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

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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…

This results in a complex dynamic interplay between space environment, satellite motion, and materials properties.
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, $\Delta V(xy,t)$
- **Energy**
  - Temperature, $k_B T$
  - Deposited Energy (Dose), $D$
  - Power Deposition (Dose) Rate, $\dot{D}$
- **Charge**
  - Accumulated Charge, $\Delta Q$ or $\Delta V(Q, \Delta V,D,\dot{D},t)$
  - Charge Profiles, $Q(z,t)$
  - Charge Rate (Current), $\dot{Q}$
  - Conductivity Profiles, $\sigma(z,t,Q,\dot{Q},D,\dot{D})$
  - Electron emission ($e^-, I^+$, $\Gamma$)
- **Light emission**
  - Cathodoluminescence $I_{\Gamma}(t,xy,Q,D,\dot{D})$
  - Arcing $I_{\Gamma}(t,xy,Q,D,\dot{D})$, $\dot{I}_{\Gamma}(t,z,Q,D,\dot{D})$
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>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>[1] Relative dielectric constant; ( \varepsilon_r ) (Input as 1 for conductors)</td>
<td>1, NA</td>
</tr>
<tr>
<td>[2] Dielectric film thickness; ( d )</td>
<td>0 m, NA</td>
</tr>
<tr>
<td>[3] Bulk conductivity; ( \sigma_o ) (Input as -1 for conductors)</td>
<td>-1; ((4.26 \pm 0.04) \cdot 10^7 \text{ohm}^{-1} \cdot \text{m}^{-1})</td>
</tr>
<tr>
<td>[4] Effective mean atomic number ( &lt;Z_{\text{eff}}&gt; )</td>
<td>50.9 \pm 0.5</td>
</tr>
<tr>
<td>[5] Maximum SE yield for electron impact; ( \delta_{\text{max}} )</td>
<td>1.47 \pm 0.01</td>
</tr>
<tr>
<td>[6] Primary electron energy for ( \delta_{\text{max}}: E_{\text{max}} )</td>
<td>((0.569 \pm 0.07) \text{ keV})</td>
</tr>
<tr>
<td>[7] First coefficient for bi-exponential range law, ( b_1 )</td>
<td>1 Å, NA</td>
</tr>
<tr>
<td>[8] First power for bi-exponential range law, ( n_1 )</td>
<td>1.39 \pm 0.02</td>
</tr>
<tr>
<td>[9] Second coefficient for bi-exponential range law, ( b_2 )</td>
<td>0 Å</td>
</tr>
<tr>
<td>[10] Second power for bi-exponential range law, ( n_2 )</td>
<td>0</td>
</tr>
<tr>
<td>[11] SE yield due to proton impact ( \delta'(1\text{keV}) )</td>
<td>0.3364 \pm 0.0003</td>
</tr>
<tr>
<td>[12] Incident proton energy for ( \delta''<em>{\text{max}}: E''</em>{\text{max}} )</td>
<td>((1238 \pm 30) \text{ keV})</td>
</tr>
<tr>
<td>[13] Photoelectron yield, normally incident sunlight, ( j_{\text{pho}} )</td>
<td>((3.64 \pm 0.4) \cdot 10^5 \text{ A} \cdot \text{m}^{-2})</td>
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<tr>
<td>[14] Surface resistivity; ( \rho_s ) (Input as -1 for non-conductors)</td>
<td>-1 ohms-square^{-1}, NA</td>
</tr>
<tr>
<td>[15] Maximum potential before discharge to space; ( V_{\text{max}} )</td>
<td>100000 V, NA</td>
</tr>
<tr>
<td>[16] Maximum surface potential difference before dielectric breakdown discharge; ( V_{\text{punch}} )</td>
<td>2000 V, NA</td>
</tr>
<tr>
<td>[17] Coefficient of radiation-induced conductivity, ( \sigma_r: k )</td>
<td>0 ohms^{-1} \cdot \text{m}^{-2}, NA</td>
</tr>
<tr>
<td>[18] Power of radiation-induced conductivity, ( \sigma_r: \Delta )</td>
<td>0, NA</td>
</tr>
</tbody>
</table>
Materials Physics Group Measurement Capabilities

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

Dependence on: Press., Temp., Charge, E-field, Dose, Dose Rate
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)
- Evolution of internal charge distributions (EA)
- Multilayers, contamination, surface modification
- Radiation damage
- Modeling
- Sample Characterization
Extremely Low Conductivity
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) Isometric view of the HGRFA detailing the flood gun, optical ports, and wire harness.
Surface Voltage

(a) T P U V
(b) H L Q P F

EFP 6 axis Translator

Sample Current Lead (R)

Wire (O)

Witness Plates (X)

Vacuum Wall

9/24/12 LANL Seminar
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
Sample cooled with l-N$_2$ to 100-135 K.

Chamber walls at ambient.
• 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 >10⁴ s
Electrostatic Breakdown

![Diagram of vacuum chamber and electrostatic breakdown setup]

- **Vacuum Chamber**
  - Aluminum Cold Reservoir
  - Sample Plate
  - Test Sample
  - Electrode

- **Circuit Diagram**
  - Variable High Voltage Power Supply
  - Voltmeter
  - Computer
  - Ammeter

- **Graphs**
  - Electric Field Strength (MV/m) vs. Current (μA)
  - Electric Field x10^6 (V/m) vs. Endurance Time (s)

- **Images**
  - Photos of breakdown sites

- **Key Terms**
  - Electric Field Strength
  - Critical Field
  - Bond Breaking Field

- **Equation**
  - \[ F_{critical} \]

- **Breakdown**
  - Definition of breakdown in electrostatics
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

```
<table>
<thead>
<tr>
<th>Contamination (Exposure Time in hours)</th>
<th>0</th>
<th>10</th>
<th>20</th>
<th>30</th>
<th>40</th>
<th>50</th>
<th>60</th>
<th>70</th>
</tr>
</thead>
<tbody>
<tr>
<td>Negative Potential (10-V_{eq}) in volts</td>
<td>0</td>
<td>10</td>
<td>20</td>
<td>30</td>
<td>40</td>
<td>50</td>
<td>60</td>
<td>70</td>
</tr>
<tr>
<td>Approx. Contamination Thickness (nm)</td>
<td>0</td>
<td>5</td>
<td>10</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Primary Energy (eV) vs. SE Yield

SE Yield Evolution
(0 - 300 angstroms Carbon Contamination)

10-angstrom Increments

0 angstroms
300 angstroms
Emax Evolution

C on Au

Au

Neg. Charging

Pos. Charging
```
Case I: Evolution of Contamination and Oxidation

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

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

Grounded Guard Plate
- +5 VDC
- -15 VDC

Ag coated Mylar with micrometeoroid impact

See poster by Dennison, Evans and Prebola
Case II: Surface Modification

Diffuse and Specular Reflectivity changes with surface roughness

Successive stages of roughened Cu

View photon (electron) scattering as a competition for deposited energy and charge:
- Reflectivity—γ out  (Luminescence—γ out )
- Photoyield—e out (SE/BSE—e out )
Case III: Temperature Effects

Strong T Dependence for Insulators

Charge Transport
- Conductivity
- RIC
- Dielectric Constant
- ESD

\[ k(T) \rightarrow k_{RIC_0} \]

\[ \Delta(T) \rightarrow 1 \]

\[ k(T) \rightarrow k_{RIC_1} \left[ 2 \left( \frac{m_e k_B T}{2 \pi h^2} \right)^{3/2} \left( \frac{m_e^* m_h^*}{m_e m_h} \right)^{3/4} \right]^{T/T_c} \]

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

\[ \sigma_{VRH} \sim \exp(T^{-1/4}) \]

\[ \sigma_{TAH} \sim \exp(T^{-1}) \]
Case V: Temperature and Dose Effects

Wide Temperature 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
“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 $R_s$

Wide Temperature Range
<100 K to >1800 K

Wide Dose Rate Range
Five orders of magnitude variation!
**Case V: Temperature and Dose Effects**

**Dark Conductivity**

\[
\sigma_{DC}(T) = \sigma_{oDC} e^{-E_o / k_B T}
\]

**RIC**

\[
\sigma_{RIC}(T) = k_{RIC}(T) D
\]

**Dielectric Constant**

\[
\varepsilon_r(T) = \varepsilon_{RT} + \Delta \varepsilon (T - 298 K)
\]

**Electrostatic Breakdown**

\[
E_{ESD}(T) = E_{ESD}^{RT} e^{-\alpha_{ESD}(T - 298 K)}
\]
A peak in charging at \(~0.3\) to \(2\) AU

“…Curiouser and curiouser…”

--Alice
Case V: Temperature and Dose Effects

A fascinating trade-off

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

General Trends

- Dose rate decreases as $\sim r^{-2}$
- $T$ decreases as $\sim e^{-r}$
- $\sigma_{DC}$ decreases as $\sim e^{-1/T}$
- $\sigma_{RIC}$ decreases as $\sim e^{-1/T}$
- and decreases as $\sim r^{-2}$
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
Model for Luminescence Intensity in Fused Silica

\[ I_Y \propto \dot{D}(J_b, E_b) \left[ \frac{1}{D + D_{\text{sat}}} \left( \frac{e^{\varepsilon_{ST}}}{k_BT} \right) \right] \{A_f(\lambda)[1 + R_m(\lambda)] \} \quad (1) \]

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

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

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 \( \sim k_BT \) below the CB edge, and two deep trap (DT) distributions centered at \( E_{DT} = E_{red} \) and \( E_{DT} = E_{blue} \). Energy depths are exaggerated for clarity. (b) At \( T=0 \) K, the deeper DT band is filled, so that there is no blue photon emission if \( E_{blue} < \varepsilon_{eff} \). (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). Radiation induced

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].
Fig. 1. Optical measurements of luminescent thin film disordered SiO₂ 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/cm² incident flux for epoxy-resin M55J carbon composite (red; linear fit), SiO₂ coated mirror (green; fit with (1)), and
Diversity of Emission Phenomena in Black Kapton

**Ball Black Kapton**
- 22 keV
- Runs 131 and 131A
- 135 K
- 110 or 4100 uW/cm²
- 5 or 188 nA/cm²

**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

**Electrometer**
- Sample Current

**CCD Video Camera**
- (400 nm to 900 nm)

**InGaAs Video Camera**
- (900 nm to 1700 nm)
## Comparison of Luminescence Images

### Sustained Glow

<table>
<thead>
<tr>
<th>Material</th>
<th>Current Density</th>
<th>Energy</th>
<th>Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kapton XC</td>
<td>500 nA/cm²</td>
<td>22 keV</td>
<td>150 K</td>
</tr>
<tr>
<td>M55J</td>
<td>1 nA/cm²</td>
<td>22 keV</td>
<td>100 K</td>
</tr>
<tr>
<td>IEC Shell Face Epoxy Resin with Carbon Veil</td>
<td>1 nA/cm²</td>
<td>22 keV</td>
<td>100 K</td>
</tr>
<tr>
<td>Kapton E</td>
<td>500 nA/cm²</td>
<td>22 keV</td>
<td>150 K</td>
</tr>
<tr>
<td>IEA Shell Face Epoxy Resin with Carbon Veil</td>
<td>5 nA/cm²</td>
<td>22 keV</td>
<td>100 K</td>
</tr>
<tr>
<td>IEA Shell Face Epoxy Resin with Carbon Veil</td>
<td>5 nA/cm²</td>
<td>22 keV</td>
<td>100 K</td>
</tr>
</tbody>
</table>

### “Flare”

<table>
<thead>
<tr>
<th>Material</th>
<th>Current Density</th>
<th>Energy</th>
<th>Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kapton XC</td>
<td>50 nA/cm²</td>
<td>22 keV</td>
<td>150 K</td>
</tr>
<tr>
<td>M55J</td>
<td>1 nA/cm²</td>
<td>22 keV</td>
<td>100 K</td>
</tr>
<tr>
<td>IEC Shell Face Epoxy Resin with Carbon Veil</td>
<td>1 nA/cm²</td>
<td>22 keV</td>
<td>100 K</td>
</tr>
<tr>
<td>Kapton E</td>
<td>5 nA/cm²</td>
<td>22 keV</td>
<td>135 K</td>
</tr>
<tr>
<td>IEA Shell Face Epoxy Resin with Carbon Veil</td>
<td>5 nA/cm²</td>
<td>22 keV</td>
<td>135 K</td>
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### Arcs

<table>
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<th>Material</th>
<th>Current Density</th>
<th>Energy</th>
<th>Temperature</th>
</tr>
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<tbody>
<tr>
<td>Kapton XC</td>
<td>5 nA/cm²</td>
<td>22 keV</td>
<td>1350 K</td>
</tr>
<tr>
<td>M55J</td>
<td>5 nA/cm²</td>
<td>22 keV</td>
<td>135 K</td>
</tr>
<tr>
<td>IEC Shell Face Epoxy Resin with Carbon Veil</td>
<td>5 nA/cm²</td>
<td>22 keV</td>
<td>135 K</td>
</tr>
<tr>
<td>1 cm Dia test samples</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>30 s Exposure SLR Camera (400nm-640nm)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>33 ms Exposure CCD Video Camera (500nm-900nm)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>17 ms Exposure InGaAs Video Camera (900nm-1700nm)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Arcs Observed in Black Kapton and M55J

**Arc Characteristics**

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

**Arc Freq. at 110 µW/cm²:**
~10 arcs/hr for Black Kapton
~30 arcs/hr for M55J

**Arc Intensity:**
~10X to 1000X glow amplitude
~5% to 20% of glow power

---

**Ball Black Kapton**
- 22 keV
- 135 K

**Runs 131 and 131A**
- 110 or 4100 uW/cm²
- 5 or 188 nA/cm²

---

**Rapid Arcing at 4 mW/cm²**
~20000 arcs/hr

---

**Electrometer**

**InGaAs Video**

**CCD Video**

---

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

---

**Electrometer**

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

**CCD camera (400nm-900nm)**
“Flares” Observed in Black Kapton

**“Flare” Characteristics**

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

- **Flare” Frequency:**
  - 0-2 flares/hr

- **Flare” Intensity:**
  - ~ 2X to 20X glow amplitude
  - ~5% to 20% of glow power

---

**Ball Black Kapton**

- Runs 131
- 110 uW/cm²
- 5 nA/cm²
- 22 keV
- 135 K

**CCD Camera (RGB)**

- InGaAs Video

---

**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

Two very large arcs with many other small arcs.

Flares

Arcs

Sample nA
Sample GND nA
Stage nA
Glow Increases with Increasing Flux, Energy and Power

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

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.
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.
Complete set of dynamic transport equations:

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

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

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

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

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

A quantum mechanical model 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

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.
Combining all the pieces

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

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

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

\[ \sigma(E_o Q) = \eta(E_o) + \delta(E_o Q) \]

Decay curve data

DDLM model for surface potential

 Depth profile for net positive charging

\[ \delta(EV_s) = \left( \sigma_o(E_o) - 1 \right) \cdot \left( 1 - \frac{\lambda_{SE}}{2d} \right) \cdot \left( \frac{h(E)}{h(50\, eV)} - 1 \right) - \left[ \eta_o \cdot \left( 1 - \frac{\lambda_{SE}}{2d} \right) - \left( 1 + \frac{R}{2d} \right) \right] \]

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 anomalous 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...
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.