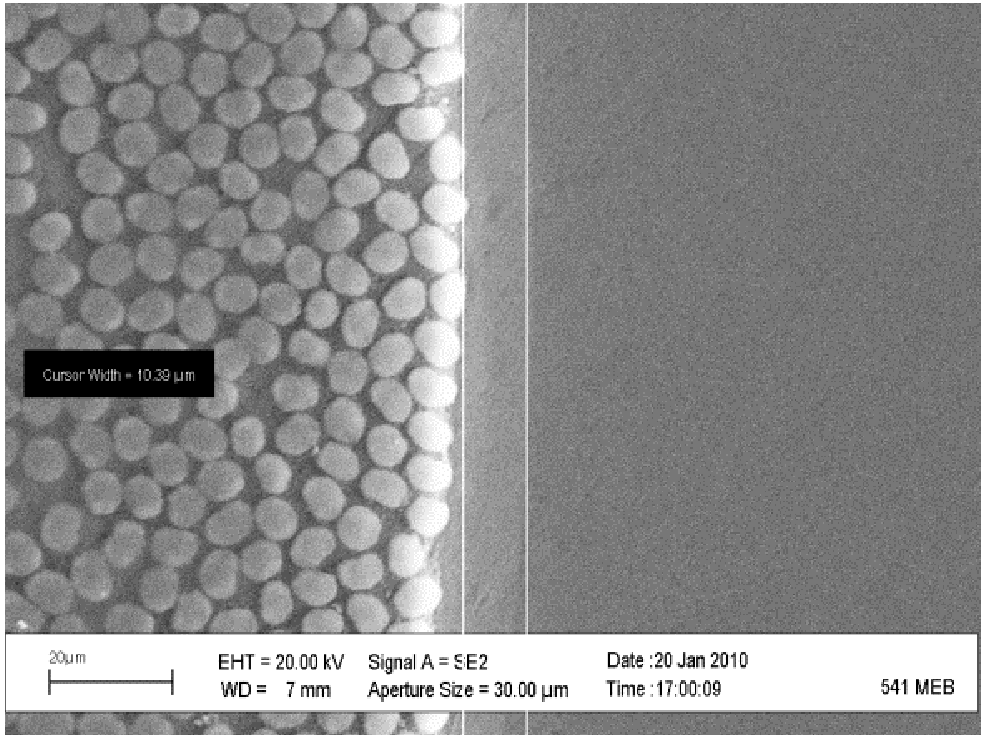
Modeling Composite Materials

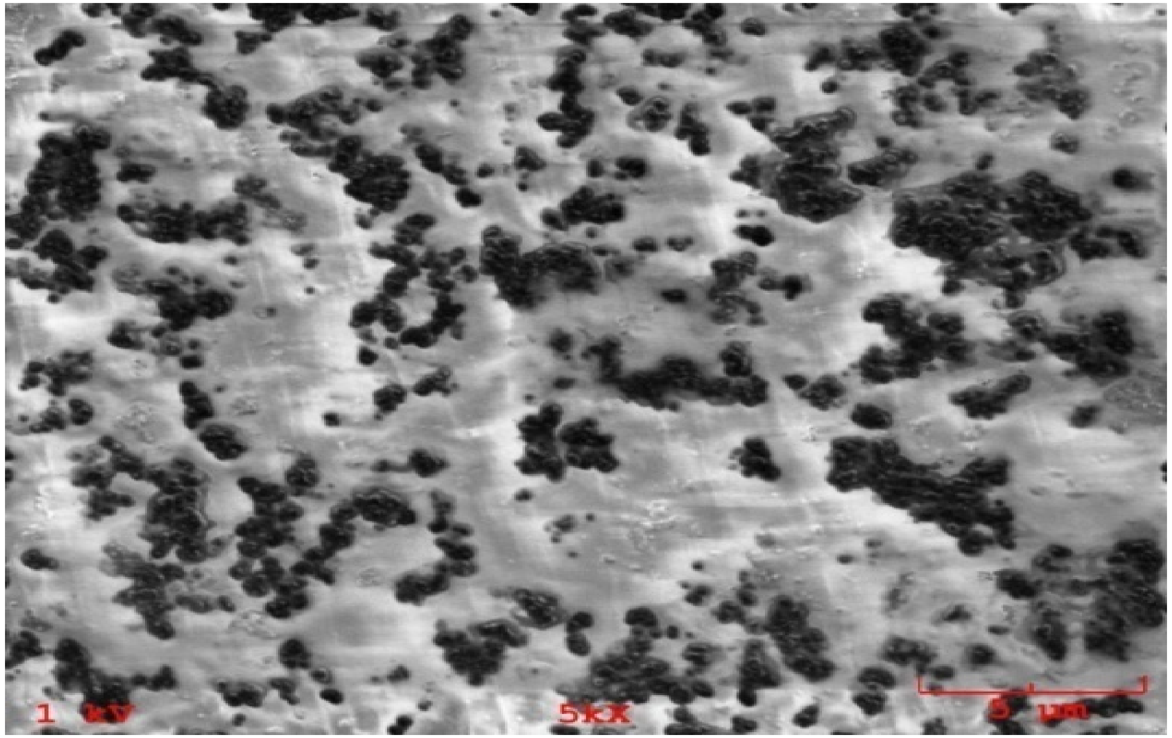


Possible Problem Areas for Electroluminescent Glow



Multilayer/Nanocomposite Effects???





10 µm

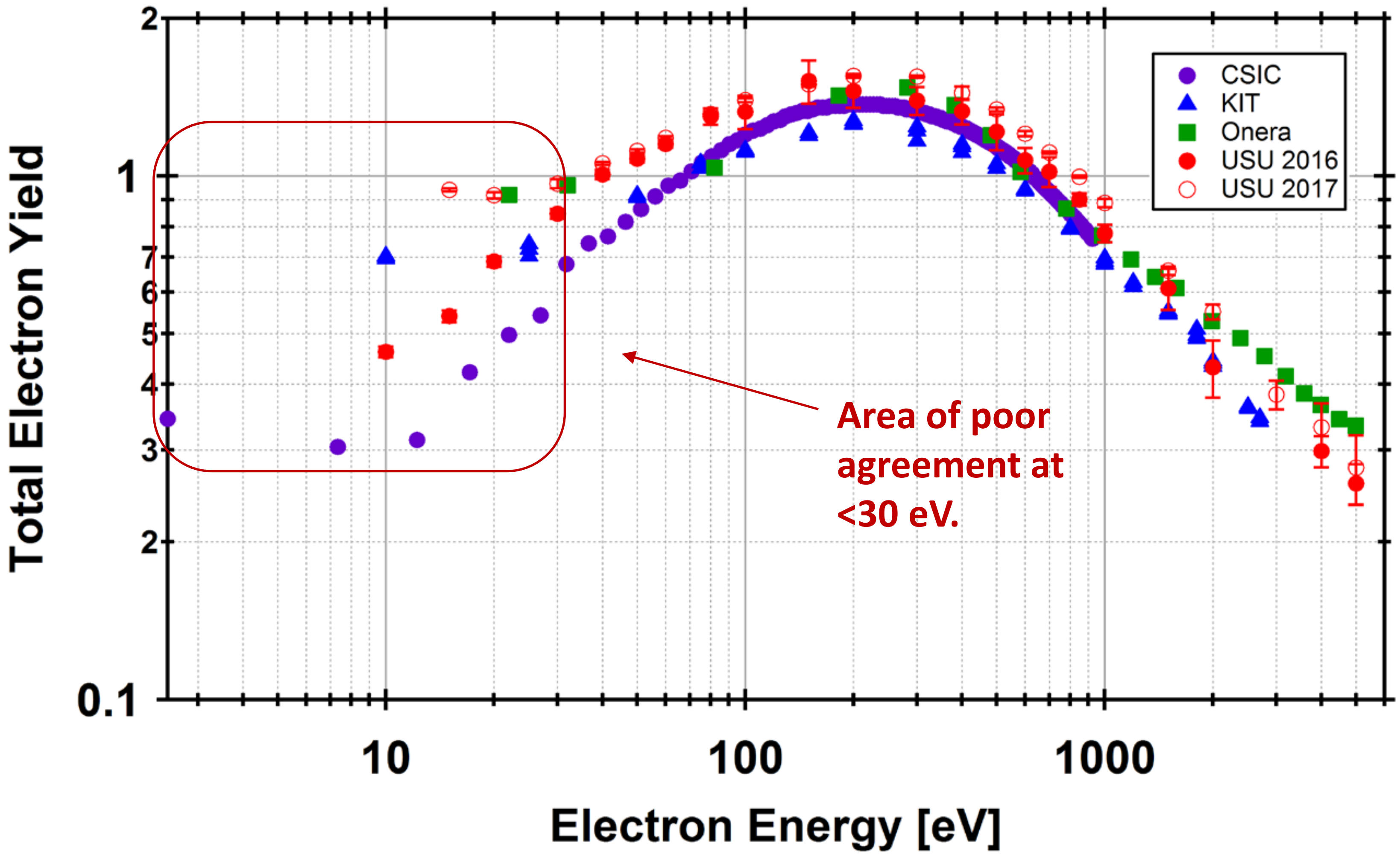
C-fiber composite with thin ~1-10 µm resin surface layer

Black Kapton™ (C-loaded PI)

Length Scale

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

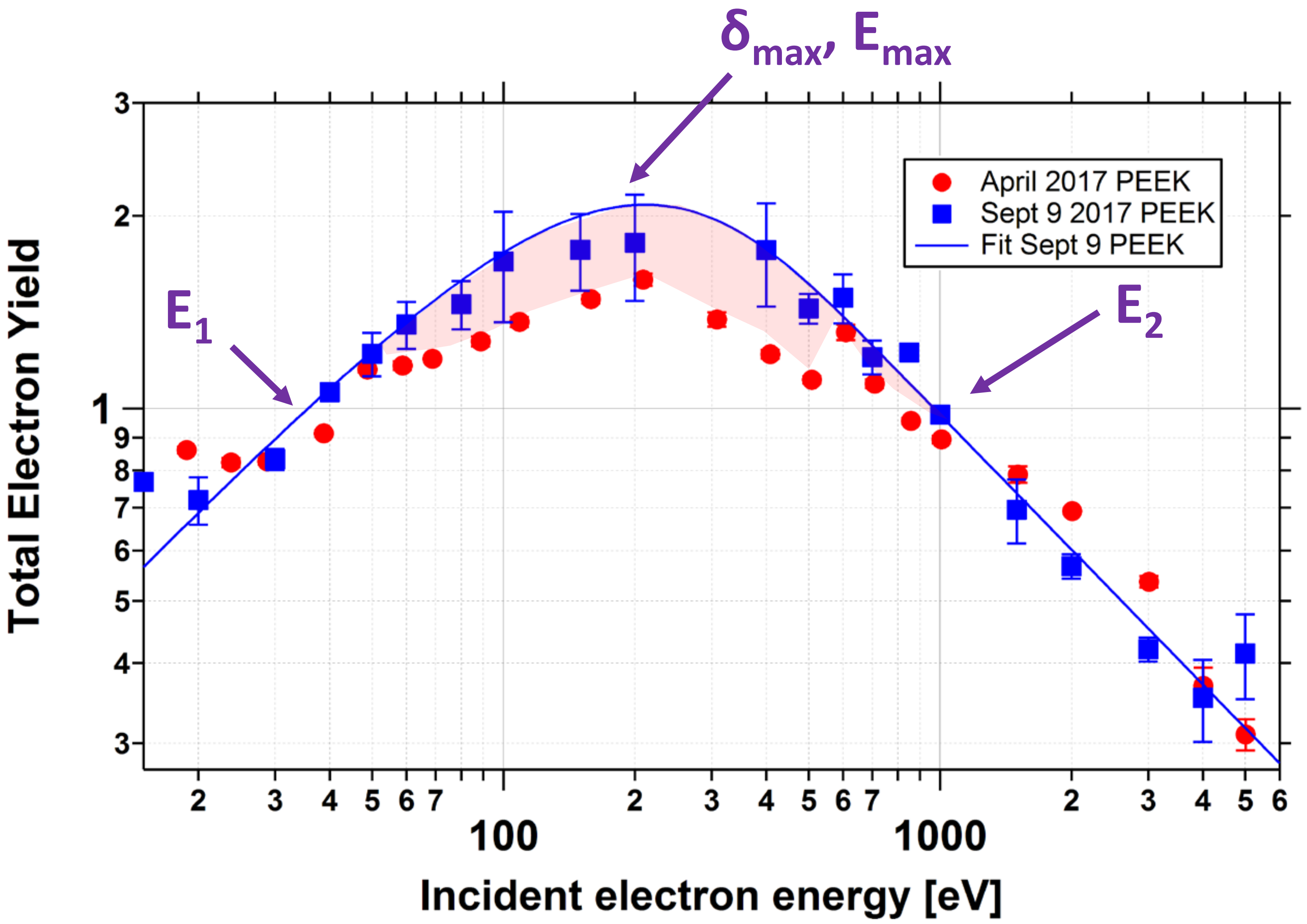
Round Robin Comparison of HOPG Graphite Data



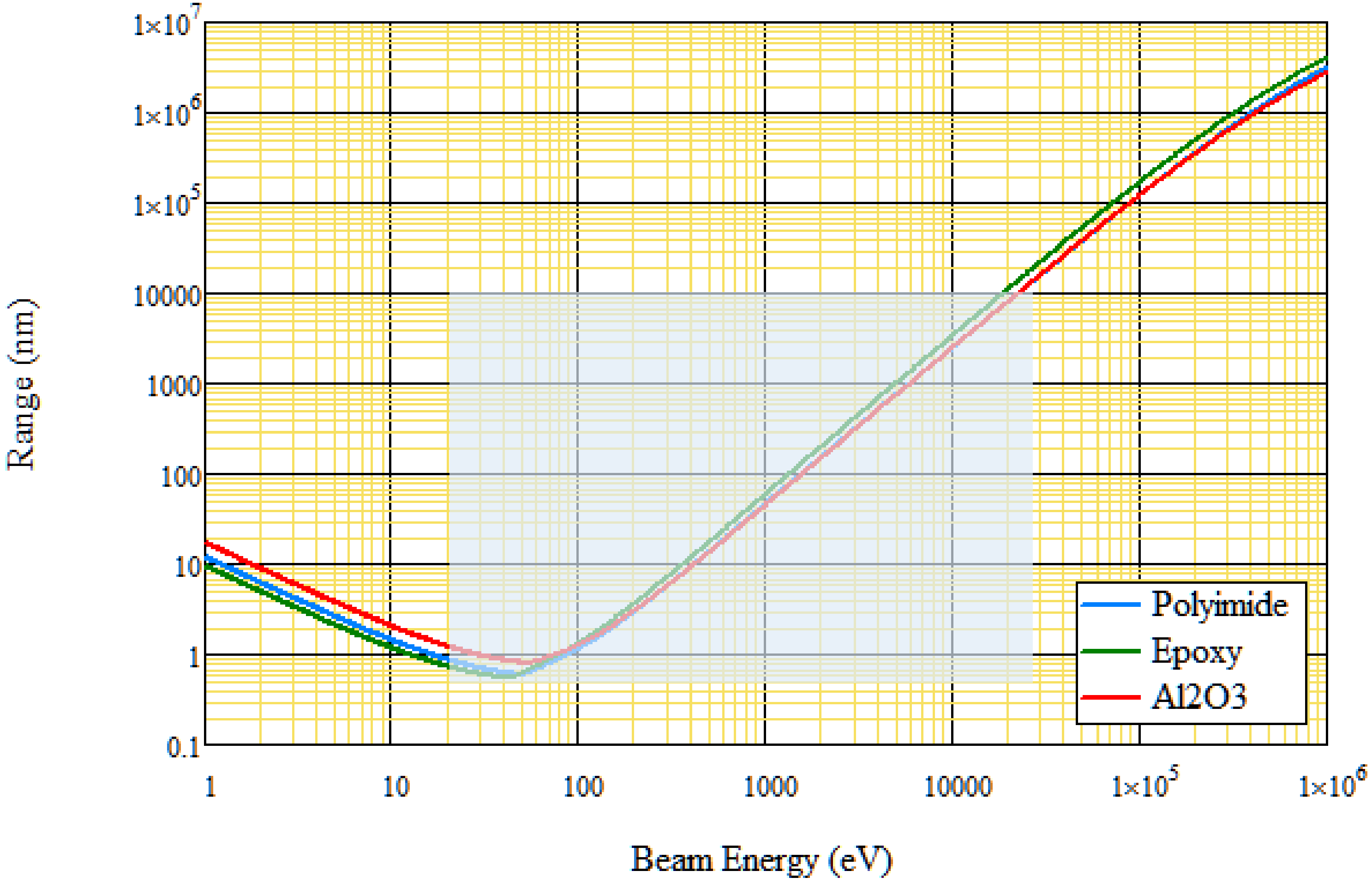
- **HOPG data have been compared with data taken by other laboratories in a Round Robin test and show that Agreement between data from different labs is good above ~30-50 eV.**
- **Values agree within ~10% above 200 eV and ~20 % down to ~30 eV.**
- **USU data may be noisy due to low yield or to negative charging. Yield values <30 eV may be higher than actual values due to stage bias.**

JR Dennison, Justin Christensen, Justin Dekany, Clint Thomson, Neal Nickles, Robert E. Davies, Mohamed Belhaj, Kazuhiro Toyoda, Arifur R. Khan, Kazutaka Kawasaki, Shunsuke Inoue, Isabel Montero, María E. Dávila and Leandro Olano, "Absolute Electron Emission Calibration: Round Robin Tests of Au and Polyimide," *Proceedings of the 14th Spacecraft Charging Technology Conference*, Space Research and Technology Centre of the European Space Agency (ESA/ESTEC), (Noordwijk, Netherlands, April 4-8, 2016) , 7 p.

PEEK Sample Comparison

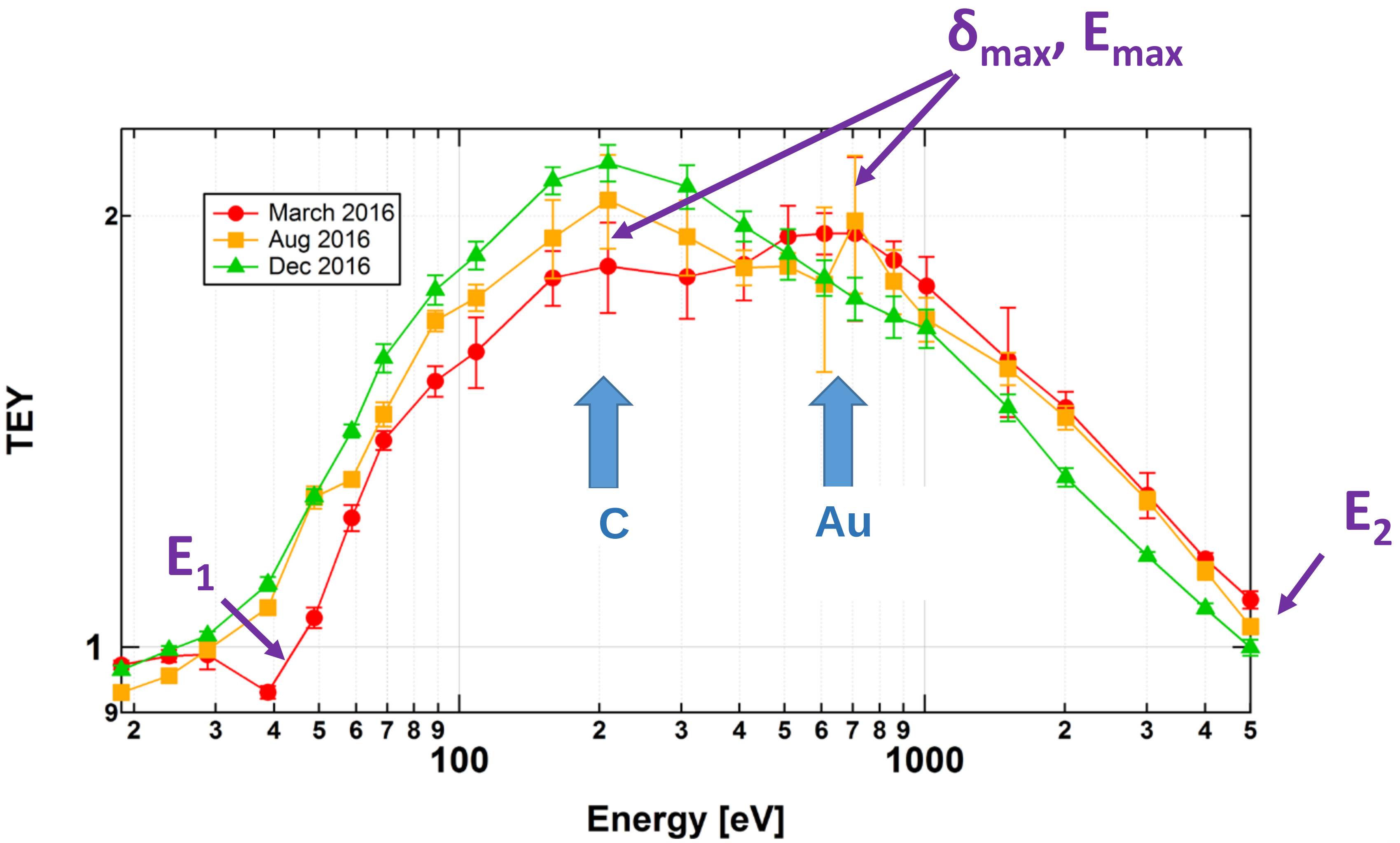


Range of Materials versus Incident Energy

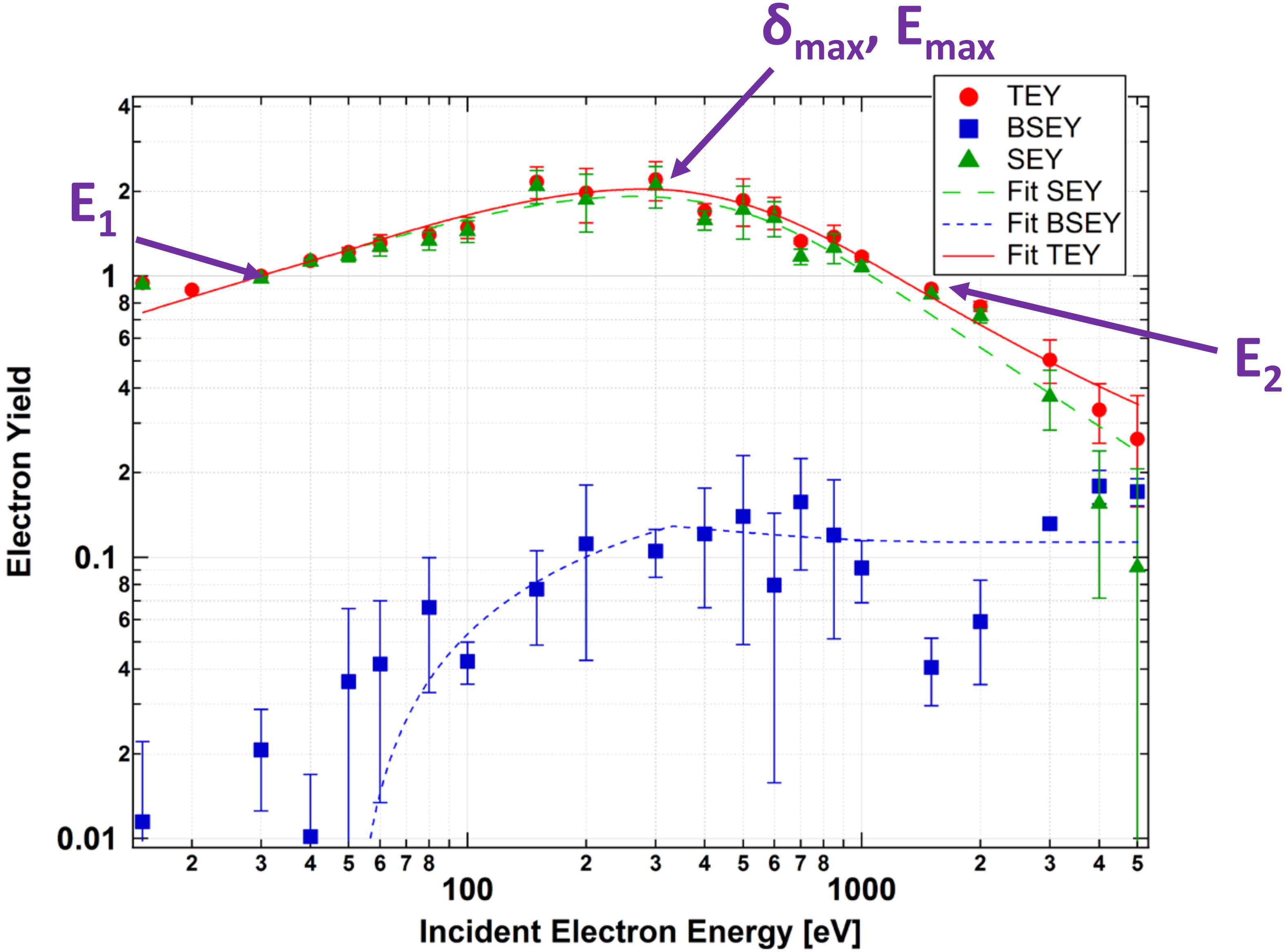


0.7 nm to 1000 nm

Gold with Carbon Contamination



Electron Yield of M55J



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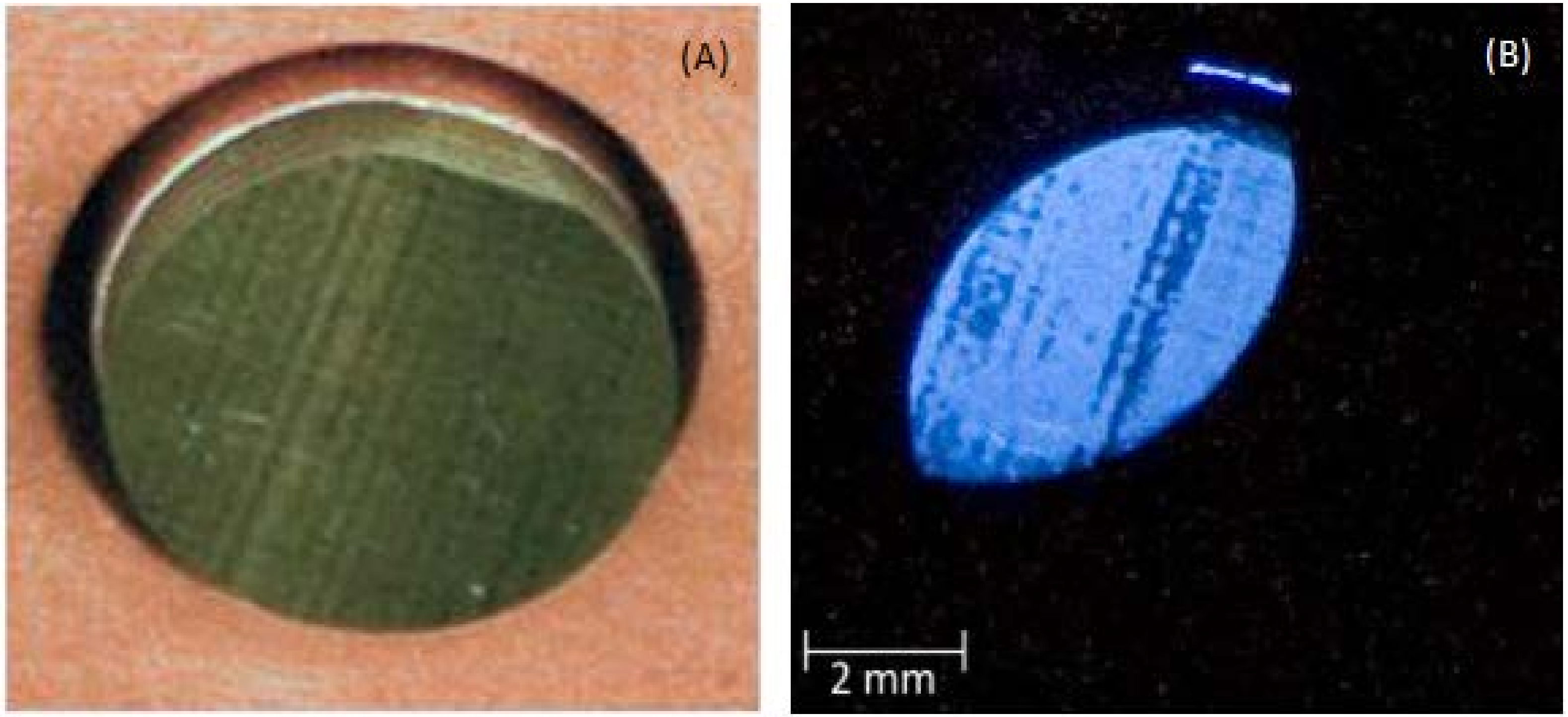
The sample glows when charged with the electron beam.



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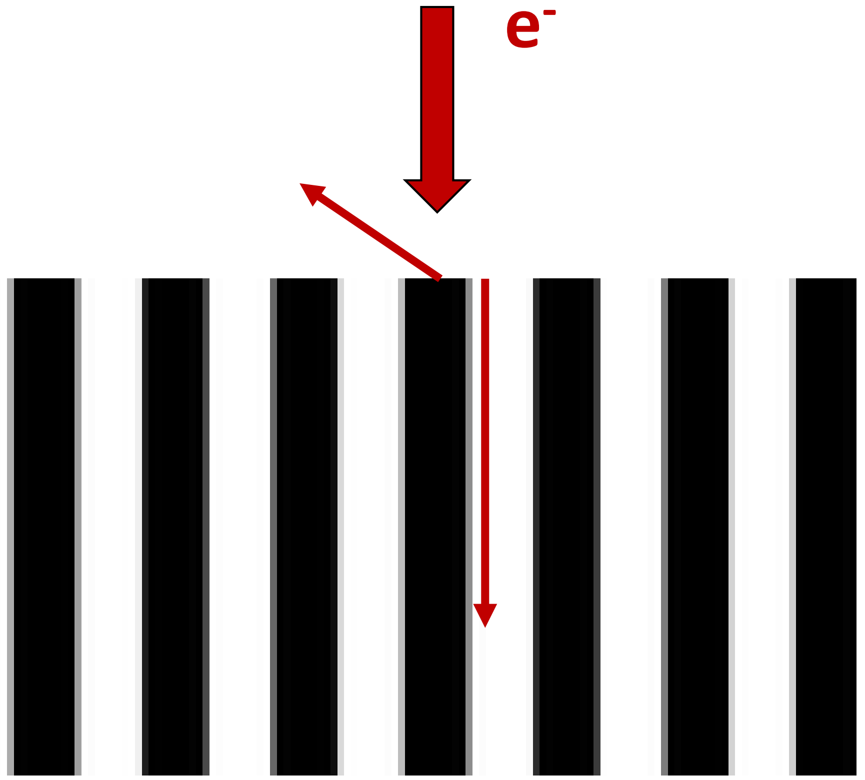
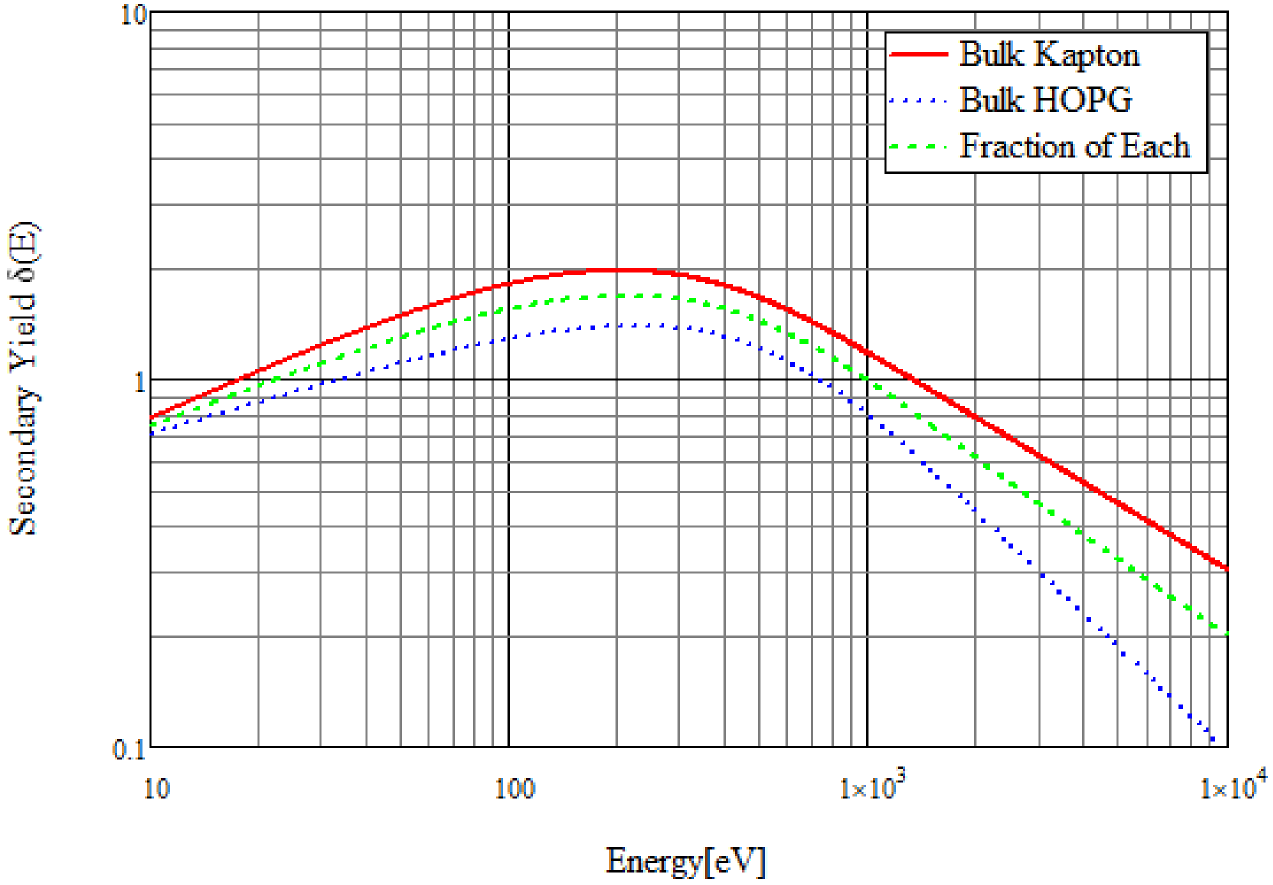
Vertical layers





Horizontal layers