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THE FRENCH AEROSPACE LAB

Secondary Electron Emission in DIELECTRICS Experimental and modelling challenges

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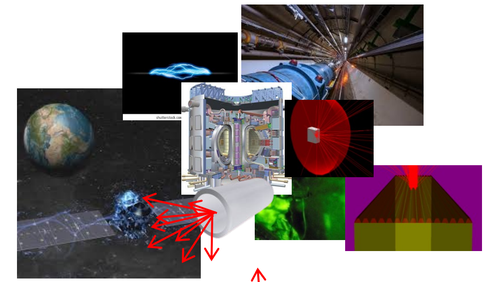
Q. Gibaru, P. Caron

Low energy Monte Carlo electron transport [eV, keV]

Low energy Monte Carlo electron transport

- Low energy : typically < some keV
- ionization processes
  - Effects of the radiative space environment in electronic devices
  - SEY for satellite charging mechanisms
  - **SEY for Multipactor mitigation (RF devices, particle accelerators)**
  - SEY for plasma thruster propulsion
  - SEY for signal magnification for night vision systems



GEANT4 Monte Carlo transport code

A SIMULATION TOOLKIT

- International collaboration driven by CERN (high energy physics)
- esa made it a standard for space community (lower energy)

MicroElec

cnes CENTRE NATIONAL D'ÉTUDES SPATIALES — cea — ONERA THE FRENCH AEROSPACE LAB

C.Inguimbert, Q.Gibaru, P. Caron
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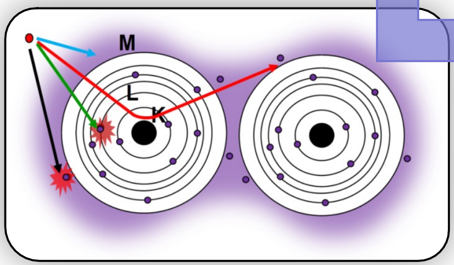
MicroElec module : Main challenges

Low energy : typically < some keV

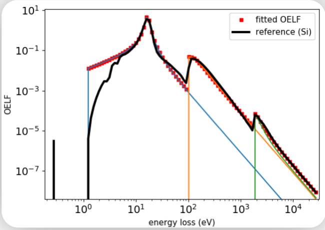
- Energies and speeds comparable to shell electrons of the target atoms
- Energy losses dominated by weakly bound electrons
- **No comprehensive model capable to account for typical band structures**

PLASMON



Exploiting experimental data
Optical energy loss function

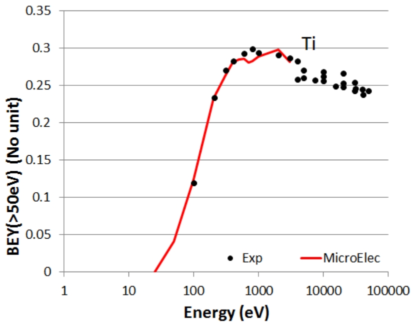
PLASMON

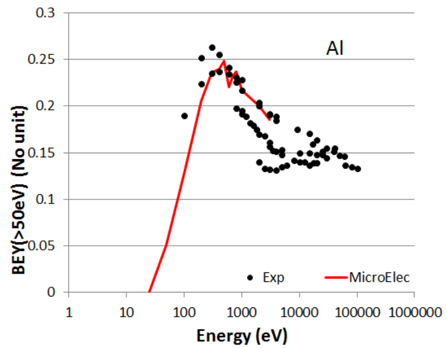


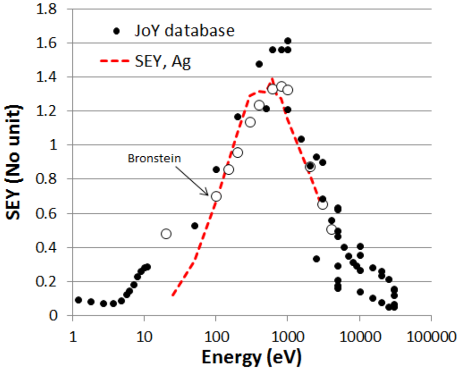
$$\boldsymbol{OELF}(\boldsymbol{\omega},\vec{\mathbf{0}}) = Im\left[-\frac{1}{\varepsilon(\omega,\vec{0})}\right] = \frac{2nk}{(n^2+k^2)^2}$$

$$]Im\left[-\frac{1}{\varepsilon(\omega,\vec{0})}\right] = \sum_j F(\omega)A_j Im\left[-\frac{1}{\varepsilon_M(\omega,\vec{0},E_j,\gamma_j)}\right]$$

$$\frac{d\sigma}{d(\hbar\omega)}(E,\hbar\omega) = \frac{Z_{eff}^2}{\pi N a_0 E'}\int_{q-}^{q+}\sum_j F(\omega)A_j\, Im\left[-\frac{1}{\varepsilon(\omega,q)}\right]\frac{dq}{q}$$







GEANT4 MicroElec module : validation using Secondary Electron Emission measurements

Graphite/Copper

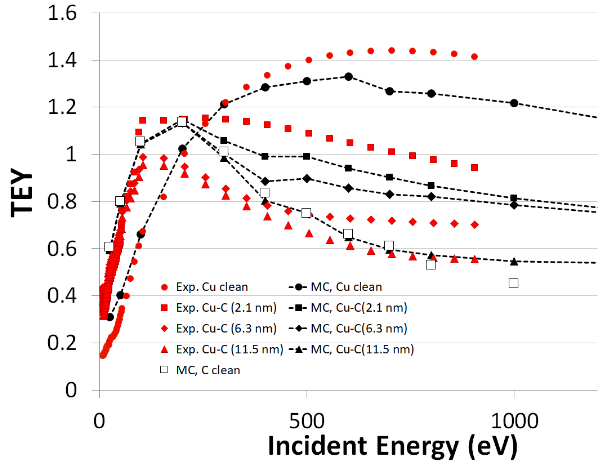
"Modelling the impact on the secondary electron yield of carbon layers of various thicknesses on copper substrate"
C. Inguimbert, Q. Gibaru, P. Caron, M. Angelucci, L. Spalino, R. Cimino
NIMB, Volume 526, 1 September **2022**, Pages 1-8

"Surface ionizing dose deposited by low energy electrons (10eV-10keV) in eleven monoatomic materials: Monte Carlo calculations and analytical expressions"
Q. Gibaru, C. Inguimbert, P. Caron, M. Belhaj, M. Raine, D. Lambert
Applied Surface Science, 576, Part A, (**2022**) 151813

"Monte-Carlo simulation and analytical expressions for the extrapolated range and transmission rate of low energy electrons [10 eV - 10 keV] in 11 monoatomic materials"
Q. Gibaru, C. Inguimbert, M. Belhaj, M. Raine, D. Lambert
Applied Surface Science 570, (**2022**), 151154

"Surface Ionizing Dose for Space Applications Estimated With Low Energy Spectra Going Down to Hundreds of Electronvolt"
C. Inguimbert, P. Caron, Q. Gibaru, A. Sicard, N. Balcon, et R. Ecoffet
IEEE Transactions on Nuclear Science, vol. 68, no 8, p. 1754 1763, aug. **2021**

"Geant4 physics processes for microdosimetry and secondary electron emission simulation: Extension of MicroElec to very low energies and 11 materials (C, Al, Si, Ti, Ni, Cu, Ge, Ag, W, Kapton and SiO2)"
Q. Gibaru, C. Inguimbert, P. Caron, M. Raine, D. Lambert, et J. Puech
NIM B, vol. 487, p. 66 77, jan. **2021**



Model extended to 17 materials, Dec 2023 release

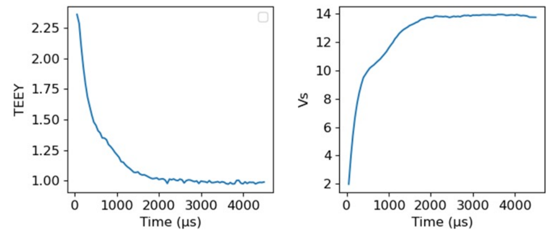
- **Be, C, Al, Si, Ti, Fe, Ni, Cu, Ge, Ag, W, Au**
- **SiO_2, Kapton ($C_{22}H_{10}N_2O_5$), Al_2O_3, BN, TiN**

DIELECTRICS

- Large gap materials : transport driven at very low energy **by phonon interactions**
- Electron trapping mechanism
- Charge buildup during the irradiation
- Elecric field impact the motion of incident electrons
- Electron/hole recombination

SEY modeling in Dielectrics (PHD Q. Gibaru cnes cea ONERA THE FRENCH AEROSPACE LAB)

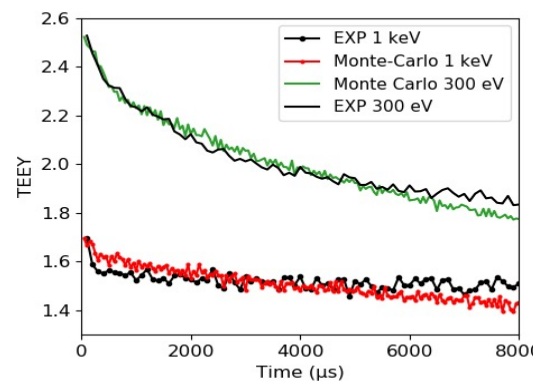
TEY changes with time reversely to potential build up



Transport of Electrons in dielectric materials strongly depends on the charging equilibrium state.

Main effects : **recombination of escaping electrons with holes**

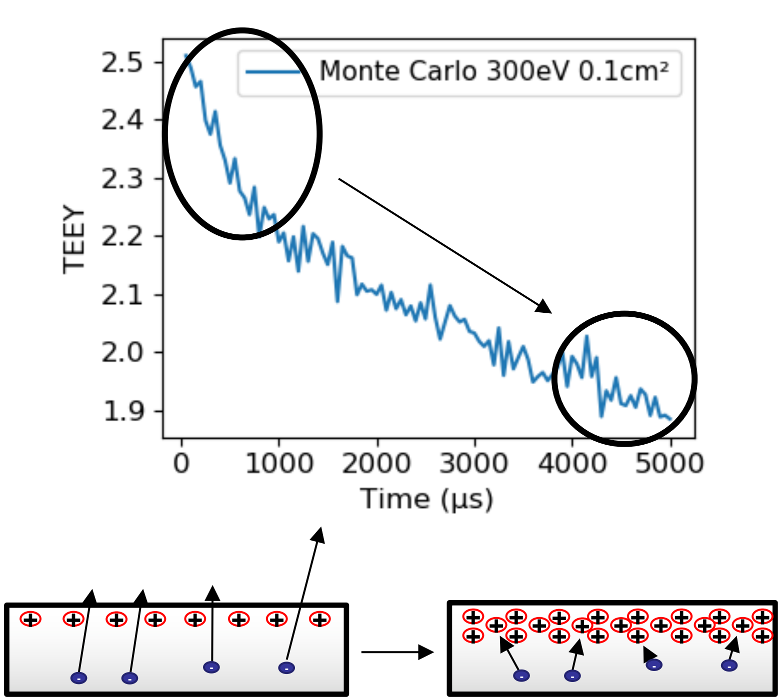
Combination of 1D Poisson Solver with GEANT4



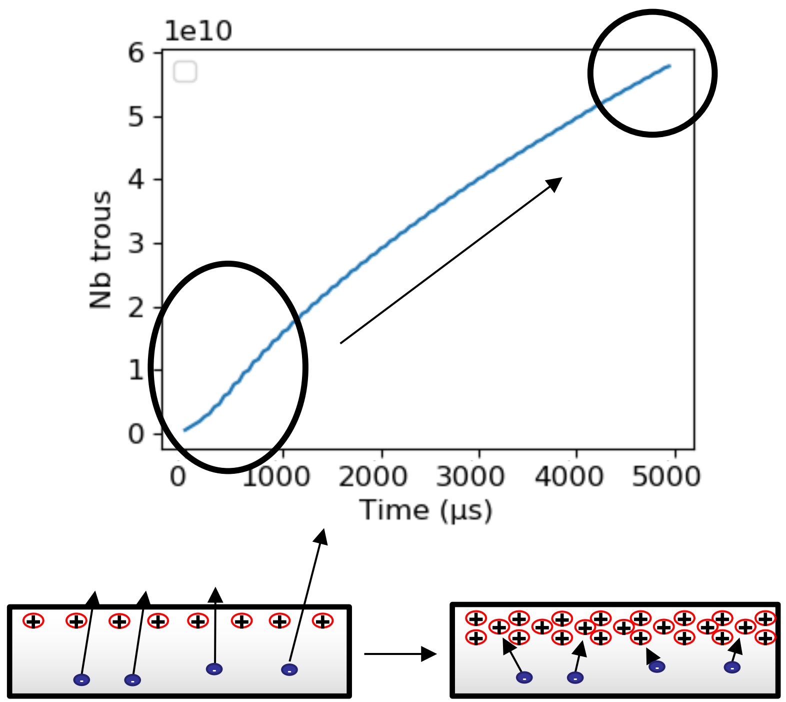
- **Drift diffusion process occurs for both electrons and holes**
- **Trapping and detrapping effects**

  Tunneling and Phonon Assisted Tunneling, Poole Frenkel
- **Recombination with thermalized electrons**

Highlighting the effect of recombination on the TEEY



Increased recombination

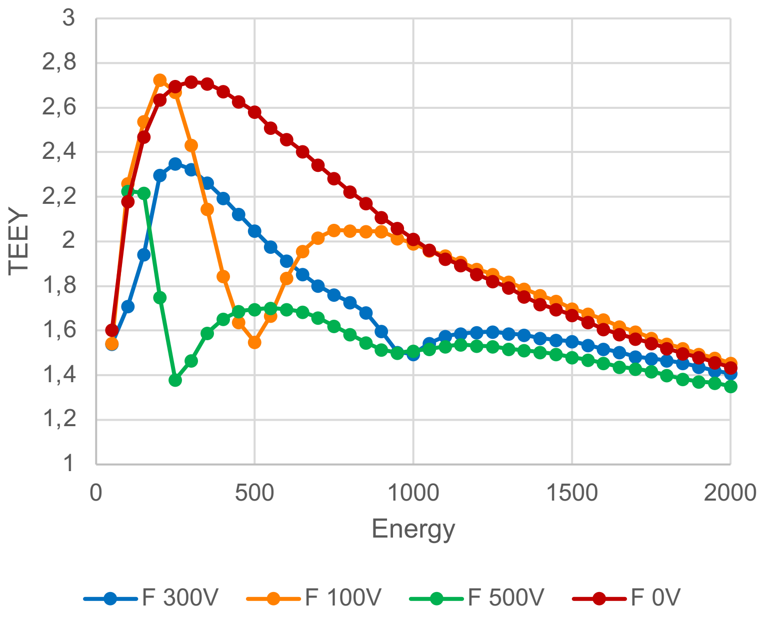


Increased charge level

Experimental measurements of multiple hump TEEY curves

Apparition of TEEY local minimums at select energies

- Known phenomenon*, attributed to internal charging effects
- **TEEY shape varies depending on the beam parameters (focus voltage)**



S. Yu *et al.*, 'Double- to single-hump shape change of secondary electron emission curve for thermal SiO2 layers', *Appl. Phys. Lett.*, vol. 79, no. 20, pp. 3281–3283, Nov. 2001, doi: 10.1063/1.1419046.
C. Rigoudy, K. Makasheva, M. Belhaj, S. Dadouch, G. Teyssedre, and L. Boudou, 'Atypical secondary electron emission yield curves of very thin SiO2 layers: Experiments and modeling', *J. Appl. Phys.*, vol. 130, no. 13, p. 135305, Oct. 2021, doi: 10.1063/5.0056218.

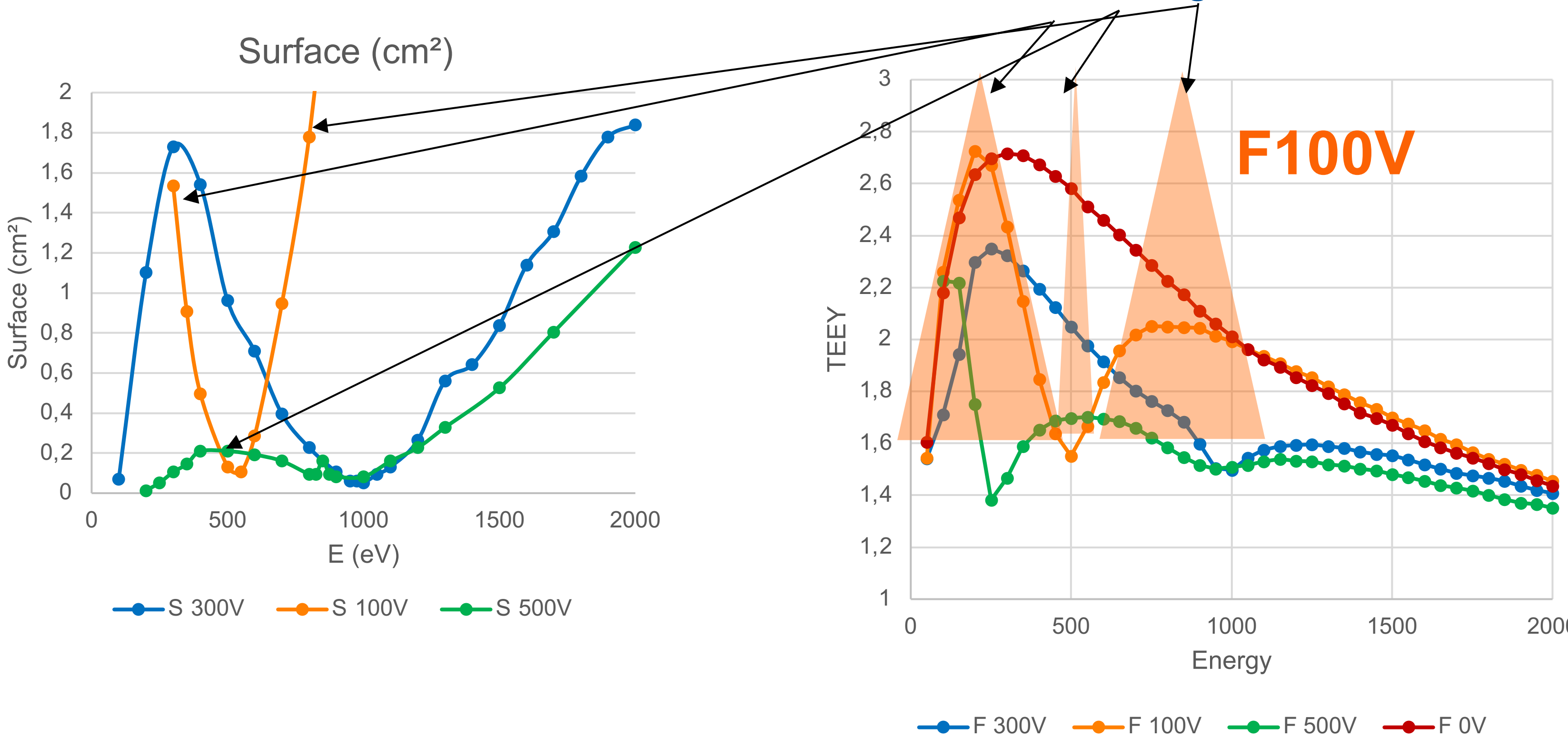
Measurement of the variation of the beam area

For a given focus voltage, the real beam focus varies with the energy of the beam

Incident current stays constant regardless of the focus => variable current density

Correlation between the minimums of beam area and the TEEY minimums

Electron gun beam size

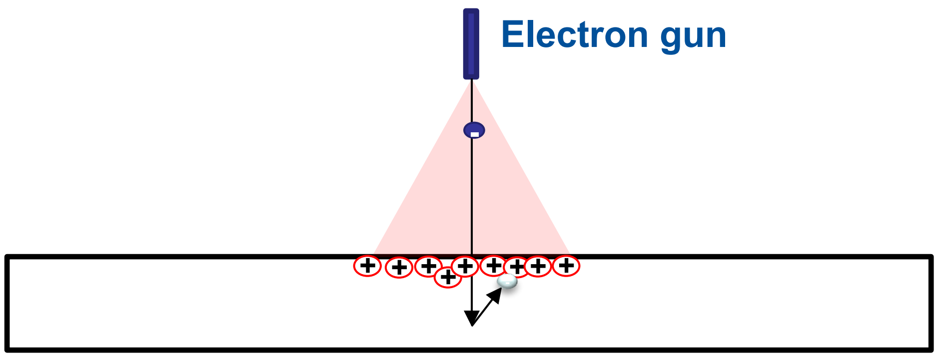


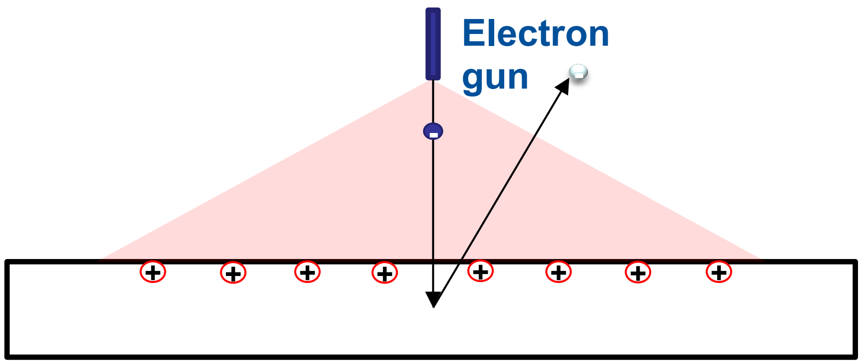
Study of the effect of current density on the TEEY

High current density (1 µA / 0,1 cm²)

Large density of holes on the irradiated surface

Reduction of the TEEY by recombination





Low current density (1 µA / 1 cm²)

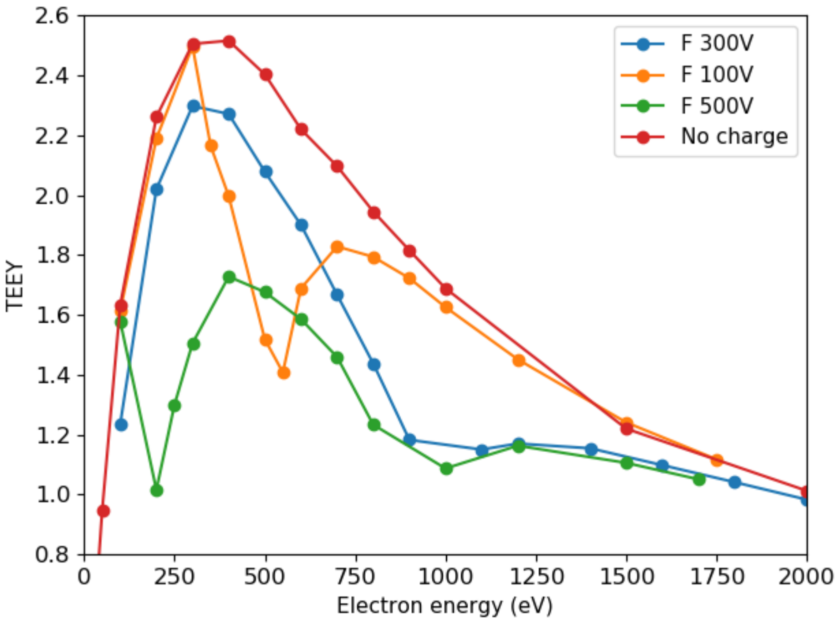
Charges created in select zones with a low uniformity on the surface

Incident electrons can hit zones that are free of charges

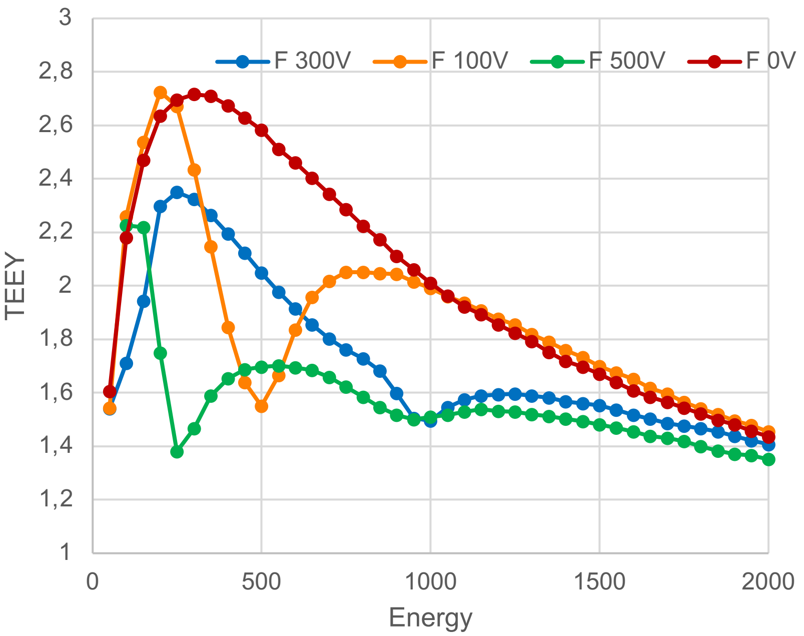
Increased escape probability for secondaries

Simulation of the TEEY depending on the current density

Simulation with a variable current density depending on the focus



Experimental measurements

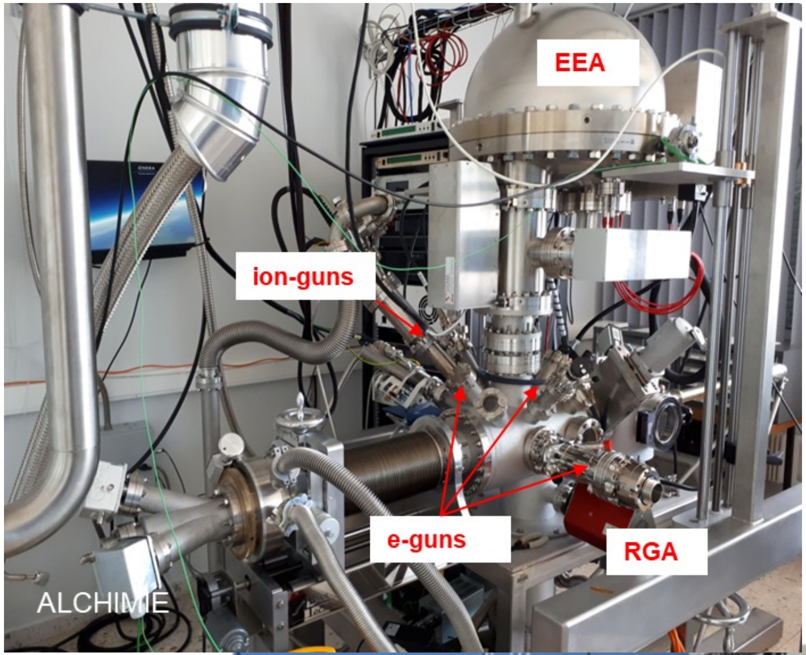


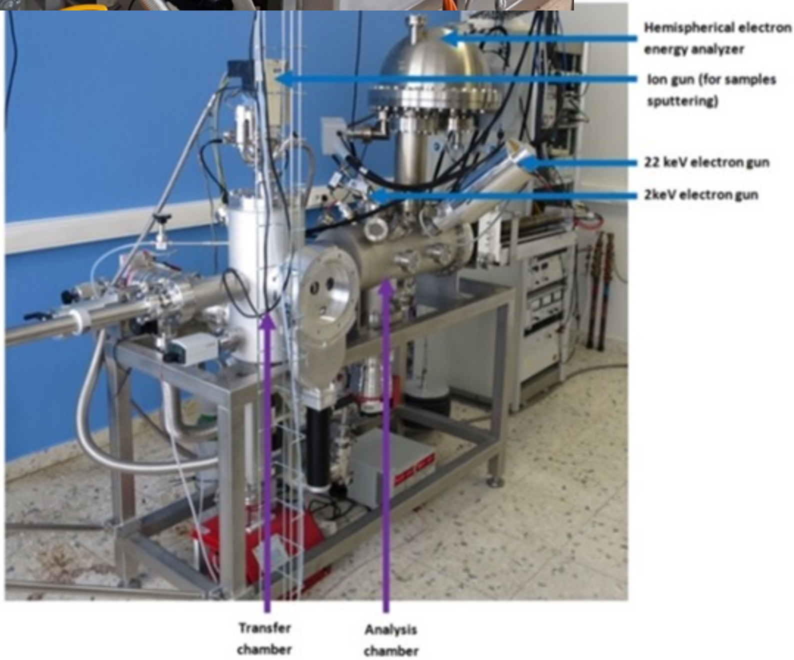
Reproduction of the experimental TEEY curves by the simulation
Double-hump curves are induced by the uncontrolled variation of beam area

Experimental setup

DEESSE and **ALCHIMIE** facilities UHV (10^{-10} to 10^{-9} mbar) specially developed @ ONERA for electro emission studies, equipped with:

- 3 e-guns ALCHIMIE and 2 in DEESSE
- Hemispherical electron energy analyser (EEA)
- Residual gas analyser (RGA)
- X-Ray source
- VUV source (Lyman alpha line)
- Charge measurement capability: Kelvin Probe (from ±0.1 V to ±200 V
- In situ ion sputtering capability
- In situ surface analyses technics AES and XPS
- Sample holder : from -200° C to +500° C





Conclusion

- Monte Carlo modelling is a usefull complementary tool to experiments for SEY mechanisms understanding
  - Predicting SEY for metals
  - Understanding charge induce effects in dielectrics
  - Modelling complex systems where SEY is a key parameter
- NEED of relevant experimental measurements in DIELECTRIC

Perspectives

- Extending GEANT4 microelec material database
  - AlGaAs, Kapton, Graphene, TiW, Epoxy
  - Complex dielectric function estimated with first principle calculations (DFT)
- Predicting SEY for heavy particles (protons, ions)