Electron emission model for Hall thruster plasma modelling

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M. Villemant[*] P. Sarrailh[†] M. Belhaj[‡] and C. Inguimbert[§]
ONERA - The French Aerospace Lab, 31055 CEDEX, FRANCE

L. Garrigues[¶]
LAPLACE Laboratory, Toulouse University, CNRS, INPT, UPS, FRANCE

and

C. Boniface[‖]
CNES - French National Space Agency, 18 Avenue Edouard Belin, F-31401 Toulouse, FRANCE

Electron emission at low incident energy is a topic of interest for Hall Thrusters plasma modeling. Among others, it is suspected that it could have a non-negligible impact on unexplained plasma behaviors such as anomalous electron transport. Consequently, a precise model of electron emission fitted to Hall Thruster simulations could improve Hall Thrusters plasma understanding.This article present a complete model of electron emission at low energy, which describes emitted electrons in terms of yield, angular and energy distribution. It is based on a physical and analytic approach and allows describing electron emission variations depending on physical parameters. Preliminary results of this model are presented.

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[*] Ph.D. student, Department Physics, Instrumentation, Environment, spacE (DPhIEE), marc.villemant@onera.fr
[†] Research Scientist, Department Physics, Instrumentation, Environment, spacE (DPhIEE), pierre.sarrailh@onera.fr
[‡] Research Scientist, Department Physics, Instrumentation, Environment, spacE (DPhIEE), mohamed.belhaj@onera.fr
[§] Research Scientist, Department Physics, Instrumentation, Environment, spacE (DPhIEE), christophe.inguimbert@onera.fr
[¶] Senior Scientist at CNRS, GREPHE group, laurent.garrigues@laplace.univ-tlse.fr
[‖] Dr, electric propulsion R&T manager, Propulsion, Pyrotechnics and Aerothermodynamics section, Claude.Boniface@cnes.fr

Nomenclature

EBE = Elastically backscattered electrons
EBEY = Elastic backscattered electron yield
ECDI = Electron-cyclotron drift instability
EE = Electron Emission
EEB = Elastic electron back-scattering
HT = Hall Thruster
IBE = Inelastically backscattered electrons
IBEY = Inelastic back-scattered electron yield
IEB = Inelastic electron back-scattering
SE = Secondary electrons
SEE = Secondary electron emission
SEEY = Secondary electron emission yield
SLAB = Single Large Angle Backscattering
TEEY = Total electron emission yield
E_e = Emitted electron energy [eV]
E_0 = Incident electron energy [eV]
w_f = Material work function [eV]
α = Emission angle [rad]
δ = Secondary electron emission yield (SEEY)
η = Elastic backscattering emission yield (EBEY)
σ = Total electron emission yield (TEEY)
θ = Deviation angle [rad]
θ_0 = Incident angle [rad]
σ_e = Elastic collision cross section [nm^2]
σ_i = Inelastic collision cross section [nm^2]
φ = Precession angle [rad]
Γ_0 = Incident electron flux to the wall [$\mathrm{m}^{-2}\,\mathrm{s}^{-1}$]
Γ_{se} = Incident electron flux to the wall [$\mathrm{m}^{-2}\,\mathrm{s}^{-1}$]
Γ_{eb} = Elastcially backscattered electron flux [$\mathrm{m}^{-2}\,\mathrm{s}^{-1}$]
Γ_{ib} = Inelastically backscattered electron flux [$\mathrm{m}^{-2}\,\mathrm{s}^{-1}$]
$d\Omega$ = Differential deviation solid angle [sr]

I. Introduction

Under electron impacts, electrons are emitted from the surface and near surface region of materials. This phenomenon is called electron emission induced by electrons (EE). It is a major issue for Hall Thruster (HT) industry to physically and accurately model plasma thruster behavior. As plasma-wall interaction plays a non-negligible role in HT plasma behavior, it is essential to model EE precisely. This interaction is mainly due to EE phenomenon and consequently it is essential to have implemented an accurate EE model in HT plasma simulation to represent its behavior accurately.

In the introduction, a sample of experimental and modeling examples is presented to show the impact of EE on HT performance and to highlight the need to describe it precisely. EE phenomenon is then described. In a second part, the model used to describe EE is presented. In the last part, preliminary results are presented.

A. Electron Emission impact on Hall Thruster plasma behaviour

A large amount of elements allows assuming that EE has a non-negligible impact on Hall Thruster plasma behavior. Indeed, several experiments have shown that modifying EE also modify plasma thrusters performances and plasma behavior. In 2003 Gascon et al. have shown the effect of wall materials on current oscillations in SPT-100.[1] In 2006, Raitses et al. have achieved a measurement campaign on a 2 kW Hall Thruster.[2] This thruster has had its walls covered with an extremely low emissive material (carbon velvet) in order to measure, amongst others, the impact of EE on HT plasma behavior. Moreover, it has been experimentally shown by Tsikata et al. that modifying electron emission at the wall has an impact on HT performance and range of operation.[3] Indeed, it can be shown that decreasing EE in HT decreases the thruster efficiency and the range of operation. In the mean time, the plume divergence also decreases with the EE. Modelling also have proven a link between electron emission and plasma behavior in HT. Indeed, Heron et al. have proven that electron emission has a direct impact on electron cyclotron drift instability (ECDI).[4] It has also been modelled that ECDI could explain a non-negligible part of anomalous electron transport in HT.[5] The experiments and modelling show a complex influence of EE on HT plasma, which push to model it more precisely in HT plasma simulations.

B. Electron Emission phenomenon

EE is generally described in term of ratio of the emitted electrons flux on the incident electrons flux. This ratio is called total electron emission yield (TEEY) and noted σ:

$$\sigma = \frac{\Gamma_e}{\Gamma_0} \tag{1}$$

With:

- Γ_0: The incident electron flux $[\mathrm{m^{-2}\,s^{-1}}]$
- Γ_e: The emitted electron flux $[\mathrm{m^{-2}\,s^{-1}}]$

This ratio depends on incident electron energy, incident angle, wall material, surface state, etc. Nonetheless, it can be notice that EE should not be described only in term of emitted electron number, but also in term of emitted electron energy distribution and angular distribution.

Moreover, it can also be noticed that EE regroups in fact three different phenomena: the secondary electron emission (SEE, cf. Fig.1a), the elastic electron backscattering (EEB, cf. Fig.1b) and the inelastic electron back-scattering (IEB, cf. Fig.1c).

The quantities of electrons of these three categories are represented by the secondary electron emission yield (SEEY, noted δ), the elastic backscattering electron yield (EBEY, noted η_e) and the inelastic backscattering electron yield:

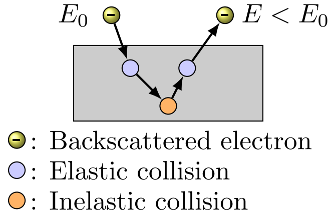
$$\delta = \frac{\Gamma_{se}}{\Gamma_0} \qquad \eta_{eb} = \frac{\Gamma_{eb}}{\Gamma_0} \qquad \eta_{ib} = \frac{\Gamma_{ib}}{\Gamma_0} \tag{2}$$

With:

- Γ_{se}: The secondary electron flux $[\mathrm{m^{-2}\,s^{-1}}]$

(a) Secondary electron emission

(b) Elastic backscattering



(c) Inelastic backscattering

Figure 1: Electron Emission phenomenon

- Γ_{eb}: The elastically backscattered electron flux [$\mathrm{m}^{-2}\,\mathrm{s}^{-1}$]
- Γ_{ib}: The inelastically backscattered electron flux [$\mathrm{m}^{-2}\,\mathrm{s}^{-1}$]

As Γ_e is the sum of all emitted electrons ($\Gamma_e = \Gamma_{se} + \Gamma_{eb} + \Gamma_{ib}$), TEEY can be expressed as the sum of these three terms:

$$\sigma = \delta + \eta_e + \eta_i \tag{3}$$

However, the electron emission yields are not sufficient to fully describe EE. Angular and energy distribution of the emitted electrons need also to be described.

The energy distribution of electrons is defined as:

$$\delta_E \Gamma = \frac{1}{\Gamma}\frac{d\Gamma}{dE} \tag{4}$$

The angular distribution of electrons is defined as:

$$\delta_\Omega \Gamma = \frac{1}{\Gamma}\frac{d\Gamma}{d\Omega} \tag{5}$$

With:

- Ω : The considered solid angle [sr]

$\delta_E\Gamma$ and $\delta_\Omega\Gamma$ are, by definition, normalized to 1.

A precise and complete description of EE phenomenon implies the description of these three values (yield, angular and energy distribution) and for the three electrons families (SE, EBE, IBE).

II. Model description

As explained in previous part, EE is composed of three distinct phenomena: SEE, EBEE and IBEE. These three phenomena have to be described in term of emitted electrons number, energy and angular distribution. For practical reasons - lack of analytic models, impact considered as negligible - the inelastically backscattered electrons have been neglected in our model. Besides, it is known from experimental data[6] and Monte-Carlo models,[7] that SEs have a quasi-Lambertian distribution. Thus SEs angular distribution will be considered as isotropic. Moreover by definition EBEs have an emission energy equal to incident energy

E_0. In order to have a full description of EE, four additional data are needed: the expressions of SEEY (δ), EBEY (η_e), the angular distribution of EBEs ($\delta_\Omega\Gamma_{eb}$) and the energy distribution of secondary electrons ($\delta_E\Gamma_{se}$). δ is described with Inguimbert model[8] (cf.II.A), η_e and $\delta_\Omega\Gamma_{eb}$ are described with the single large angle backscattering model (SLAB model)[9] and $\delta_E\Gamma_{se}$ is described with Chung and Everheart model.[10] The complete EE model is resumed in Table.1. Inguimbert, Chung and Everheart and SLAB models will be described thereafter.

	Secondary electron emission	Elastic backscattering	Inelastic backscattering
Emission Yield	Inguimbert model	SLAB model[9]	Neglected
Angular distribution	Lambertian distribution		
Energy distribution	Chung and Everheart model[10]	Mono-energetic distribution	

Table 1: Electron emission model description

A. Secondary electron yield model: Inguimbert model

Inguimbert model is currently being published.[8] It depends on material physical parameters as: incident angle, incident electron energy, material, etc. It allows describing analytically the secondary electron emission. This model consist in four steps:

1. Calculate deposited dose by the incident electron beam into the material.
2. Calculate secondary electrons generation in the material.
3. Evaluate the probability of a created secondary electron to reach the surface.
4. Evaluate the probability of a secondary electron to cross the surface.

The entry parameters of this model are the incident electron energy E_0, θ_0 and material properties.

B. Secondary electron energy distribution model: Chung and Everheart model

Chung and Everheart model has been chosen to describe secondary electrons energy distribution because it presents several advantages: it gives good agreement with experimental data, it can be expressed by using one physical parameter (material work function: φ), and it is based on a physical reasoning and not empirical fitting.

According to Chung and Everheart model, energy distribution of secondary electrons can be written as:

$$\delta_E\Gamma_{se}(E_{se}, w_f) = \frac{1}{\Gamma_{se}}\frac{d\Gamma_{se}}{dE} = 6w_f^2\frac{E}{(E+w_f)^4} \tag{6}$$

With:

- E_{se}: The secondary electron emission energy [eV]
- w_f: The material work function [eV]
- $\delta\Gamma_{se}$: The probability density of the secondary electrons to be emitted with the energy E_{se}

It can be deduced from this formula that:

$$\Delta_E\Gamma_{se}(E_{se}, w_f) = \int_0^{E_{se}} \delta_E\Gamma_{se}(E, w_f).dE = \frac{E_{se}^2(E_{se}+3w_f)}{(E_{se}+w_f)^3} \tag{7}$$

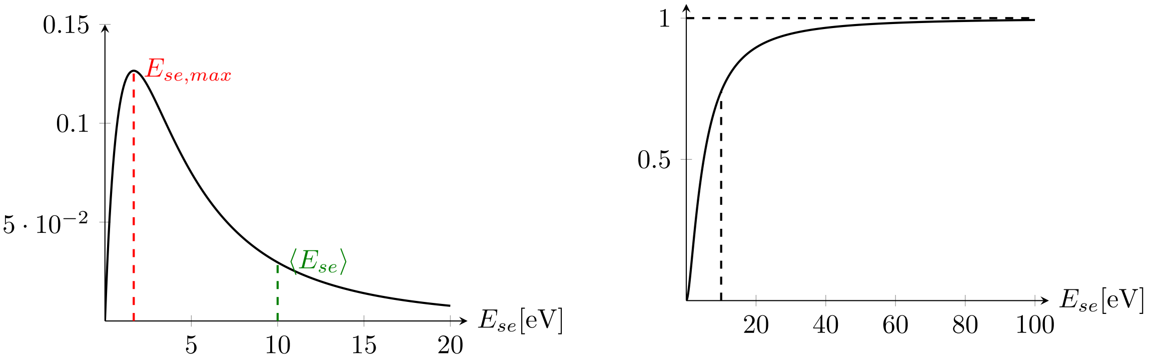
$$\langle E_{se}\rangle = 2w_f \tag{8}$$

$$E_{se,max} = \frac{w_f}{3} \tag{9}$$

With:

- $\Delta_E\Gamma_{se}$: The cumulated electrons energy distribution [$\varnothing$]
- $\langle E_{se}\rangle$: The secondary electron energy [eV]
- $E_{se,max}$: The energy at the maximum of the distribution [eV]

$\Delta_E\Gamma_{se}(E_{se}, w_f)$ is useful for PIC modeling as it directly gives the probability to find a secondary electron with an energy below E_{se}. Nonetheless Chung and Evereheart model is restricted to conductors. It will be check in future works if this model can be adapted to dielectric materials (e.g. SiO_2).



(a) Secondary electrons energy distribution

(b) Secondary electrons cumulated energy distribution

Figure 2: Energy distribution of secondary electrons according to Chung and Everheart model.

Fig.2a represent $\delta\Gamma_{se}$ as a function of emitted secondary electron energy (E_{se}) and Fig.2b represent the probability to find a SE with an energy below E_{se} as a function of E_{se}. Both have been represented for $\varphi = 5\,\text{eV}$. It can be observed that a majority of secondary electrons are emitted with a very low energy. Indeed φ value is typically around 5 eV, consequently according to (7), 74 % of SEs are emitted with an energy below 10 eV.

C. Elastic backscattering model: SLAB model

Precise models of elastic backscattering exist today especially due to the importance of this effect on scanning electron microscope (SEM) resolution. However they are essentially Monte-Carlo models. They give precise results but require important computation time for one given incident energy E_0, one material, and one incident angle θ_0. This is incompatible with EE description in HT where values must be given on a wide range of E_0, θ_0 and for different wall material (BN, SiO_2, Al_2O_3, etc.). Thus a quicker model has to be employed. The OKG model[11] gives an analytic description of EBEY. It considers that incident electron endure a number of elastic collisions along its trajectory but the emission direction can be reduce only to one elastic collision contribution.

A simpler model derived from OKG model is given by Jablonski.[9] The single large angle backscattering model (SLAB model) averages the amount of elastic collisions as one elastic collision (cf. Fig.3). This model needs five entry parameters: the incident electron energy, the incident electron angle, the total and pertial elastic backscattering cross section and the inelastic backscattering cross section of the material. Elastic total and differential cross sections of the material are obtained from ELSEPA code.[12] Inelastic cross section of the material is obtained from OSMOSEE code (ONERA).[13]

The differential EBEY can be analytically written as:

$$\frac{d\eta_e}{d\Omega} = \frac{\cos(\alpha)}{\cos(\alpha)+\cos(\theta_0)}\left(\frac{1}{\sigma_e}\frac{d\sigma_e}{d\Omega}\right)(\theta, E_0)\ln(1+\frac{\sigma_e}{\sigma_i}) \tag{10}$$

With:

- E_0: Incident electron energy [eV]
- θ_0: The incident angle [rad]

- α: The emission angle [rad]
- φ: The precession angle [rad]
- θ: The deviation angle [rad]
- $d\Omega$: Differential solid deviation angle [sr]
- σ_e: The elastic collision cross section [nm^2]
- σ_i: The inelastic collision cross section [nm^2]
- $\frac{d\eta_e}{d\Omega}$: The differential electron backscattering emission yield [sr^{-1}]
- $\frac{d\sigma_e}{d\Omega}$: The differential elastic collision cross-section [nm^2 sr^{-1}]

$\frac{d\eta_e}{d\Omega}$ can be expressed as a function of η_e and $\delta_\Omega\Gamma_{eb}$:

$$\frac{d\eta_e}{d\Omega} = \eta_e \cdot \delta_\Omega\Gamma_{eb} \tag{11}$$

Knowing α, θ_0 and φ, θ can be geometrically deduced from Fig.3:

$$\theta = \arccos\left[\sin(\theta_0)\sin(\alpha)\cos(\varphi) - \cos(\theta_0)\cos(\alpha)\right] \tag{12}$$

SLAB model allows calculating in a short time the angular distribution and the EBEY for a large number of E_0 and θ_0 values. This model is very simple. It can be observed though that the considered values of E_0 are below 200 eV. In these conditions, it is relevant to consider that elastically backscattered electrons have only endure a reduced number of elastic collisions. Consequently, the single large angle backscattering hypothesis seems relevant. η can be deduced from $\frac{d\eta}{d\Omega}$ by integration on a 2π sr solid angle according to:

$$\eta(E_0,\theta_0) = \int_{\alpha=-\frac{\pi}{2}}^{\alpha=\frac{\pi}{2}} \int_{\varphi=-\frac{\pi}{2}}^{\varphi=\frac{\pi}{2}} \frac{d\eta}{d\Omega}(E_0,\theta_0,\alpha,\varphi)\sin(\alpha)d\alpha d\varphi \tag{13}$$

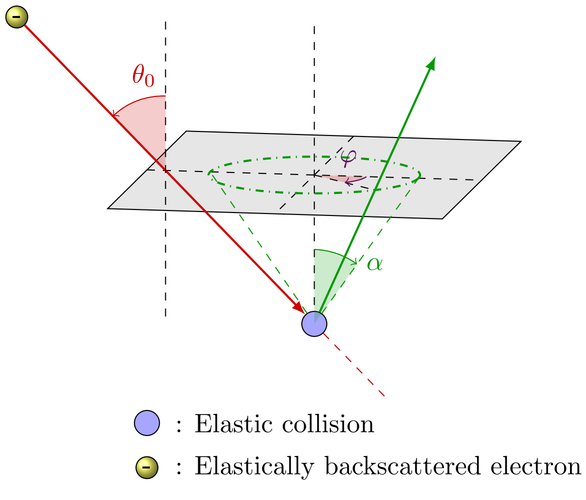


Figure 3: Elastic backscattering phenomenon according to SLAB model

All these data give a complete model of electron emission, which will allow describing the EE phenomenon precisely enough for plasma thruster PIC modelling. The current results of this model are described in the next section.

III. Electron emission model results

The complete model composed of Chung and Everheart, SLAB and Inguimbert models allows describing EE in term of yields, energy and angular distributions.

A. Emitted electrons yield

It is essential to represent accurately electron emission yield at HT walls because it directly influences non-linear phenomena as electron cascade in HT plasma. Indeed, if the TEEY at a walls exceeds 1, the electrons number will rapidly increase in the channel. Emitted electrons yield is well described in HT models comparatively to angular and energy distribution. Different models as Vaughan,[14] Scholtz[15] or Barral[16] models are used. These models present good fit with experimental values and gives the dependency of TEEY to E_0 and θ_0 (for Vaughan only).

However several points push us to develop a physical and more detailed model of electron emission phenomenon. First of all, the current used models do not take into account the influence of back-scattered electrons on SEEY. Secondly, they are essentially based on fitting parameters. Consequently, it is difficult to extrapolate this models to a large variety of material and to make physical reasoning on results. Besides, they only describe TEEY. Therefore, it is not possible to distinguish the behavior of the different types of emitted electrons(SEs and EBEs).

Combining Chung and Everheart, SLAB and Inguimbert models allows giving the yield of secondary and elastically back-scattered electrons. By assuming that inelastically back-scattered electrons are negligible, TEEY can be deduced:

$$\sigma \simeq \eta_e + \delta \tag{14}$$

Fig.4 shows the TEEY, SEEY and EBEY calculated by this model for an aluminum surface and an incident angle (θ_0) equal to 0°.

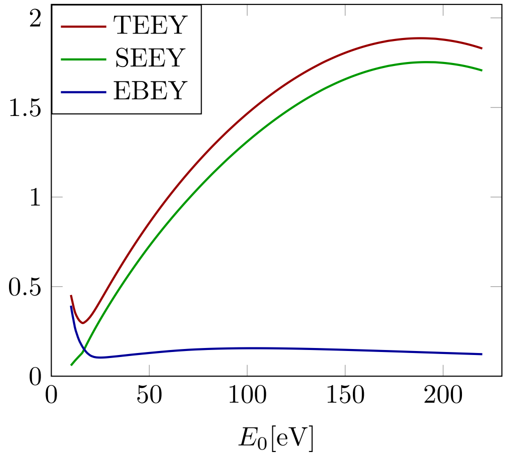


Figure 4: TEEY modeling on aluminum surface as a function of the incident electrons energy (E_0) and for $\theta_0 = 0°$

It can be noticed that EBEY is not negligible, especially at low energy where it represents the majority of TEEY. This is important in HT plasma where a non-negligible part of the incident electrons arrive at the wall with a low energy. Besides, it can be seen that η_e remains equal to 15 % at higher energy, which is in agreement with Monte-Carlo model and experimental results.[17] It can be observed that, for $E > 30\,\text{eV}$, TEEY is dominated by SEEY. However, EBEY do not become negligible as it still represents 15 % of TEEY. Moreover, as their energy and angular distributions are very different from secondary electrons, neglecting them could lead to miss their specific effect on plasma behavior.

B. Energy distribution of electrons

A realistic description of emitted electrons energy distribution (EEED) is essential because it can have a non-negligible impact on HT plasma behavior. Indeed, the emitted electrons at a wall are necessarily able to reach the opposite wall due to the acceleration in the sheath. Moreover it is known that TEEY is influenced by incident electrons energy. Consequently EEED at a wall has a direct impact on EE at the opposite wall. Thus a good description of EEED is essential to model non-linear phenomena such as electrons cascades. Nonetheless, it can be noticed that, for numerous HT modeling, emitted electrons energy are fixed to a single value E_e (E_e is generally equal to $2\,\mathrm{eV}$ or $3\,\mathrm{eV}$).[18]

Fig.5 represents measured EEED on a silver sample at ONERA (green curve) and secondary electron energy distribution according to Chung and Everheart model (dashed curve). They are given as functions of the emitted electrons energy (E_e). The first wide peak is the SEs peak. The EBEs peak can be observed at $E_e = E_0 = 105\,\mathrm{eV}$. This peak presents a small divergence to a monoenergetic one due to the electron energy analyzer resolution. It can be observed that Chung and Everheart model presents good agreement with experimental data. Nonetheless, EEED presents a small deviation present a small deviation to Chung and Everheart model for intermediate values (E_e between $10\,\mathrm{eV}$ and $105\,\mathrm{eV}$). This deviation can be explained by the fact that IBEs have been neglected in this model. Nonetheless, it appears that this difference is negligible in first approximation.

Finally, it can be noticed that there is a non negligible difference between considered EEED in HT models and Chung and Everheart model. It will also have an impact on electron temperature in the plasma.

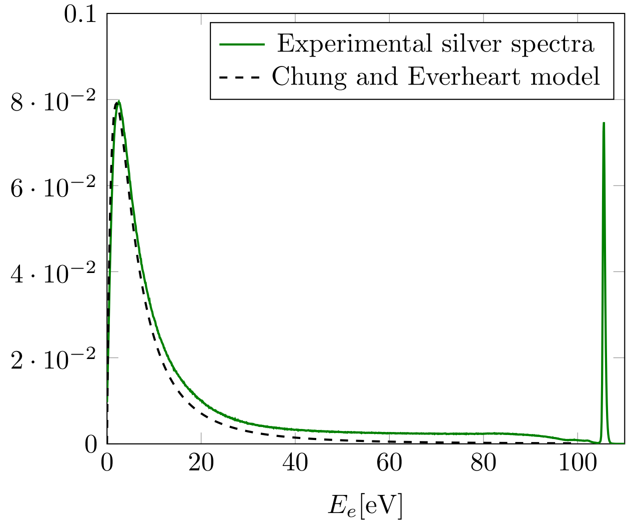


Figure 5: Comparison between Chung and Everheart model and experimental silver spectra

C. Angular distribution of emitted electrons

Angular distribution of emitted electrons is also important in order to have a good representation of EE impact on HT plasma behavior. Indeed, it is shown experimentally and according to numerous models that EE is highly influenced by incident angle of impacting electrons. Fig.6 represents the TEEY of a silver sample as a function of the incident electron energy (E_0) for four different incident angles. These measurements have been achieved in ONERA. It can be observed that for a given E_0, TEEY increases with incident angle (θ_0).

Consequently it is important to precisely model angular distribution of emitted electrons especially for elastically back-scattered electrons which can impact walls with both razing angle and high incident energy.

It is common in HT plasma modelling not to differentiate back-scattered and secondary electrons and to consider only isotropic distribution or specular reflection. Nonetheless SLAB model as well as Monte-Carlo models and experimental measurements present a more complex angular distribution.[7] On one hand, secondary electrons angular distribution can be approximated by an isotropic distribution. On the other

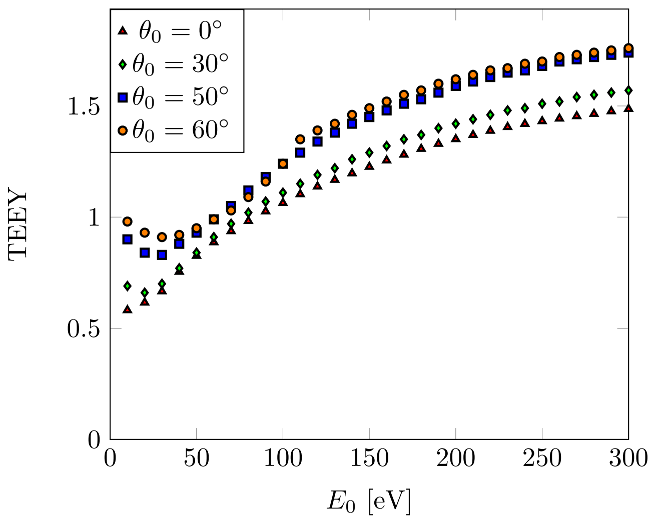
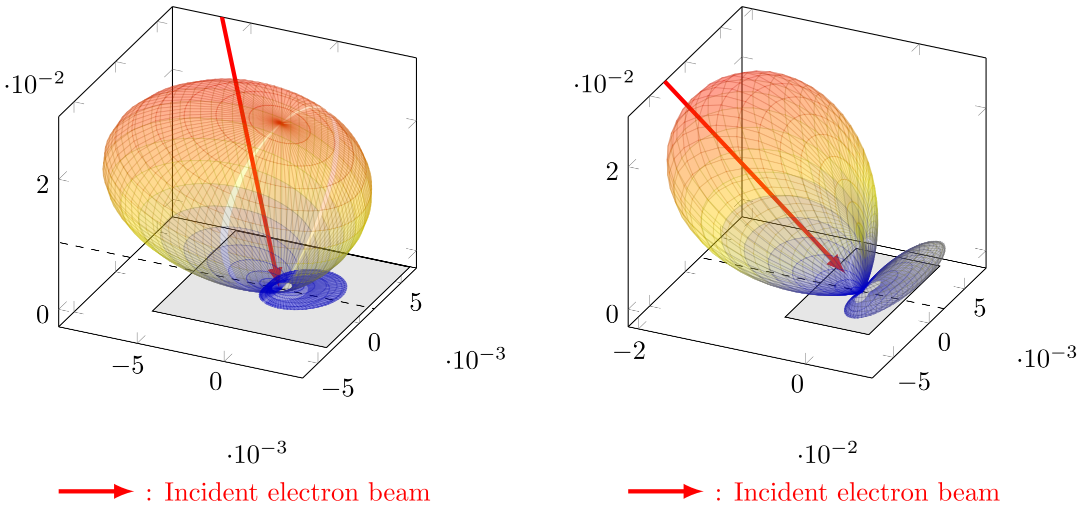


Figure 6: TEEY measurement (ONERA) on silver sample as a function of the incident electrons energy (E_0) for several values of the incident angle (θ_0).

hand, elastically back-scattered electrons are emitted over two emission lobes axed on incident and specular direction (cf. Fig.7). The forms of these lobes depends on incident angle and energy, and wall material. It is important to represent emitted electrons angular distribution especially in the case of HT plasma modeling where anomalous mobility is observed.



(a) $\theta_0 = 10°$

(b) $\theta_0 = 45°$

Figure 7: Elastic backscattering lobes for an aluminium surface with an incident electron energy $E_0 = 40\,\text{eV}$ and two different incident angle: $\theta_0 = 10°$ and $\theta_0 = 45°$

Fig.7 represents angular distribution of elastically back-scattered electrons according to SLAB model. They have been calculated for an aluminum surface with $E_0 = 40\,\text{eV}$ and with θ_0 equal to 10°(Fig.7a) and 45° (Fig.7b). Firstly it can be observed that a majority of electrons are backscattered toward the incident direction. This result differs strongly from specular reflection and isotropic distribution hypotheses. Besides, it can be observed that incident angle has a strong influence on angular distribution of back-scattered electrons. Finally it can be observed that incident electrons energy has a non-negligible impact on EBEY.

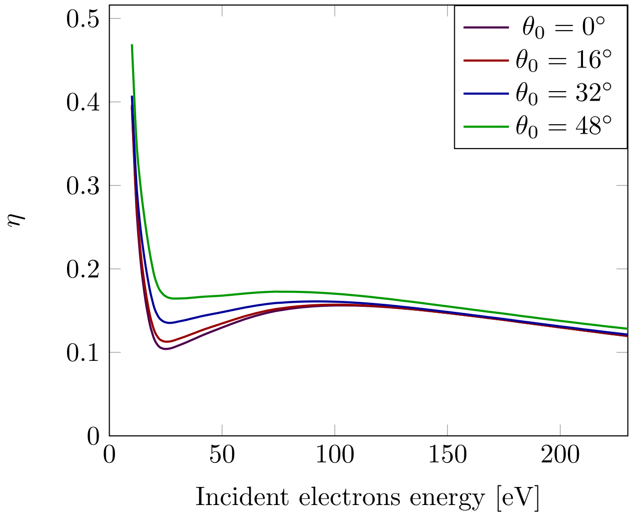


Figure 8: EBEY modeling according to SLAB model on an aluminum surface as a function of the incident electrons energy (E_0) and for different values of θ_0

Fig.8 represents the EBEY as a function of E_0 according to SLAB model. It has been calculated for an aluminum surface and for three different θ_0. All these curves show a stiff decrease of EBEY at very low E_0 (between 10 eV and 25 eV). Then they reach a local minimum around 25 eV. They endures then a slow increase until E_0 reaches 100 eV and then a slow decrease. It can be observed that EBEY increases with θ_0.

On Fig.8, EBEY modeling of aluminum has been plotted as a function of incident electrons energy E_0 and for several values of θ_0. EBEY dependency to E_0 and θ_0 can be observed and it can be seen that they can't be neglected in EBEEY modeling.

IV. Conclusion and further studies

A new model of electron emission fitted to HT modelling has been developped and compared to experimental results. This model has shown numerous advantages for HT plasma modelling. First of all and contrary to numerous models used until now, this model described not only the TEEY but also the angular and energy distribution of the emitted electrons. It is hoped that this model will allow a better understanding of the impact of plasma-wall interaction on HT performances. Secondly, as this model is based on physical reasoning (contrary to miscellaneous used models in PIC modelling), it will allow a better understanding of physical phenomena underlying HT plasma behavior. Finally, as this is an analytic model, computation time very short and allows getting a rich variety of data in reduced computation time (currently, a simulation last between a few minutes and a few hours).

Nonetheless EE model needs to be validated, both with experimental data and Monte-Carlo model.[13] The next step in this study is to implement EE model into a PIC simulation of HT plasma developed in LAPLACE Laboratory. It is anticipated that this will allow a physical and self-sustaining modeling of HT plasma. On the long term, we hope to be able to extract HT plasma characteristics depending on physical parameters (electrons temperature, wall material, electrons and ions densities, etc.) and to implement a fluid model based on these conclusions. Such a fluid model would finally allow plasma thrusters manufacturers to design and optimize HT without a long and costly campaign of measurement.

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