Code comparisons and benchmarking with different SEY models in electron cloud build-up simulations

G Bellodi*, ASTeC Intense Beams Group, RAL, Chilton, Didcot OX11 0QX, UK

Abstract

Several phenomenological fits modelling the secondary electron emission process (yield and energy spectrum) are currently used in computer codes simulating electron cloud formation. Here we present a comparison of preliminary simulation results for two of these existing fits [1, 2] and a set of recent experimental measurements [3], when using identical or nearly identical input parameters.

INTRODUCTION

A number of computer codes has been developed in laboratories worldwide to simulate electron cloud formation and dissipation in accelerators. The codes’ underlying assumptions and physical models are often different and based on alternative experimental inputs. As part of an inter-laboratory code-code and code-experiment benchmarking effort re-launched after the ECloud’04 workshop [4], the present study explores the effect on simulation results of a reference case of using different descriptions of secondary emission properties for electrons impinging on the vacuum chamber walls. The two models currently used in the codes ECLOUD [5, 6] and POSINST [7, 8] (and described respectively in [1] and [2]) have been compared, along with some tentative phenomenological fits of recent laboratory measurements obtained in surface science experiments realised at CERN [3].

MODEL DESCRIPTION

The two main quantities describing electron secondary emission are the yield per incident particle and the secondary energy spectrum. The yield $\delta$ is a function of the kinetic energy of the incident electron $E_0$, its incident angle $\theta_0$ and the type and condition of the surface material. $\delta$ is conventionally considered as consisting of two to three components, namely an elastic part (backscattered electrons), a true secondary and a rediffused part (electrons scattered in the material and reflected back):

$$\delta(E_0, \theta_0) = \delta_{true}(E_0, \theta_0) + \delta_{el}(E_0, \theta_0) + \delta_{red}(E_0, \theta_0).$$

(1)

The last component is not always included in all models though, owing to what some surface scientists consider too high a level of arbitrariness in the distinction from the true secondaries at low energies.

An analytical formula given in [7] has been adopted by both

$$\delta_{true}(E_0, \theta_0) = \delta_{max} D(E_0/E_{max}),$$

$$D(x) = \frac{s(x)}{s - 1 + (x)^p},$$

where $s \approx 1.54$ for Copper and $\delta_{max}$ and $E_{max}$ include a dependency on $\cos \theta_0$. The expression for $D(x)$ was chosen as the simplest function satisfying the conditions: $D(1)=1$ and $D'(1)=0$, and that allowed a good fit to experimental data [9].

In the original version of ECLOUD, the elastic component is then defined as a function $f$ of the true secondary [1]:

$$\delta_{el} = \frac{f}{1 - f} \delta_{true},$$

(3)

where $\ln(f) = A_0 + A_1 \ln(E_0 + E_c) + A_2 (\ln(E_0 + E_c))^2 + A_3 (\ln(E_0 + E_c))^3$, with $A_0 \approx 20.7$, $A_1 \approx -7.08$, $A_2 \approx 0.48$, $A_3 \approx 0$ and $E_c \approx 56.9$ eV for incident energies $E_0$ below 300 eV. Fig. 1 shows the secondary emission yield curves that can be extracted from this model, when assuming $\delta_{max}=2.03$ and $E_{max}=262$ eV for the case of Copper.

In POSINST, on the other hand, the elastic component is modelled by:

$$\delta_{el} = P_{1,el}(\infty) + \left[ \hat{P}_{1,el} - P_{1,el}(\infty) \right] e^{-((E_0-E_c)/W)^p/p},$$

(4)

where $P_{1,el}(\infty) \approx 0.02$, $\hat{P}_{1,el} \approx 0.476$, $W \approx 60.86$ eV, $E_c=0$ eV and $p=1$. A rediffused component is also included, and is described by:

$$\delta_{red} = P_{1,red}(\infty) \left[ 1 - e^{-((E_0/E_c)^p)} \right],$$

(5)

\[\text{Figure 1: ECLOUD SEY model for Copper, with } \delta_{max}=2.03 \text{ and } E_{max}=262 \text{ eV (normal incidence).}\]
where $P_{1}(\infty) \approx 0.19$, $E_{r} \approx 0.041$ eV and $r \approx 0.104$. Fig. 2 shows these curves as a function of the primary electron energy for the case of perpendicular incidence.

Another difference between the codes is in the modelling of the secondary energy distribution: in ECLoud the true secondary energy spectrum is described by a formula first presented in [10]:

$$dN_{s}/dE_{s} \propto \exp \left[-0.5(\ln(E_{s}/E_{0}))^{2}/\tau^{2}\right], \quad (6)$$

where $E_{0}$ and $\tau$ are fitting parameters assumed to be $\approx 1.8$ eV and $\approx 1$ respectively. Alternative descriptions might employ a Gaussian or Lorentzian distribution, falling to zero at $E_{s}=0$ eV. Reflected secondary electrons are assigned the same energy and angular distribution as the incoming electron, whereas the true secondaries are individually assigned an energy from a uniform distribution between 0 and 30 eV.

POsINST adopts a more complicated, mathematically self-consistent, probabilistic model, where every event is assigned a set of probabilities for the generation of electrons, following a Monte Carlo procedure where phenomenological fits are used. For the case $E_{0} \gg E$, the true secondary energy spectrum is modelled by:

$$d\delta_{s}/dE = \sum_{n=1}^{\infty} nP_{n,ts}(E_{0}) \frac{(E/\epsilon_{n})^{\nu-1}e^{-E/\epsilon_{n}}}{\epsilon_{n}^{\nu}(p_{n})}, \quad (7)$$

where $P_{n}$ is the probability for the event and $p_{n}$, $\epsilon_{n}$ are fitting parameters. Reflected secondary electrons are again assigned the same energy (minor a small Gaussian smearing) and direction as the incident electron, while the rediffused electrons’ energy follows: $E = E_{0}r^{0.7}$, where $r$ is a uniformly distributed number between 0 and 1.

### BUILD-UP SIMULATIONS FOR A REFERENCE CASE

Electron cloud build-up simulations have been carried out using the two secondary emission models described above, both inserted in the ECLoud code, for a machine reference case whose parameters, resembling those of the LHC proton beam, are listed in Table 1.

![Figure 3: Buildup results for a) the ECLoud SEY model (in blue) or b) the POSINST-like SEY model in full (in red) or with some components suppressed (magenta and green).](image)

**Table 1: Input parameters for the study reference case.**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bunch population $N_{p}$</td>
<td>$1 \times 10^{11}$</td>
</tr>
<tr>
<td>Bunches $n$</td>
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</tr>
<tr>
<td>Bunch spacing $L_{sep}$</td>
<td>7.48 m</td>
</tr>
<tr>
<td>Bunch profile Gaussian</td>
<td></td>
</tr>
<tr>
<td>Rms bunch length $\sigma_{z}$</td>
<td>7.7 cm</td>
</tr>
<tr>
<td>Rms transverse size $\sigma_{x(y)}$</td>
<td>300 $\mu$m</td>
</tr>
<tr>
<td>Chamber radius $r$</td>
<td>2 cm</td>
</tr>
<tr>
<td>Magnetic field $B$</td>
<td>0 T</td>
</tr>
<tr>
<td>Primary $e^{-}$ rate $10^{-3}$ e$^{-}$/p$m$</td>
<td></td>
</tr>
<tr>
<td>Max SEY $\delta_{\text{max}}$</td>
<td>2.03</td>
</tr>
<tr>
<td>Energy at max SEY $E_{\text{max}}$</td>
<td>262 eV</td>
</tr>
</tbody>
</table>

Build-up results are shown in Fig. 3: the red curve describes the linear electron density along the section of beamline considered when using the POSINST-like full model. The magenta and green curves are again obtained from the same model, but in the cases where the rediffused component or both the elastic and the rediffused components are respectively excluded. The results for the ECLoud-like model seem to agree with the POSINST-like case where no rediffused component is present. The inclusion of the latter one accounts for an increase in electron density by a factor of 3-4.

The modelling of the secondaries’ energy spectrum for the POSINST-like case has been simplified with respect to the original probabilistic approach. The rediffused and elastically backscattered electrons’ energies still follow the formulae described above, whereas the true secondaries’ energy is modelled on a Gaussian distribution centred at 15 eV and with $\sigma = 5$ eV, as opposed to the flat distribution used in ECLoud. The difference between the two models
is shown in Fig. 4 and is especially evident at low incident energies (the total spectrum of the true secondaries is in both cases shaped according to Eq. 6).

**EXTRACTING A THIRD MODEL FROM RECENT SEY MEASUREMENTS: FULL SCRUBBING CASE**

Recent experimental measurements of secondary emission from a Copper surface were obtained at CERN on a prototype of the LHC beam screen under different scrupling conditions [3]. Secondary yields were measured (see Fig. 5), as well as related energy distribution curves (EDC) of the secondary electrons as a function of the primary electron energy, and special attention was paid to measure-ments for very low-energy electrons (≤20 eV).

A first study was made on the data for the full scrupling case (δ_{max} ≃1), trying to fit empirical curves to the yield measurements, and testing different models for the secondaries’ energy spectrum to find which one reproduced the observations most closely. Fig. 6 shows the curves used to describe the yield as a function of incident energy: a function similar to Eq. 2 was used to model the true secondary part (green line), whereas the elastic component (in blue) was obtained by subtraction from the data for the total yield (in red). Two different distributions were studied to model the total secondary electrons’ energy spectrum: the one proposed in [1] and described by Eq. 6 , and an alternative Lorentzian model, originally proposed in [11] and slightly modified to constrain it to drop to zero at zero incident energy. The resulting electron spectra are shown in Fig. 7. Results of the study are shown in Fig. 8, where EDC curves obtained at different primary incident energies...
for the two models adopted are compared with measurements published in [3]. The difference between the two models is not very pronounced, although for higher primary energies the Lorentzian approach gives a better description of the lower energy part of the spectrum. Also some improvements could be introduced in both SEY models to better reproduce the data in the intermediate energy spectrum. Simulation results for the electron cloud build-up in a representative field-free section of the chamber for the reference case of Table 1, when using the yield curves for the full scrubbing case and the two models for the secondaries’ energy spectrum, are shown in Fig. 9.

FITTING DATA FOR ‘AS RECEIVED’ SURFACE CASE (NO SCRUBBING)

The same study has been repeated for the set of SEY measurements obtained for an ‘as received’ Copper surface. This case, however, is complicated by the fact that, at higher secondary emission yields (up to \( \delta_{\text{max}} \sim 2 \)) that enhance the electron multipacting, even small differences in the curves fitting the data can lead to substantial effects on the build-up results. In particular, a high level of uncertainty is present in the definition of the curves at high incident energy, since data are provided only in the range 0-350 eV, but in the reference case examined electrons can be accelerated up to 1.5 keV. Three different fits have been attempted here, as shown in Fig. 10: the true secondary component has been modelled via a function like Eq. 2 weighted by a factor \( e^{-\sigma/p} \) (where \( p \) is a fitting parameter), and the elastic component has been again obtained by subtraction.

Build-up results for these three different fits when using either a quasi-Lorentzian model for the secondaries’ energy spectrum or the distribution from Eq. 6 are given in Fig. 11 and 12 respectively. There is a difference of up to a factor of 3 in the level of electron cloud line density reached with the three different fits, and the choice of distribution to model the secondary energy spectrum alone accounts for a difference in the results by approximately a factor of 2. A broader picture can be obtained from the scan in Fig. 13, where the accumulated peak electron line density is plotted as a function of the bunch intensity for the six cases studied above. Even if the results are strongly sensitive to the details of the secondary emission model used, the build-up pattern is fairly constant and the intensity threshold is not severely affected. Comparing with the results presented in Fig. 3 for approximately the same \( \delta_{\text{max}} \sim 2 \), it is possible to see how the values of the electron cloud peak line density

Figure 8: EDC curves for different incident energies: in black are the measurements from [3], in blue the simulation results for the case in which model a) of Fig. 7 was adopted, and in red the results for the quasi-Lorentzian model b).

Figure 9: Comparison of build-up results with the two SEY models described for the reference case of Table 1.

Figure 10: SEY measurements for an ‘as received’ Copper surface (in red) and a few fit attempts (in blue, green and magenta). In the top right inset a zoomed-in view of the high energy tails (where no data is available) is given.
reached with the three different models have all the same order of magnitude. The cloud growth is slower for the latest fit attempted here, owing to the fact that the experimental SEY curves shown in Fig. 5 seem to fall more quickly at high energies than their corresponding curves (for the same $\delta_{\text{max}}$) from the other models, as pictured in Figs. 1 and 2.

CONCLUSIONS

We have presented results of a recent study exploring the sensitivity of the electron cloud buildup mechanism to the details of the secondary electron emission model adopted in the simulations. A tentative phenomenological fit of recent SEY experimental measurements on Copper has been described, the resulting parametrisations tested in simulations and the results compared to existing models. Electron cloud build-up results show a strong sensitivity to the models’ details (qualitative and quantitative separation of the SEY components and total energy spectrum assigned to the secondary electrons), though the intensity threshold level is not severely affected.

A level of uncertainty is however present in the fit precision at high energy, due to the lack of experimental data in the region. In conclusion, more measurements of SEY properties at primary incident energies $E_0 \geq 400$ eV and EDC data are needed to achieve a better precision in the extraction of a phenomenological model.

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REFERENCES


