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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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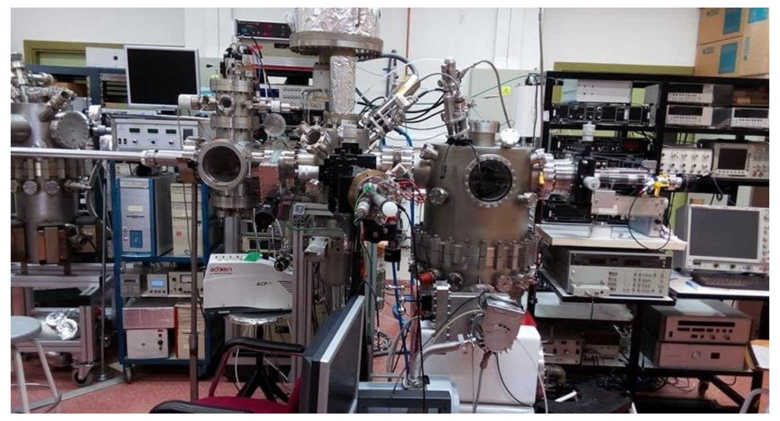
Descriptions of Facilities and Methods

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.



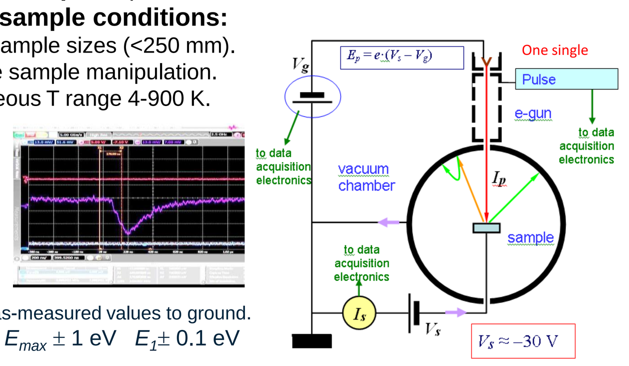
Equipped with:

- **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:** -90º to +90º
  - **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.

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

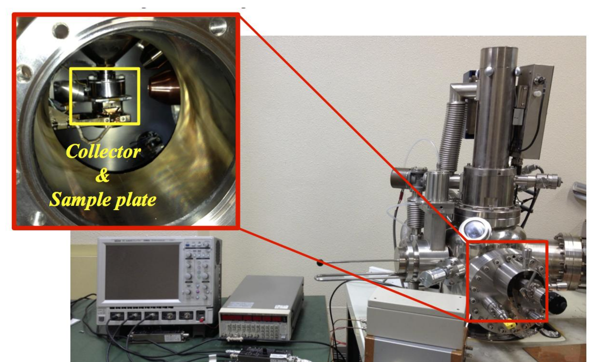


I_s and I_p are as-measured values to ground.
$\sigma \pm 0.005$ $E_{max} \pm 1$ eV $E_1 \pm 0.1$ eV

LaSEINE TEEY Facility

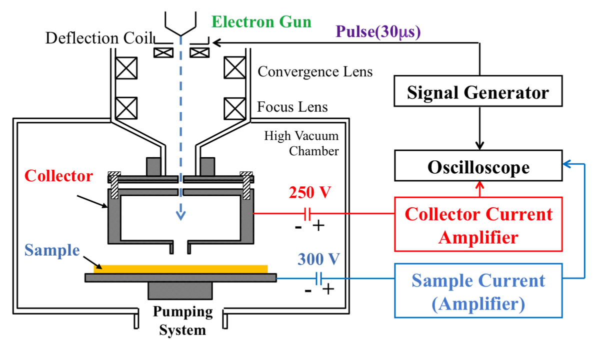
The Laboratory of Spacecraft Engineering INteraction Engineering (LaSEINE) at Kyushu Institute of Technology has studied spacecraft charging and discharging.

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:

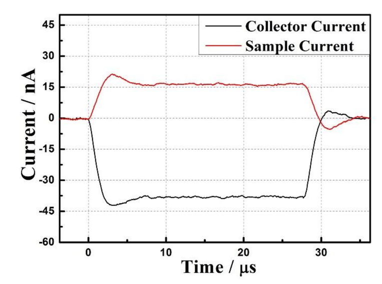
- **Vacuum** analysis chamber: below 10^{-5} Pa.
- **Electron Gun**: 300 eV-10 keV.
- **Electron Irradiation:** continuous or pulsed.
- **Sample Stage** movable in X-Y directions.
- **Temperature** sample holder control 240-370 K



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.

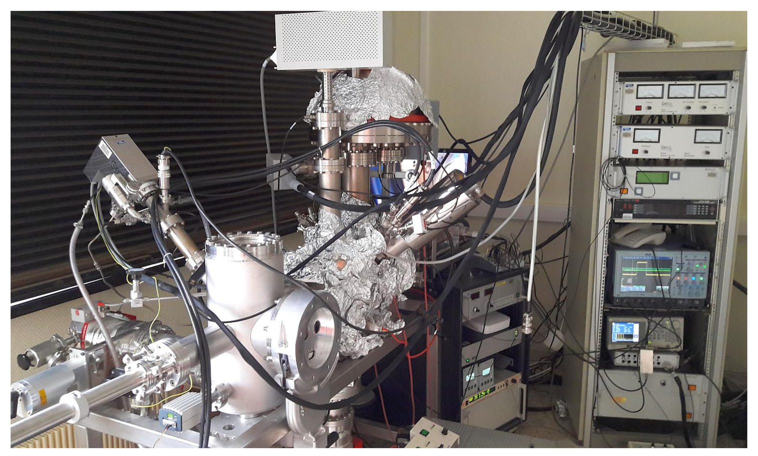
$$\sigma = 1 - \frac{I_S}{I_C + I_S}$$



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:

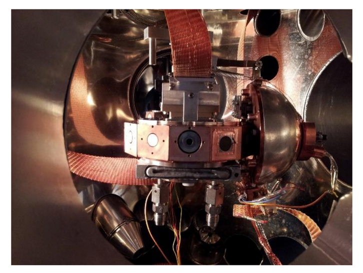
- Incident current measured as function of incident energy using the Faraday cup (polarized to +24 V).
- Thereafter, sample current was measured as function of incident energy.
- Sample holder biased to -18 V in order to avoid the collection of the low energy tertiary electrons by the sample surface.
- 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).

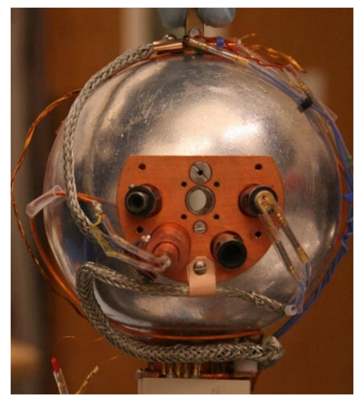
$$\sigma = 1 - \frac{I_S}{I_B}$$

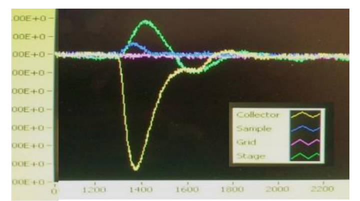
USU SEEM Facility

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.



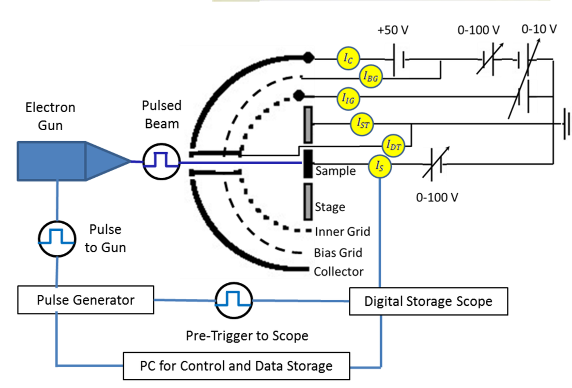




Measurements capabilities include:

- **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.

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

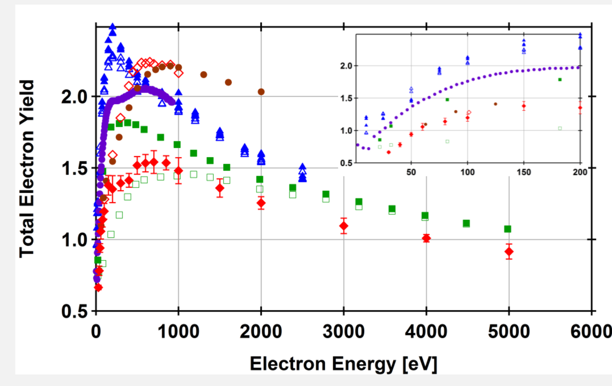


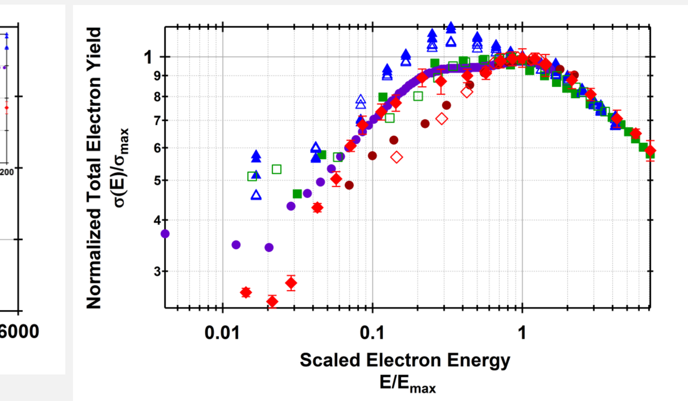
Electron yields are calculated from integrated current traces from six detector elements (A) of a fully enclosed hemispherical grid retarding field analyzer used for emission electron energy discrimination.

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}.

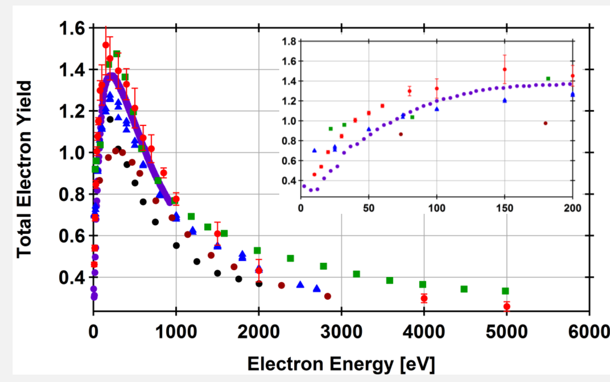
Gold

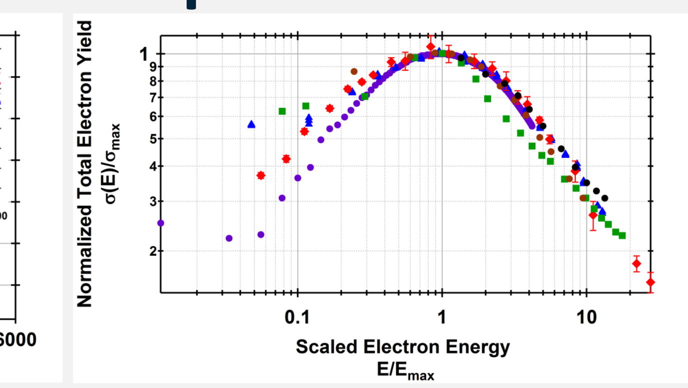




Symbol	Facility	Refs.	Measured Values			
			σ_{max}	E_{max} (eV)	E_1 (eV)	E_2 (eV)
●	CSIC SEY Facility (contin.)	1-3	2.06±0.02	600±20	24±1	NA
■	Onera—DEESSE Facility	4-5	1.81±0.03	360±20	28±1	~6000
□	Onera—DEESSE (Etched)	4-5	1.46±0.03	1250±50	NA	~6000
▲	LaSeine—TEY Facility (March 2)	6-7	2.48±0.03	200±20	NA	NA
Δ	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.