4-8-2016

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Recommended Citation

Dennison, JR; Christensen, Justin; and Dekany, Justin, "Determining Intrinsic Electron Emission Yields of High Resistivity Ceramic Materials" (2016). 14th Spacecraft Charging Technology Conference Space Research and Technology Centre of the European Space Agency (ESA/ESTEC). *Presentations.* Paper 129.
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UtahState University
MATERIALS PHYSICS GROUP

Determining Intrinsic Electron Emission Yields of High Resistivity Ceramic Materials

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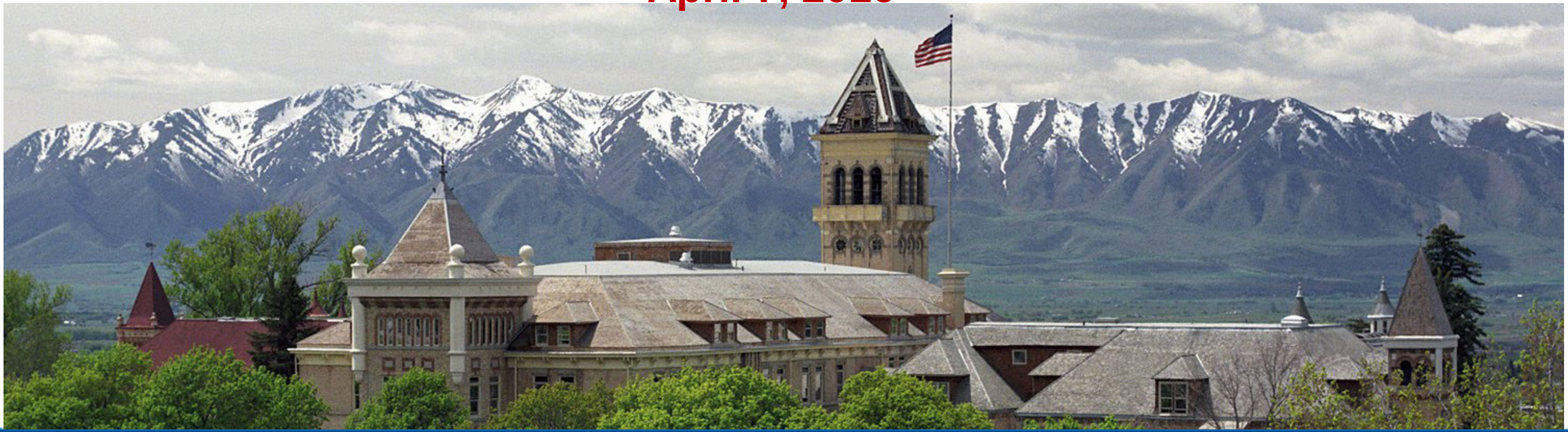
April 7, 2016



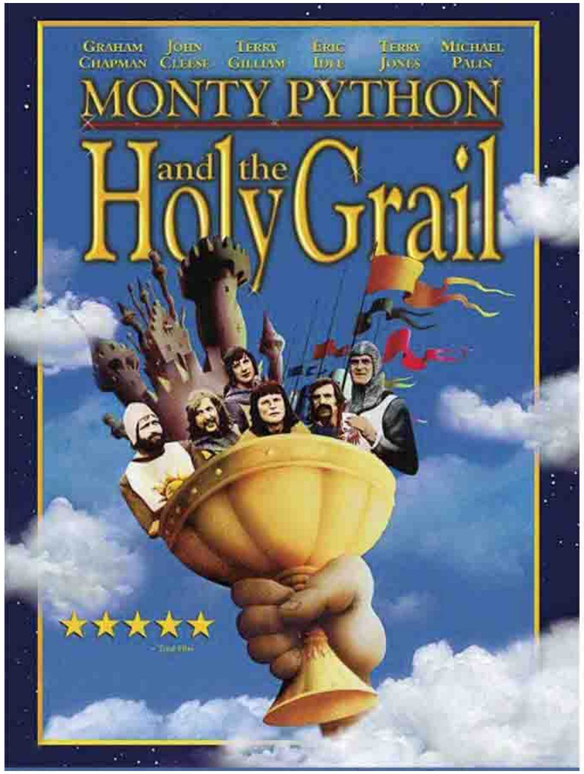
Intrinsic Yield

What is it and why do you care?

Intrinsic Yields

What is it and why do you care?

…the holy grail of spacecraft charging…



…Well, not actually a grail, but rather more like a largish cup not entirely devoid of knowledge and rather useful in understanding the flight of an African swallow….

What do you need to know about the materials properties?

Measured Materials Properties Used in Spacecraft Charging Codes

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.

Charging codes such as NASCAP-2K or SPENVIS and NUMIT2 or DICTAT.

NASCAP-2k requires 19 Materials Parameters:

NASCAP Parameter	Value
[1] Relative dielectric constant; ε_r	2.77 ± 0.1
[2] Dielectric film thickness; d	2.5 μm
[3] Bulk conductivity; σ_o	$(1.0\pm0.5)\cdot10^{-19}$ $\text{ohm}^{-1}\cdot\text{m}^{-1}$
[4] Effective mean atomic number $<Z_{eff}>$	20.6 ± 0.5
[5] Maximum SE yield for electron impact; δ_{max}	1.10 ± 0.01
[6] Primary electron energy for δ_{max}; E_{max}	(0.17 ± 0.01) keV
[7] First coefficient for bi-exponential range law, b_1	1 Å
[8] First power for bi-exponential range law, n_1	1.70 ± 0.01
[9] Second coefficient for bi-exponential range law, b_2	0.32 ± 0.02 Å
[10] Second power for bi-exponential range law, n_2	0.47 ± 0.01
[11] SE yield due to proton impact δ^H (1keV)	0.647 ± 0.001
[12] Incident proton energy for δ^H_{max}; E^H_{max}	(1000 ± 250) keV
[13] Photoelectron yield, normally incident sunlight, σ_{pho}	$(4.88 \pm 0.1) \cdot 10^{-5}$ $\text{A}\cdot\text{m}^{-2}$
[14] Surface resistivity; ρ_s	$2\cdot10^{20}$ $\text{ohms}\cdot\text{square}^{-1}$
[15] Maximum potential before discharge to space; V_{max}	10000 V
[16] Maximum surface potential difference before dielectric breakdown discharge; V_{punch}	850 V
[17] Coefficient of radiation-induced conductivity, σ_r; k	$2\cdot 10^{-15}$ $\text{ohms}^{-1}\cdot\text{m}^{-1}$
[18] Power of radiation-induced conductivity, σ_r; Δ	1
[19] Density; ρ	$(1.434 \pm 0.02)\cdot10^{3}$ $\text{kg}\cdot\text{m}^{-3}$

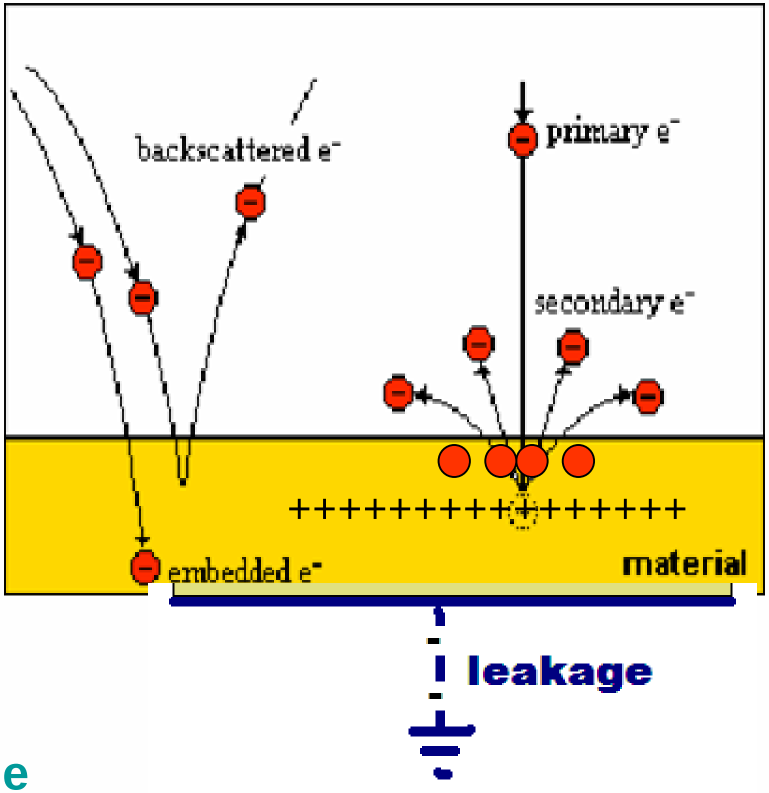
Electron Yields Determine Charge Accumulation

Electron yields characterize a material's response to incident charged particles.

$$Yield = \frac{e^-_{out}}{e^-_{in}}$$

Can be 0<σ>>1
Leading to + or - charging

- **Depends on material**
- **Incident electron energy**
- **Temperature**
- **Charge**
  - **Grounded conductors replenish net emitted charge in <ps**
  - **Yields of insulators change as charge accumulates in sample.**
  - **Intrinsic yield is the zero charge yield**



Total, BSE, SE yields of Au with Continuous Beam

Back Scattered Electron Yield(BSE)

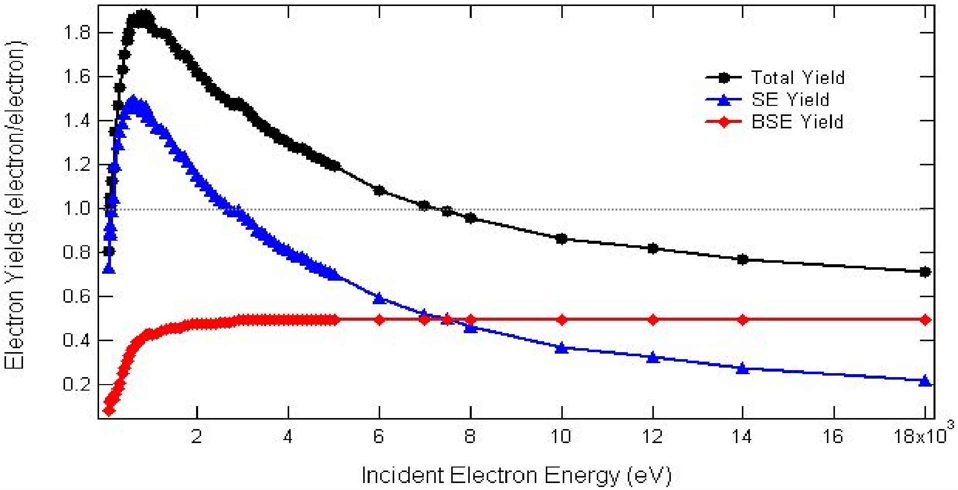
- Electrons from beam
- Includes elastically scattered e-
- By convention, >50 eV

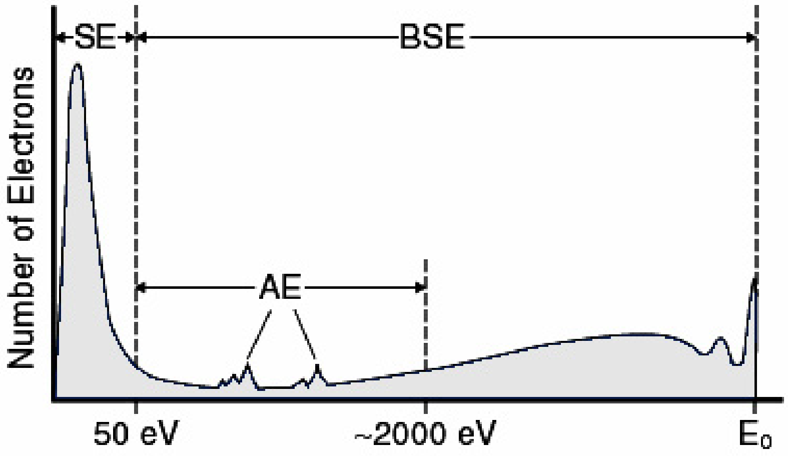
Secondary Electron Yield

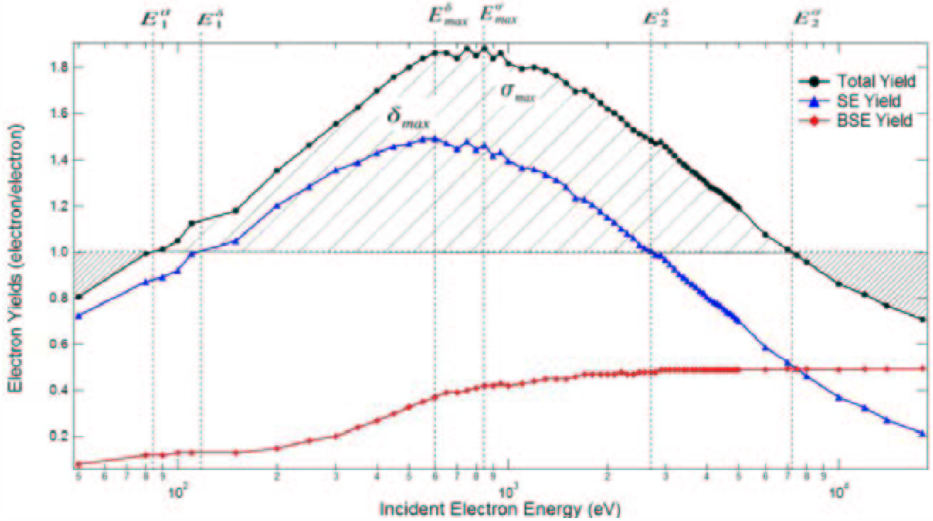
- Electrons originating from the material
- By convention, <50 eV

Total Electron Yield

- Sum of SE and BSE







Absolute Electron Emission Calibration: Round Robin Tests of Au and Graphite

JR Dennison, Justin Christensen, Justin Dekany, Clint Thomson, Neal Nickles, Robert E. Davies,
Mohamed Belhaj,
Kazuhiro Toyoda, Kazutaka Kawasaki,
Isabel Montero, Leandro Olano, María. E. Dávila, and Luis Galán

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Onera - The French Aerospace Lab
LaSEINE, Kyushu Institute of Technology
CSIC, *Instituto de Ciencia de Materiales de Madrid*

Introduction

Accurate determination of the absolute electron yields of conducting and insulating materials is essential for models of spacecraft charging and related processes involving charge accumulation and emission due to electron beam and plasma interactions. Measurements of absolute properties require careful attention to calibration, experimental methods, and uncertainties.

This study presents a round robin comparison of these absolute yields measurements performed in four international laboratories. The primary objectives were to determine the consistency and uncertainties of such tests, and to investigate the effects of the similarities and differences of the diverse facilities. Apparatus using various low-fluence pulsed electron beam sources and methods to minimize charge accumulation have been developed and employed at these facilities.

Measurements were made for identical samples with reproducible sample preparation of three standard materials:
- the elemental conductor Au (25 μm thick 6N high purity Au foils)
- the elemental semimetal HOPG (bulk DOW highly oriented pyrolytic graphite)
- the polymeric insulator polyimide (25 μm thick Kapton HN™).

Total electron yields (TEY) of Au and HOPG are reported here.

Absolute electron yield measurements for various materials are necessary to determine absolute charging levels and hence to predict possible electrostatic breakdown and injection of charges into plasmas. They have direct application to spacecraft charging, high voltage direct current (HVDC) power and transmission lines, ion thrusters, plasma deposition, multipactors, semiconductor metal-oxide interfaces, and nanodielectrics.

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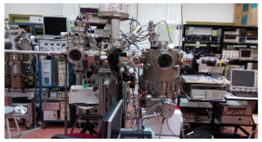
Descriptions of Facilities and Methods

CSIC SEY Facility



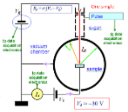
The CSIC SEY Facility of the Surface Nanostructuring for Space and Terrestrial Communications Group of ICMM-CSIC.

This CSIC group does research on dielectric, magnetic and metallic materials for space applications. A main goal of these research activities is the surface characterization by UHV spectroscopic techniques and low-secondary emission surfaces to avoid multipaction effects in RF high-power devices for satellite communications systems.

Equipped with:
- **Four interconnected UHV chambers** (10^{-7} Pa).
- **Four electron guns** (pulsed/continuous).
- **Ion gun** (Ar, O, CHx, …).
- **VUV source** (pulsed/continuous)
- **X-ray source** (Mg/Al anodes)
- **Hemispherical electron analyzer**
- **Quadrupole residual gas analyzer**
- **Flexible sample size** (12 - 250 mm).
- **Sample Manipulation**
  - **Sample rotation:** -90° to +90°
  - **UHV Helium cryostat-micrometric manipulator** XYZθ (4 K - 900 K)
  - **UHV Micrometric manipulator** XYZθ (<900K).
  - **UHV X(Zθ) nanometric manipulator**.
  - **UHV XZθ manipulator** (1.8 m length).
- **Temperature** range: 4 K – 900 K.

Measurements capabilities include:
- **SEY (true secondaries and backscattered):**
  - Continuous method: total primary current <5nA/cm2.
  - Pulsed (single pulse) method: pulse time <180 ns.
- **Energy Distribution Curves (EDC).** Primary energy: 0-5 keV and relative emission angle-dependence.
- **X-Ray Photoemission spectroscopy (XPS):** Depth Profiles.
- **Auger Spectroscopy (AES), RHEELS**
- **Intensity-Voltage and Capacitance-Voltage** characteristics.
- **VUV Photoemission** quantum yield.
- **Thermal desorption** processes.
- **Versatile sample conditions:**
  - Flexible sample sizes (<250 mm).
  - Extensive sample manipulation.
  - Simultaneous T range 4-900 K.

$$\sigma = 1 - \frac{I_S}{I_P}$$

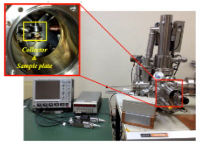


I_b and I_s are as-measured values to ground.
$\sigma \pm 0.005$ $E_{max} \pm 1$ eV $E_1 \pm 0.1$ eV

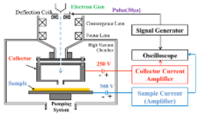
LaSEINE TEEY Facility

The Laboratory of Spacecraft Engineering INteraction Engineering (LaSEINE) at Kyushu Institute of Technology has studied spacecraft charging and discharging.

We have developed the Total Electron Emission Yield (TEEY) measurement facility for data base of the charging analysis tool MUSCAT. We have measured the TEEY of space conductive materials, as well as insulating material. We also measured TEEY after irradiation with ionizing radiation, atomic oxygen, and ultraviolet ray.

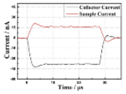


Measurements capabilities include:
- **Vacuum** analysis chamber: below 10^{-5} Pa.
- **Electron Gun**: 300 eV-10 keV.
- **Electron Irradiation:** continuous or pulsed.
- **Sample Stage** movable in X-Y directions.
- **Temperature** sample holder control 240-370 K



Total electron emission yield measurement method:
- Sample holder and collector are biased at -300V and -250V, respectively. (For example, the electron incident energy on the sample surface becomes 50eV with using 350eV electron beam.)
- Sample current and collector current are measured for calculating TEEY.
- For insulating materials, pulse scanning method is used. The sample is shifted after one shot of pulsed electron beam in order to prevent charging effect on the sample surface.

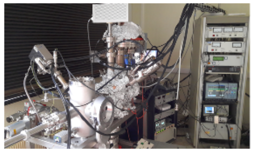
$$\sigma = 1 - \frac{I_S}{I_C + I_S}$$



ONERA DEESSE Facility

The DEESSE (Dispositif d'Etude de l'Emission Secondaire Sous Electrons) facility at ONERA is a UHV chamber equipped with:

The Space Environment Department of Onera (DESP) works on many projects closely related to space applications dealing with electron emission, such as charging effects of spacecraft and Hall Effect Thruster technology (HET).



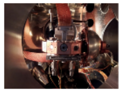
Measurements capabilities include:
- **Vacuum** Analysis chamber: 10^{-7} to 10^{-8} Pa; Transfer chamber: 10^{-6} Pa.
- **Electron Guns** Kimball Physics: 1 eV-2 keV; Kimball Physics: 50 eV-5 keV; Staib 1 keV-22 keV.
- **Electron Irradiation** continuous or pulsed.
- **Incident Current** measured by Faraday cup.
- **Energy distribution** measured by hemispherical electron analyzer.
- **Sample Rotation** -90° to +90° to study incidence angle effects.
- **Surface Analysis** Auger Electron Spectroscopy (AES) and XPS.
- **Electron Energy Loss Spectroscopy** (EELS).
- **Ion source** (Ar, Xe, H) from 25 eV -5 keV.
- **VUV and X-ray sources** (Mg/Al sources).
- **Kelvin surface potential probe.**
- Residual gas analyzer
- **Temperature Control** of sample holder from ambient to 500°C

Electron emission yield was measured using the sample current method:
- Incident current measured as function of incident energy using the Faraday cup (polarized to +24 V).
- Thereafter, sample current was measured as function of incident energy.
- Sample holder biased to -18 V in order to avoid the collection of the low energy tertiary electrons by the sample surface.
- After that, incident current stability was confirmed for select energies. With Kimball Physics electron gun, the observed variation is <2%.
- To limit conditioning effect, electron beam was pulsed (5 μs pulse for conducting materials).

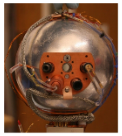
$$\sigma = 1 - \frac{I_S}{I_B}$$

USU SEEM Facility

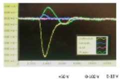
The Utah State University Materials Physics Group (MPG) Space Environment Effects Materials (SEEM) test facility performs state-of-the-art ground-based testing of electrical charging and electron transport properties of both conducting and insulating materials, emphasizing studies of electron emission, conductivity, luminescence, and electrostatic discharge.



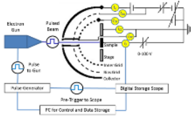
We have studied how variations in temperature, accumulated charge, exposure time, contamination, surface modification, radiation dose rate and cumulative dose affect these electrical properties—or related changes in structural, mechanical, thermal and optical properties—of materials and systems.



Measurements capabilities include:
- **Total / Secondary / Backscattered Electron Emission** using <20 eV to 50 keV mono-energetic continuous and pulsed beams with <5% absolute uncertainty.
- **Electron Emission Spectra** versus energy (0-5 keV with ~0.1 eV resolution) and emission angle-dependence.
- **Ion-Induced Electron Emission** spectra and yields for various <300 eV to 5 keV mono-energetic inert and reactive ions.
- **Photon-Induced Electron Emission** spectra and yields for <0.6 eV to >6.5 eV (165-2000 nm) monochromated photons.
- **Surface Voltage** simultaneous measurements of 0-10 kV with <0.2 eV resolution.
- **Induced Electrostatic Breakdown** simultaneous current and NIR/VIS/UV optical measurements.
- **Temperature capabilities** from <60 K to >450 K .
- **Vacuum** $<10^{-7}$ Pa.



$$\sigma = 1 - \frac{\int_{pulse}[I_S + I_{St} + I_{IG} + I_{BG} + I_{DT}]dt}{\int_{pulse}[I_C + I_S + I_{St} + I_{IG} + I_{BG} + I_{DT}]dt}$$

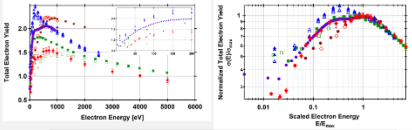


Electron yields are calculated from integrated current traces from six detector elements Ⓐ of a fully enclosed hemispherical grid retarding field analyzer used for emission electron energy discrimination.

Round Robin Tests Results

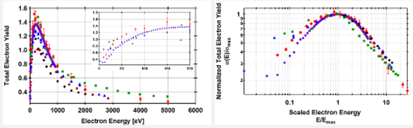
Measurements were made of the absolute total electron yields at normal incidence over the full range of incident energies accessible with each group's instrumentation (a full range of ~5 eV to ~5 keV). Figures show linear plots with low energy detail insets (left) and log-log plots of scaled yields $\sigma(E)/\sigma_{max}$ versus scaled energy E/E_{max}.

Gold



Symbol	Facility	Refs.	Measured Values			
			σ_{max}	E_{max} (eV)	E_1 (eV)	E_2 (eV)
●	CSIC SEY Facility (contin.)	1-3	2.06±0.02	600±20	24±1	NA
■	Onera DEESSE Facility	4-5	1.81±0.03	360±20	28±1	~6000
□	Onera—DEESSE (Etched)	4-5	1.46±0.03	1250±50	NA	~6000
▲	LaSeine—TEY Facility (March 2)	6-7	2.48±0.03	200±20	NA	NA
△	LaSeine—TEY Facility (March 6)	6-7	2.3±0.1	240±30	12±2	NA
♦	USU—SEEM Facility (pulsed)	8-9	1.54±0.08	700±30	55±3	4000±200
◊	USU—SEEM Facility (contin.)	8,15	2.24±0.02	650±50	NA	NA
	Round Robin Average Values		2.0±0.4	600±460	24±9	5000±1000
●	Standard: Thomas & Pattinson	11	2.21±0.02	900±30	50±10	NA

HOPG Graphite



Symbol	Facility	Refs.	Measured Values			
			σ_{max}	E_{max} (eV)	E_1 (eV)	E_2 (eV)
●	CSIC SEY Facility	1-3	1.38±0.02	215±5	68±1	629±10
■	LaSeine—TEY Facility	4-5	1.48±0.05	270±20	60±2	610±40
▲	Onera—DEESSE Facility	6-7	1.28±0.05	190±10	69±1	552±20
♦	USU SEEM Facility (clean)	8,9,15	1.4±0.1	200±30	40±2	895±20
	Round Robin Average Values		1.39±0.08	220±36	59±13	670±150
●	Standard 1: Whetten	12	1.01±0.01	300±20	250±30	350±20
●	Standard 2: Wintucky	13	NA	NA	NA	330±20

Summary

Summary of results:
- Shape of normalized curves are very consistent
- **Highly sensitive to surface contamination** [14],
- Very good agreement of absolute yield for $E>E_{max}$, but less agreement for $E<E_1$
- **HOPG agreement between facilities is the best: ~5% for σ_{max} and ~20% for energies**
- HOPG has the advantage that clean smooth surfaces are easy to prepare with tape cleaving
- Au samples exhibit differing degrees of contamination--as evidenced by surface analysis tests--exhibiting two TEY peaks near 700 eV (clean Au) and 200 eV (C contamination) [14].

Topics of future Round Robin analysis:
- Charge sensitive measurements of dielectrics: Polyimide (Kapton HN™) results,
- Energy discriminated measurements: Secondary/Backscattered results and emission spectra,
- Surface sensitivity: surface cleanliness tests, effects of contamination and Ar sputtering,
- Discussions of the relative strengths and weaknesses of our various methods.

Low Fluence Methods for Insulator Yields

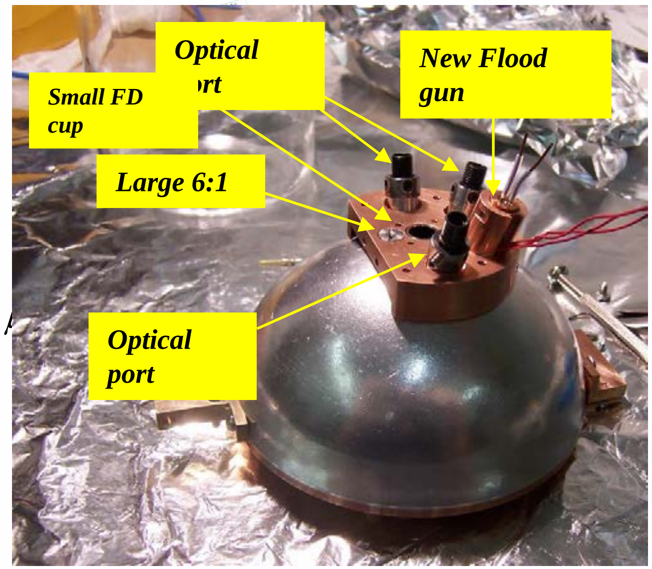
Hemispherical

Grid

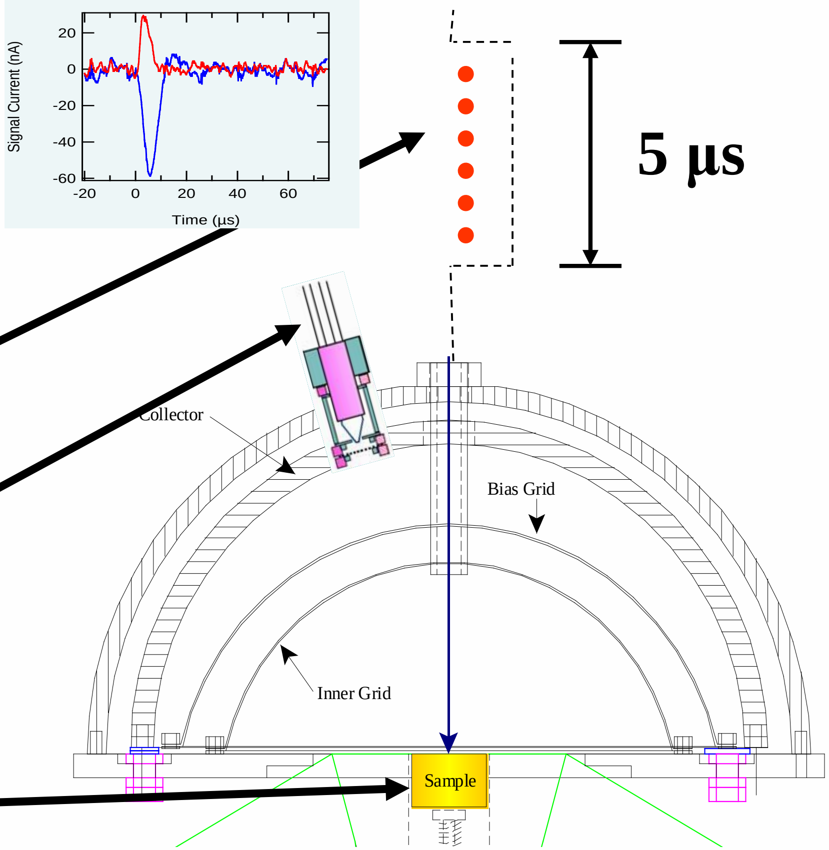
Retarding

Field

Analyzer

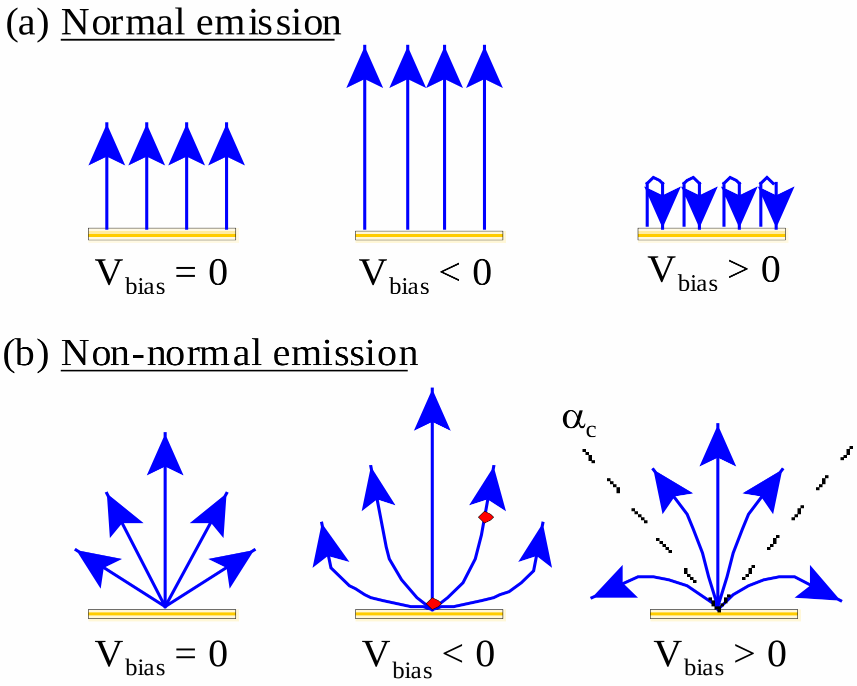


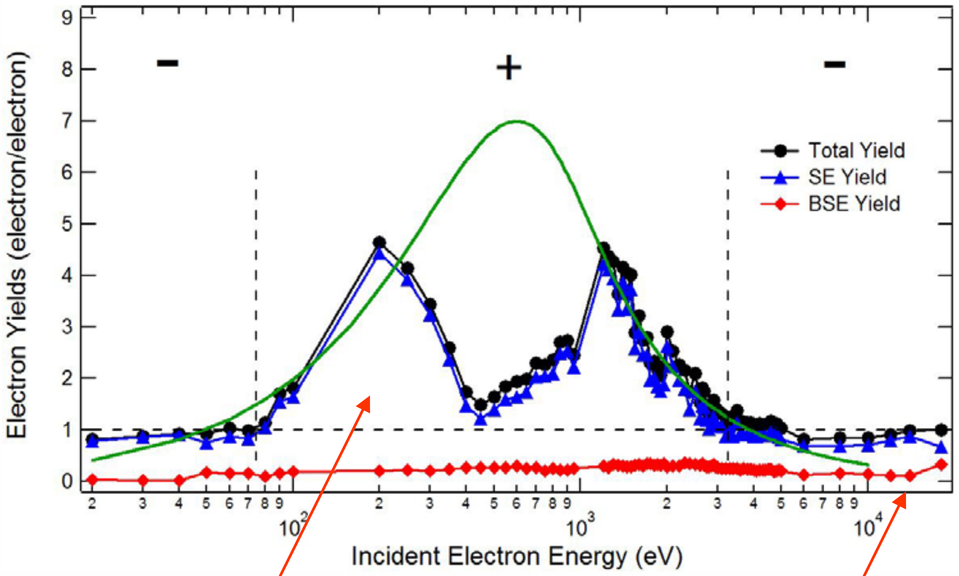
Fully enclosed detector provides highly accurate absolute yields on insulators.
1% on conductors and ~5% on insulators.

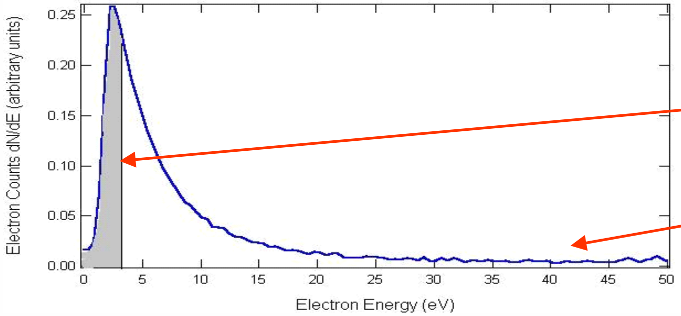


- **Pulsed low current** electron source
  - 5 µs at 5 nA →~10^6 e^-/pulse
  - $2.0*10^4$ e^-/mm^2
- **UV** and **Low Energy Electrons** to discharge material after each pulse.
- Without discharge the yield would change from pulse to pulse due to electrons being reattracted to the charged sample surface.

Return current due to biasing leads to *Modified Yields*







Positive Charging

$E_1 < E_o < E_2$ with $\sigma > 1$

Shifts emission spectra left

Depresses yield

Negative Charging

$E_o > E_2$ with $\sigma < 1$

Shift emission spectra right

Enhances yield

To know the absolute surface potential one must know the absolute yield starting with no imbedded charge, i.e., **THE ABSOLUTE INTRINSIC YIELD**

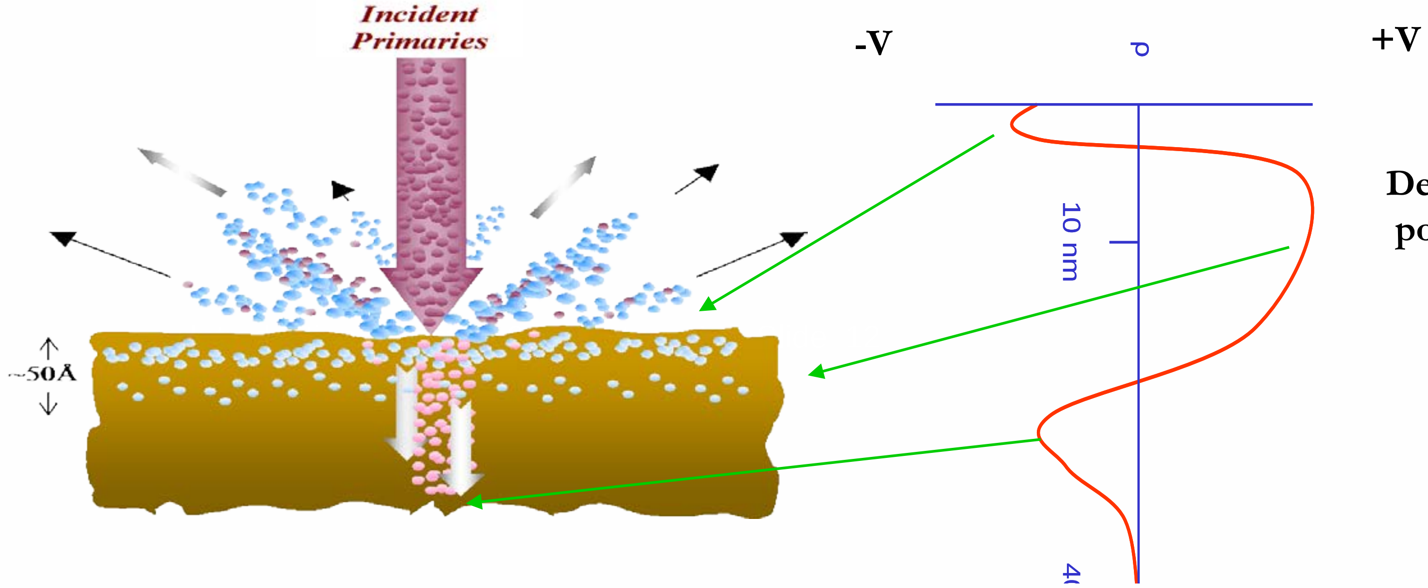
Charge Distribution for Surface Potential Under Electron Bombardment (DDLM)

Dynamic Double Layer Model

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

Charge distribution is more complex:

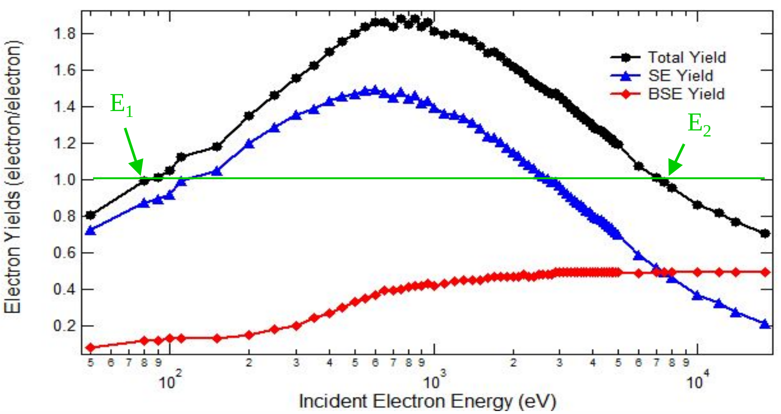
- DDLM near surface
- Charge transport in RIC region
- Sample bias adds more complex charges and fields



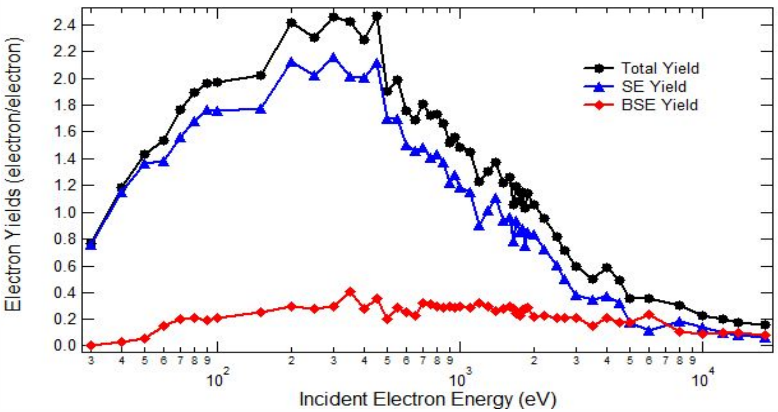
Depth profile for net positive charging

A. Melchinger, S. Hofmann, J. Appl. Phys. 78, 6224-32, (2003).

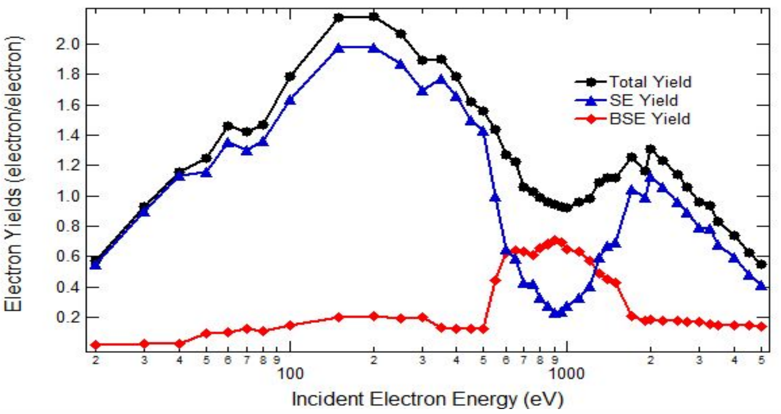
Data for Increasing Resistivity Samples



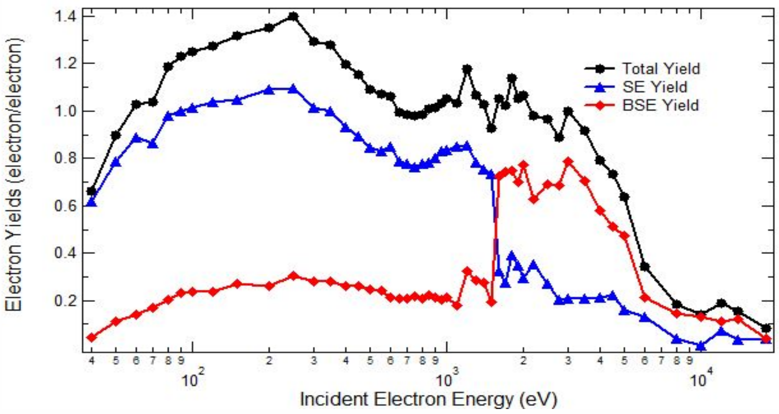
Gold Low-Yield Very Low Resistivity



Cr Coated Mylar High-Yield Low-Resistivity

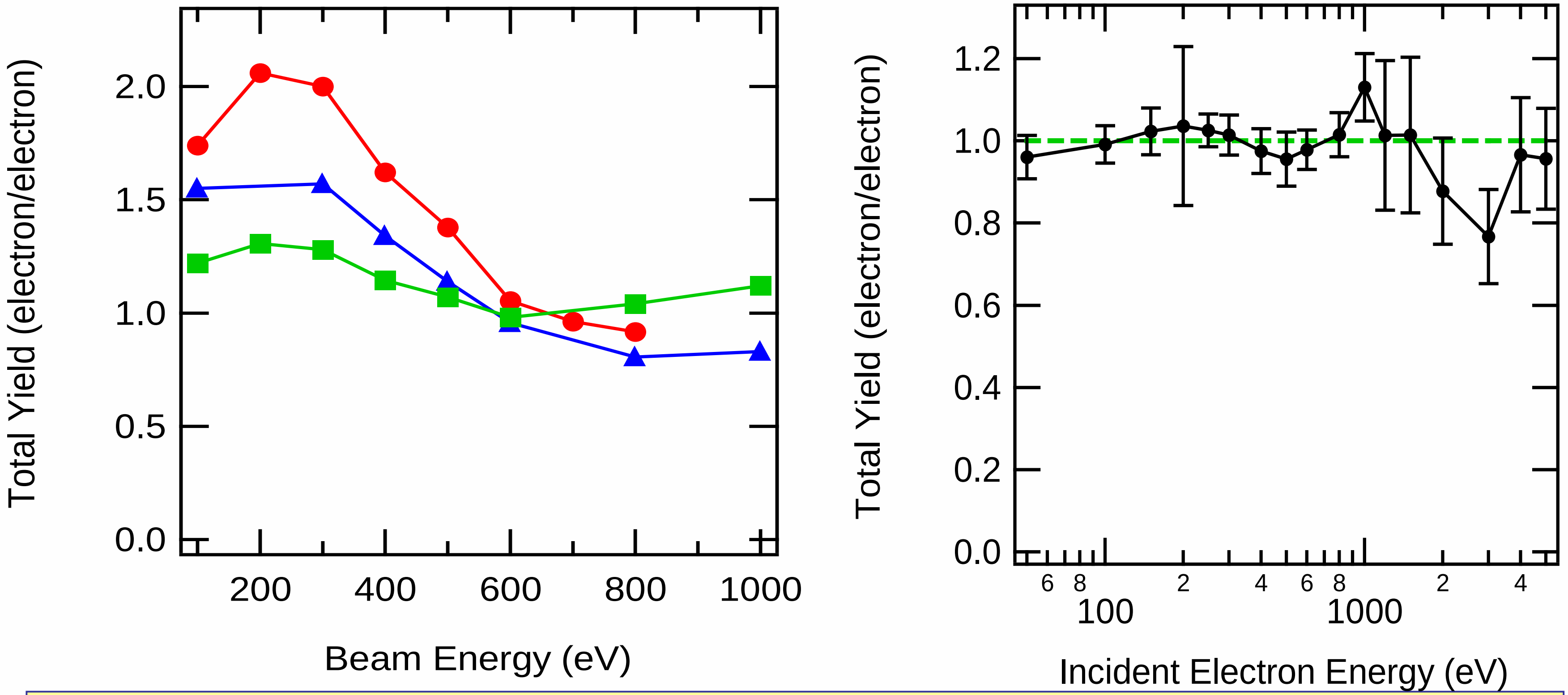


Kapton Low-Yield High-Resistivity



CP1 Low-Yield Low-Resistivity

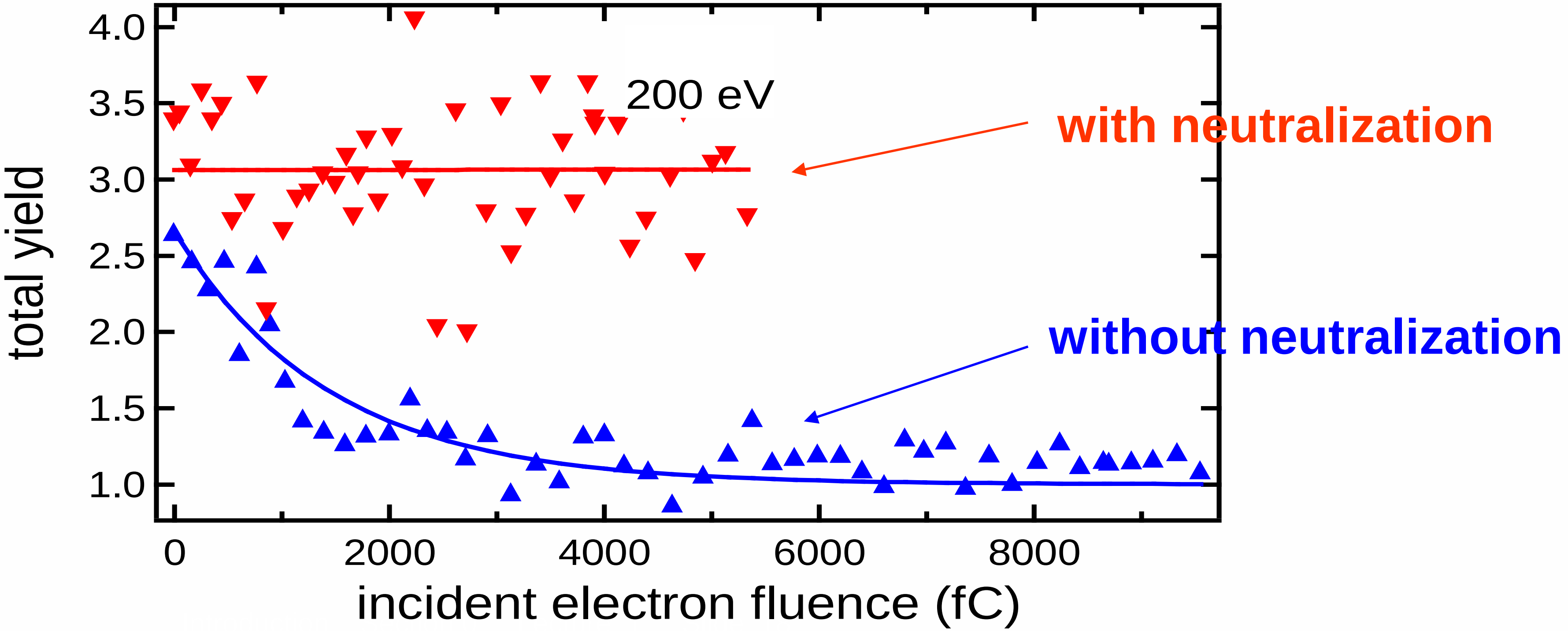
Effects of Charge Accumulation on Poor” Insulator Yields



(Left) Yield Curve in Transition—Pulsed total yield of anodized Al tends toward unity as sample charges.

(Right) Yield Curve in Equilibrium—Pulsed total yield curve of RTV-silicone. Yield fluctuates around unity: charged steady-state.

Yield Decay Curve for Kapton



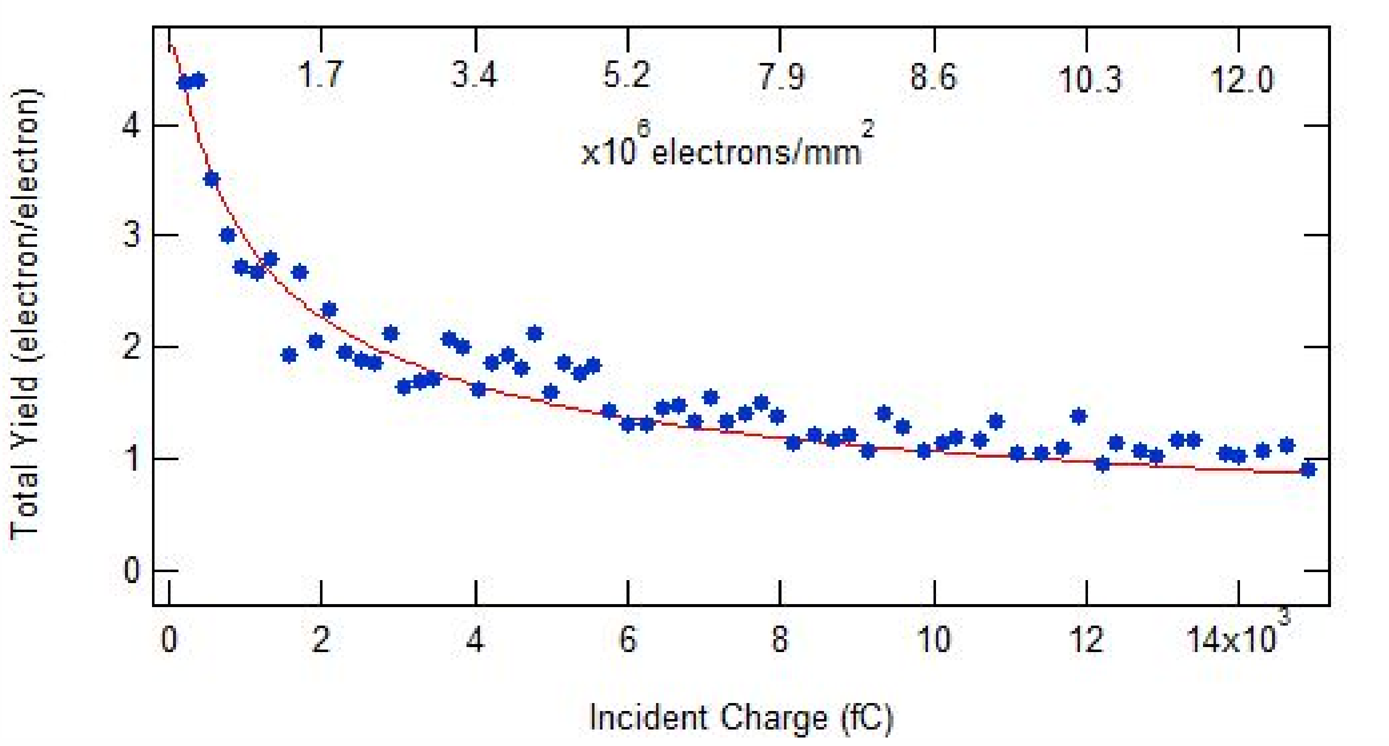
Incident pulses:

5 μs, ~25 nA, ~10 mm^2, ~13 fC/mm^2-pulse, ~1·10^6 e$^-$/mm^2-pulse

62% change over 50 pulses.

Decay Curve for Al_2O_3

Allow charge to build up



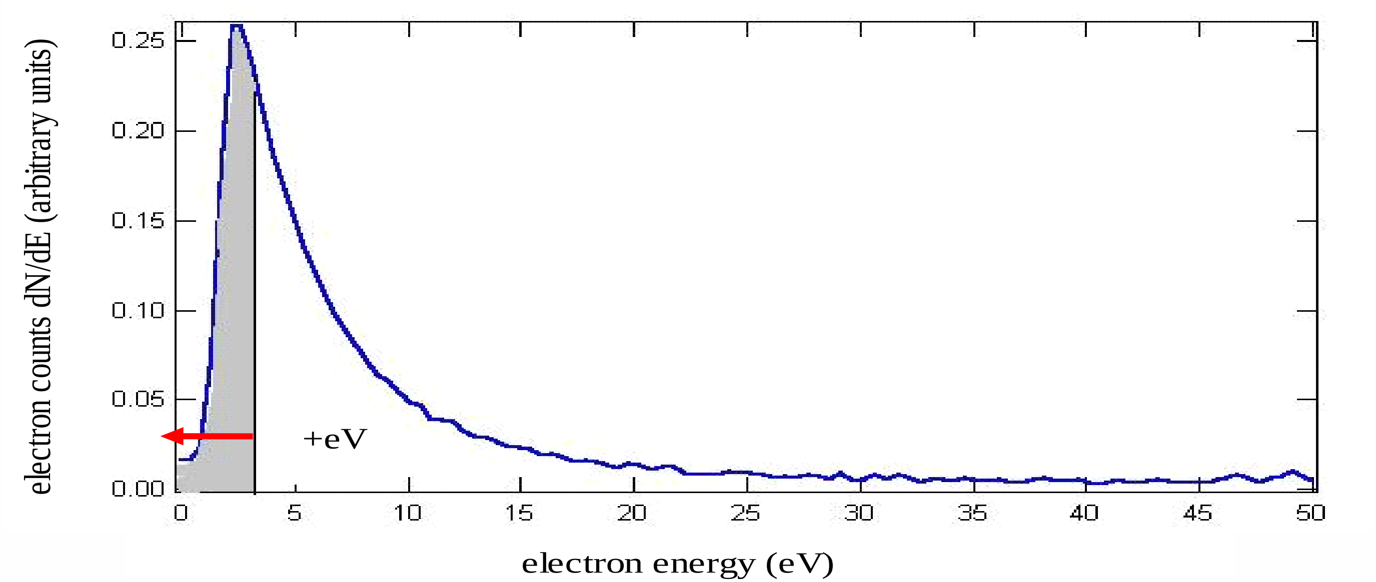
Intrinsic (uncharged) yield is given when Q→0

Modeling the SE Escape Energy

Ratio of Charged To Uncharged SE Yield as a function of Surface Potential:

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

V_s



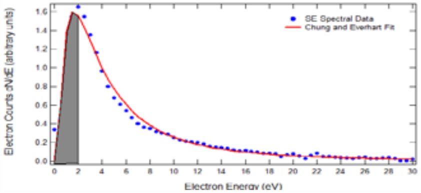
To proceed we need a model for $V_s(Q_i)$

Surface Voltage Relates to “Intrinsic” Yield Model

Combining all the pieces

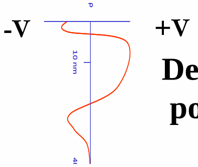
$$\frac{\delta_i(E_o,Q_i)}{\delta_o(E_o)} = \frac{\displaystyle\int_{eV_s(Q_i)}^{50\,eV} \frac{dN(E;E_o)}{dE}\,dE}{\displaystyle\int_{0\,eV}^{50\,eV} \frac{dN(E;E_o)}{dE}\,dE}$$

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



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

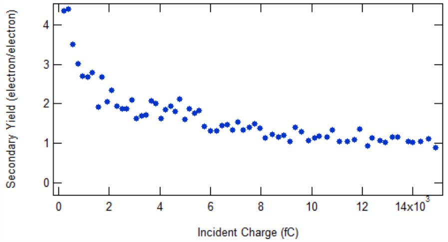
DDLM model for surface potential



Depth profile for net positive charging

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

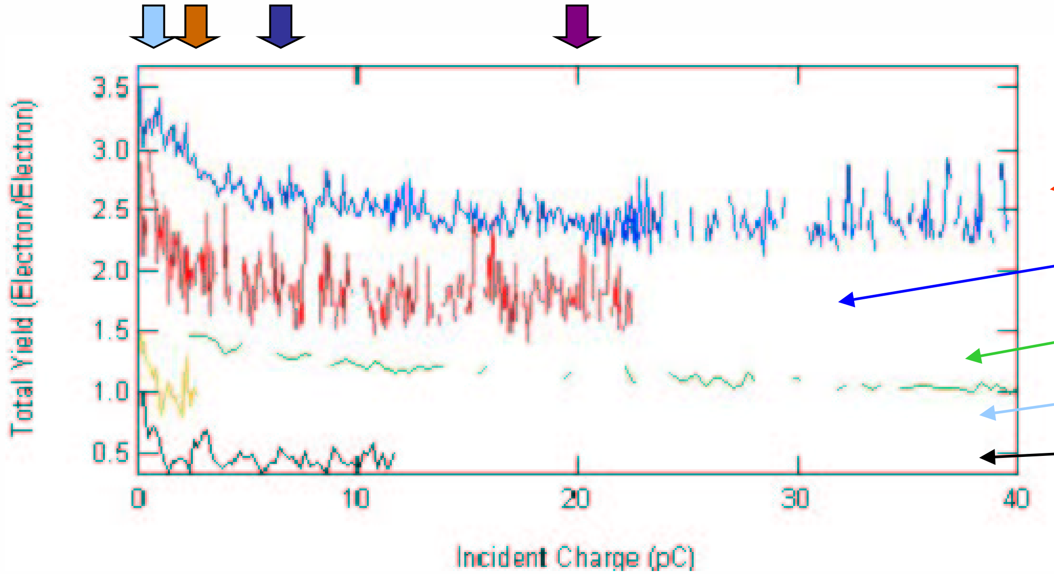
Decay curve data



Analytic solution for secondary electron yield as surface potential changes in response to incident charge.

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

“Constructing“ a Low-Fluence Yield Curve



Measured Yield Decay Curves at:

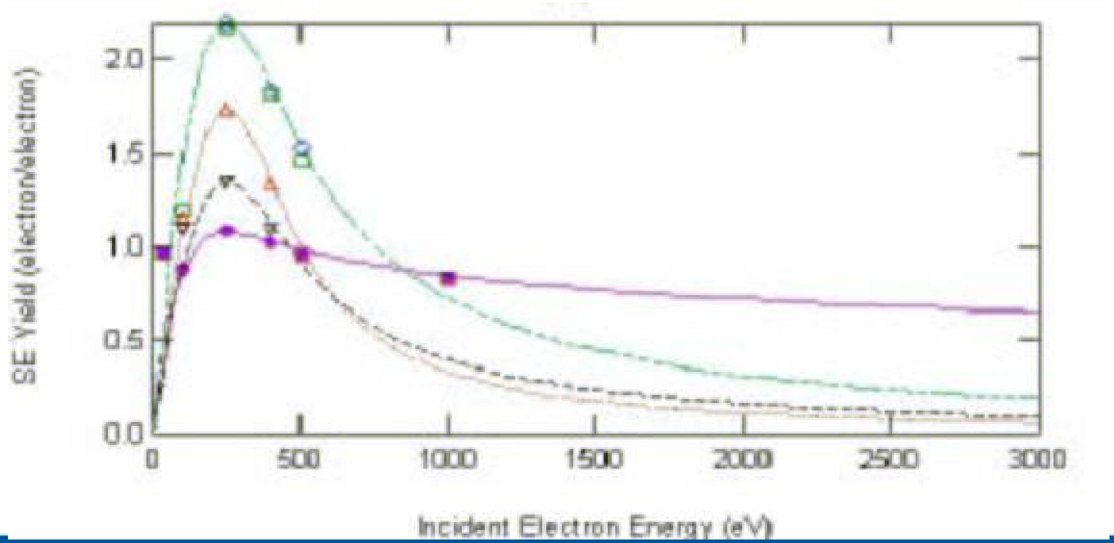
$E_o = 250$ eV

$E_o = 100$ eV

$E_o = 300$ eV

$E_o = 400$ eV

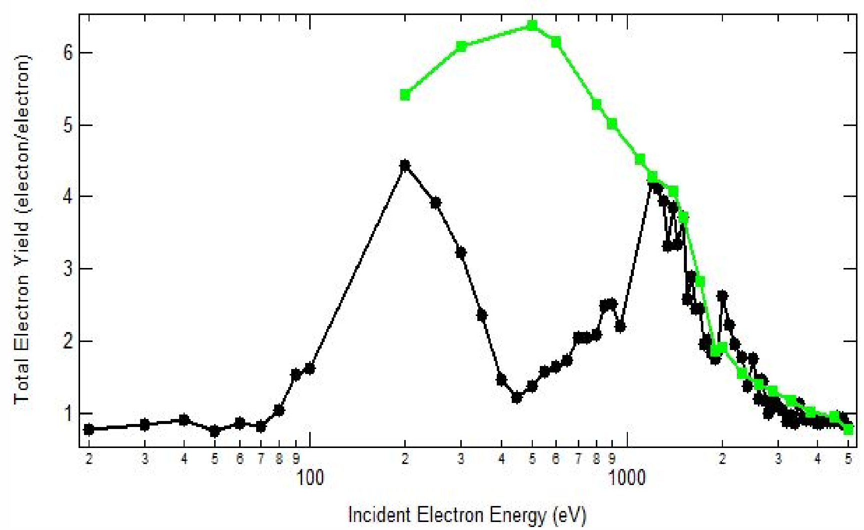
$E_o = 500$ eV

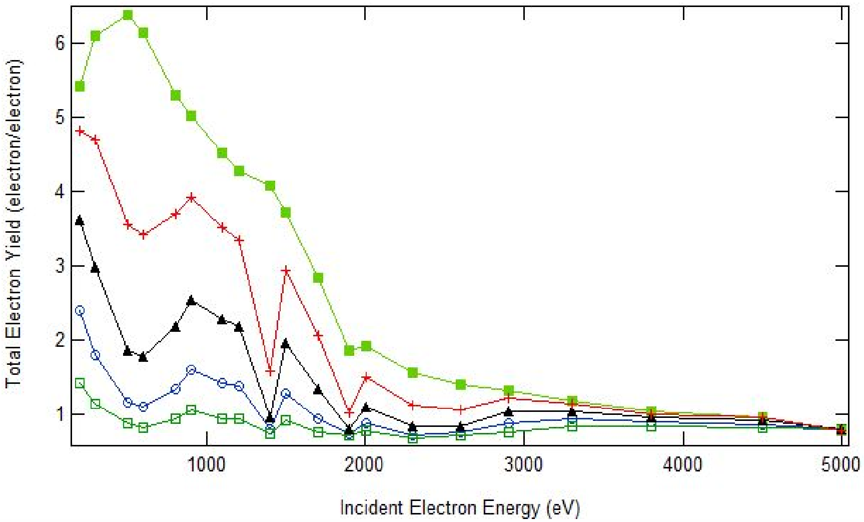


Constructed Yield Curves at Charge Density of:

- ⬇ ~4 pC/mm^2
- ⬇ ~1 pC/mm^2
- ⬇ ~0.4 pC/mm^2
- ⇩ ~3 fC/mm^2

Predicted Yield Curves at Various Surface Potentials

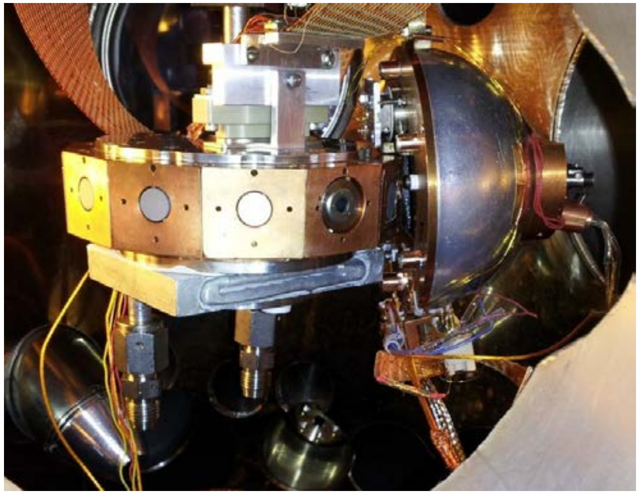


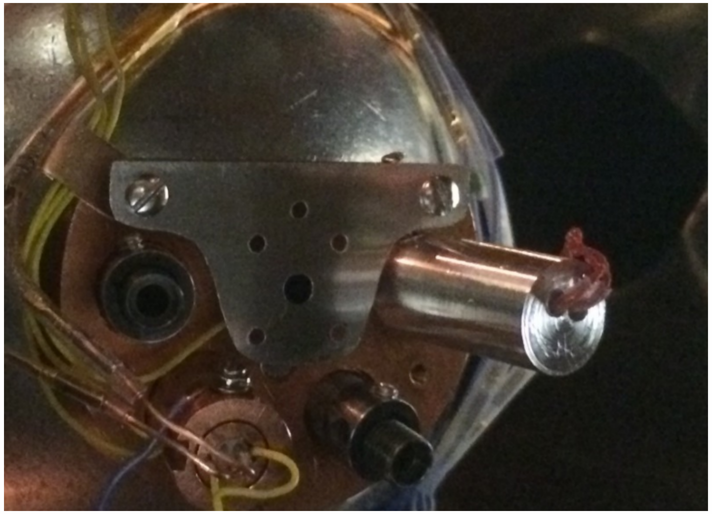


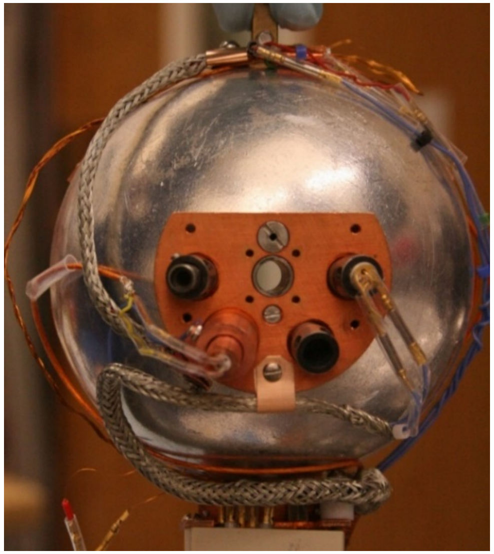
- **Measured Yield**
- **Analytic Prediction as Q→0**

- **Analytic Prediction as V_s= 0, 2, 5, 10, 20 V**
- **Notice Predicted Duel-Peak**

Enhanced Low Fluence Methods for Insulator Yields

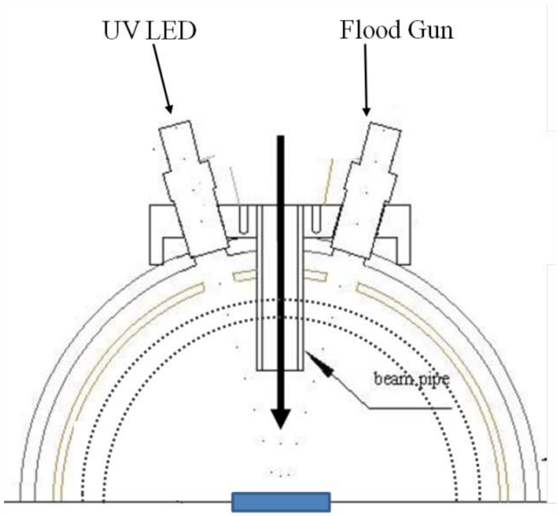




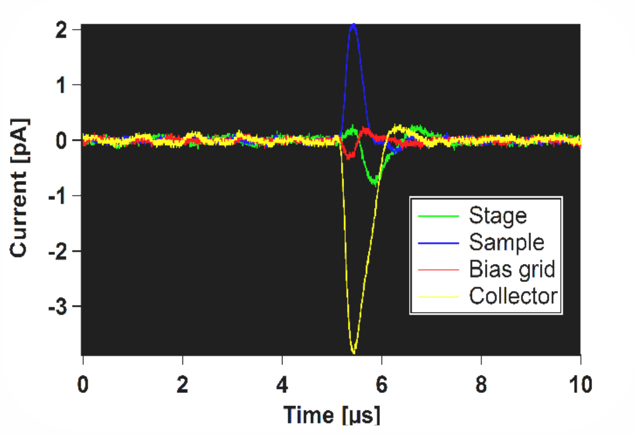


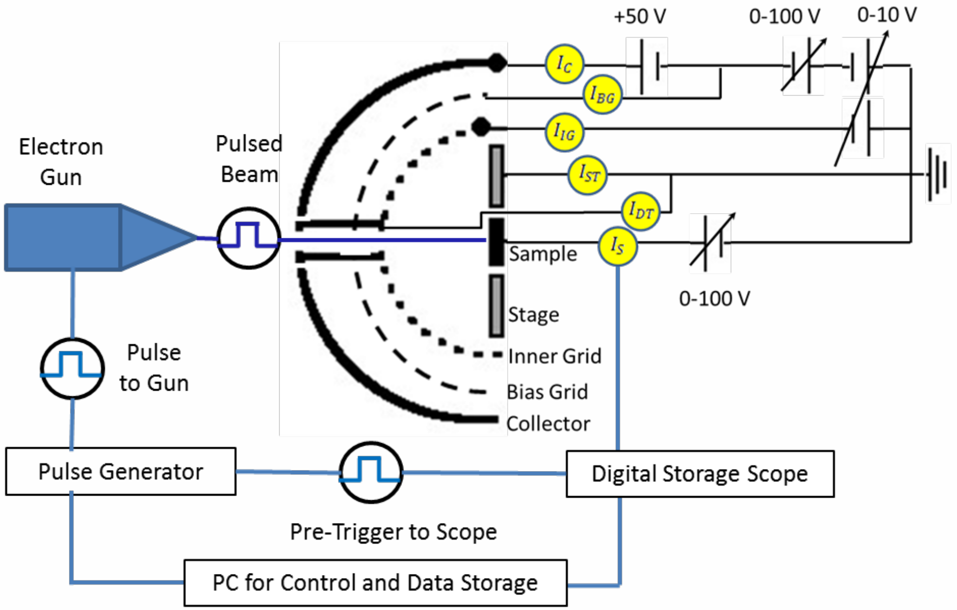
Hemispherical Grid Retarding Field Analyzer Electron Emission Detector

- o charge neutralization with low energy (~5 eV) e- and UV
- o 10 eV to 30 keV incident electrons
- o Precision absolute yield
  - o ~1-2% accuracy with conductors
  - o ~2-5% accuracy with insulators
- o fully enclosed HGRFA for emission electron energy discrimination.
- o measures all currents
- o *in situ* absolute calibration\
- o in situ surface voltage probe
- • multiple sample stage
- • ~100 K < T < 400 K
- • reduced S/N



Enhanced Low Fluence Methods for Insulator Yields

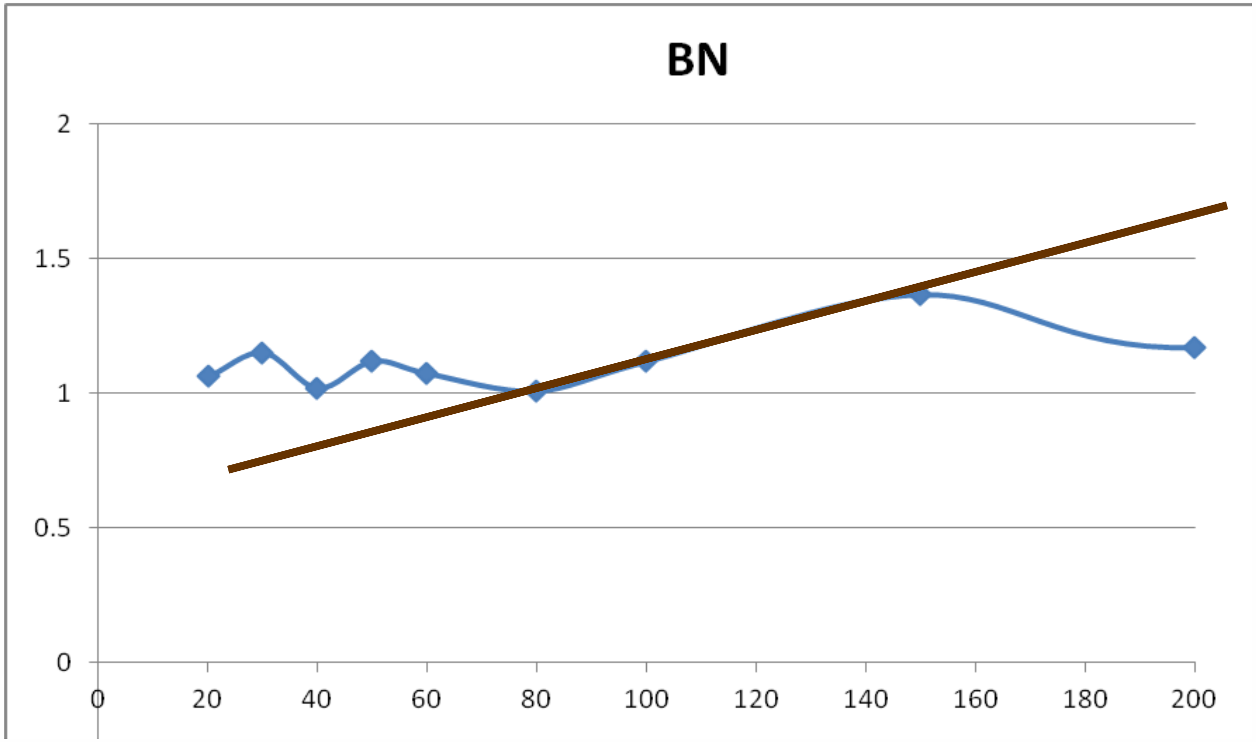




$$\sigma = 1 - \frac{\int_{pulse}[I_S + I_{St} + I_{IG} + I_{BG} + I_{DT}]dt}{\int_{pulse}[I_C + I_S + I_{St} + I_{IG} + I_{BG} + I_{DT}]dt}$$

- **Faster pulsed electron beam**
- **Fast Low-Current Measurement**
- **Monitoring 6 detector element currents, separately biased**
- **Electron yields calculated from integrated current traces**

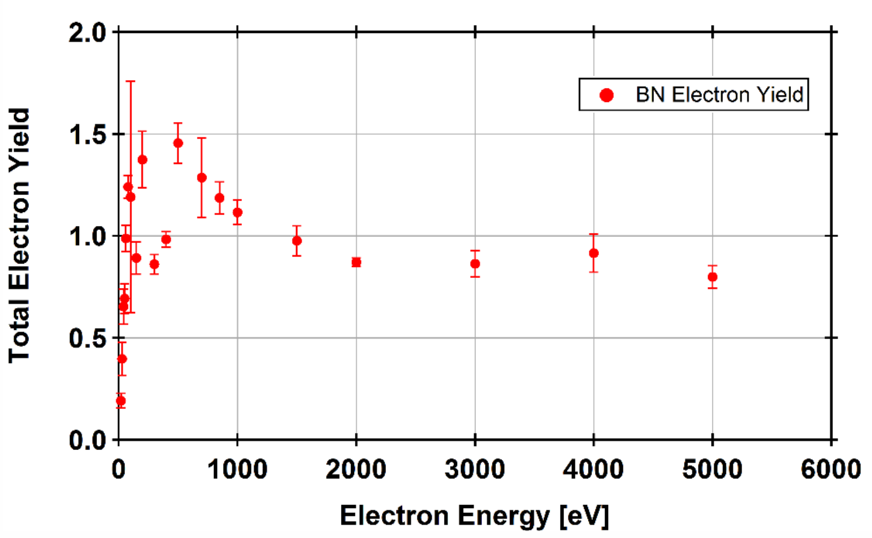
Initial Total Yields Curves of BN Near E_1

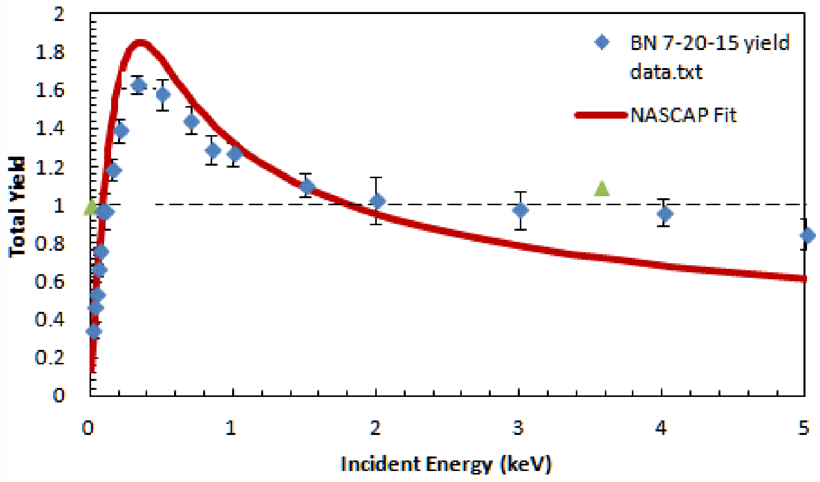


This is not impressive!!!

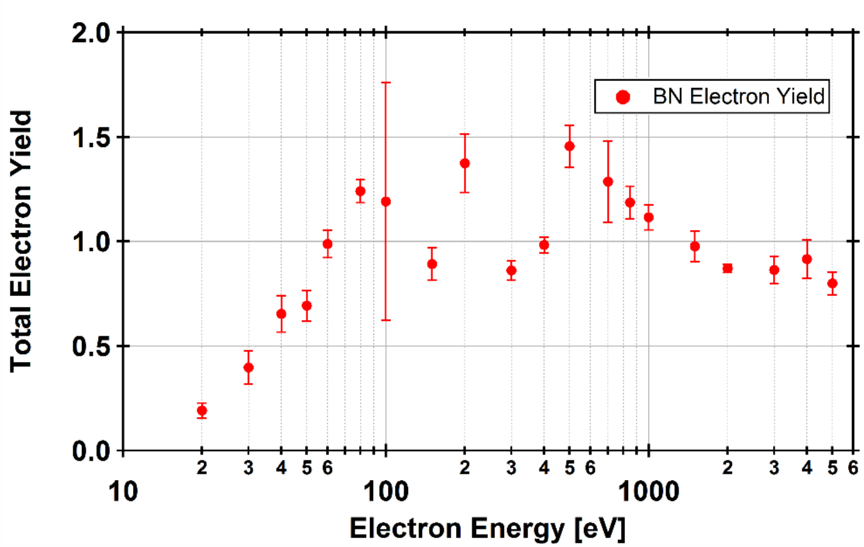
Improved Total Yields Curves of BN

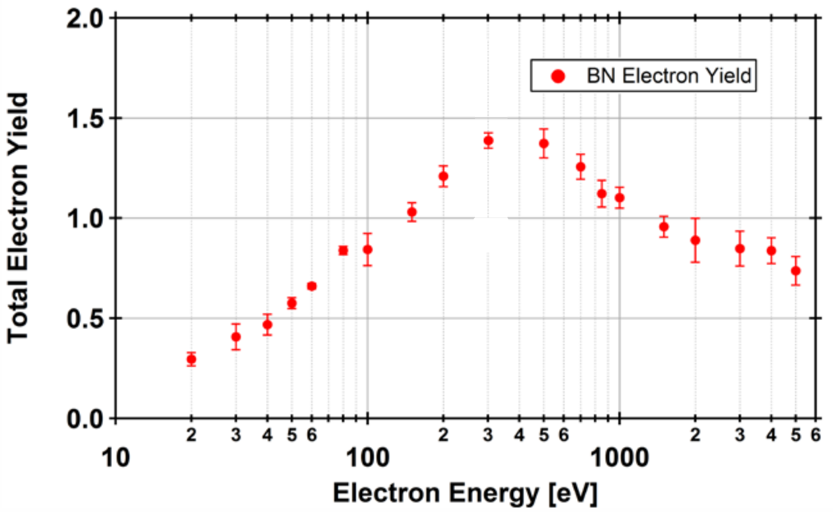
Comparison of Linear Fits





Comparison of Semilog Fits





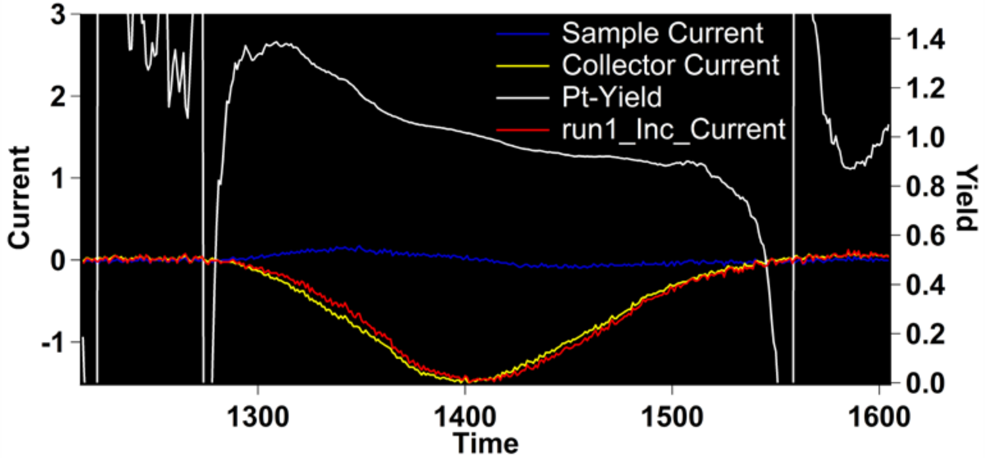
Pointwise Yield Method Slides

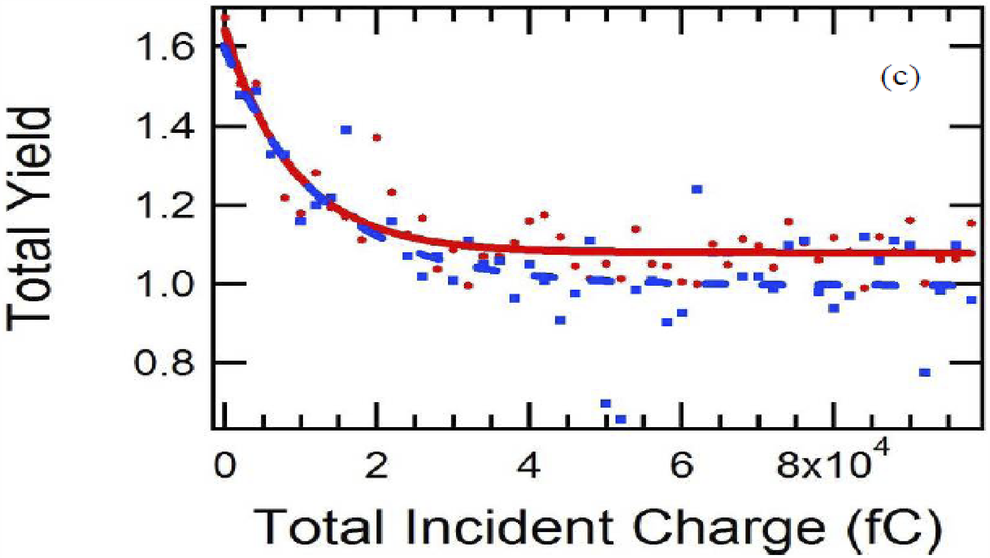
- Determine yield with pointwise method evaluated at each (or at least just a few) points of current traces

- Current analysis should show yield changes in one pulse. (~1% of total pulse charge)
- **~30 ns, ~5 nA, ~0.1 cm^2,**
- **~160 fC/cm^2-pulse,**
- **~2·10^3 e$^-$/cm^2-pulse**

- Initial Au data should show no charging effects and recover Au conductive yields

- **Finally hope to see the zero charge plateau of the intrinsic yield…that holy grail!!!**





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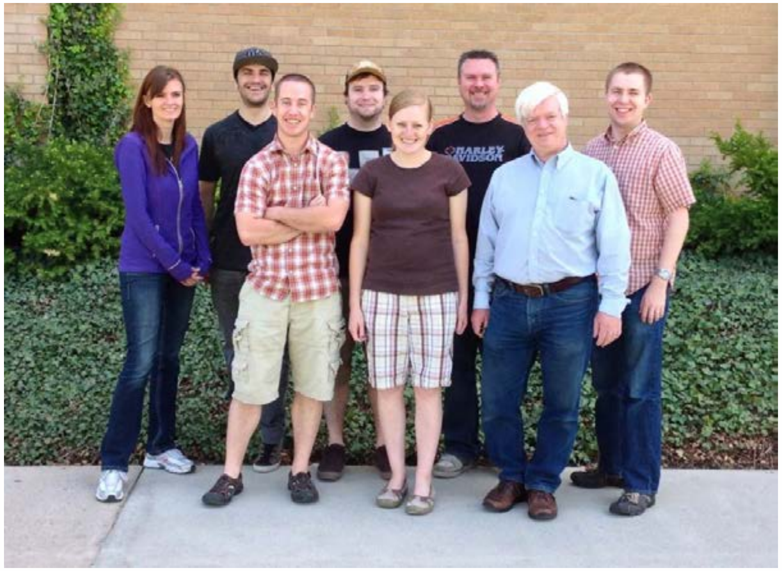

USU MPG
Webpage