EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
European Laboratory for Particle Physics

Large Hadron Collider Project

LHC Project Report 472

A SUMMARY OF MAIN EXPERIMENTAL RESULTS CONCERNING THE SECONDARY ELECTRON EMISSION OF COPPER

V. Baglin, I. Collins, B. Henrist, N. Hilleret and G. Vorlaufer

Abstract

The secondary electron emission of surfaces exposed to the impact of energetic electrons contributes significantly to the electron cloud build-up. For the prediction of the consequences of this effect the measurements of the secondary electron yield carried out at CERN are an important source of information. New experimental results concerning the total secondary electron yield for very low primary electron energy (between 5 eV and 50 eV) will be also given in the case of as received copper. Furthermore the energy distribution of the re-emitted electrons is drastically influenced by the primary electron energy. The ratio of the number of reflected electrons to the total number of re-emitted electrons has been measured and its variation with the primary electron energy will be shown. As a consequence of these new experimental data, a numerical approximation to express the secondary electron yield as a function of the primary electron energy will be given for the low incident electron energy region ($E < 50$ eV). It has been shown that the decrease of the secondary electron yield due to the electron bombardment could reduce sufficiently the consequences electron cloud effect. To understand further the origin of this decrease, the results of experiments showing the variation of the electron induced desorption yield with the incident electron dose will be compared to the concomitant reduction of the secondary electron yield.

LHC-VAC

Administrative Secretariat
LHC Division
CERN
CH - 1211 Geneva 23
Switzerland

Geneva, 24 June 2002

1 THE EXPERIMENTAL SYSTEMS

The measurements of the secondary electron yield versus electron energy have been carried out in two separate systems described previously[1,2]. They consist in an electron gun delivering a focused primary electron beam of energy variable between 45 and 3000 eV. This beam hits the surface of the sample under normal incidence at a circular spot (*approximately 3 mm diameter*). A conical cage, coaxial to the primary beam, collects the secondary electrons. The deflection plates and lens of the electron gun are driven by a computer program which optimises their settings on a dummy sample to maximise the transmitted primary current. For the measurements short pulses (30 ms) of low intensity (some nA) are used to reduce the electron dose received by the sample (10 nC/mm2 for a complete energy scan). The vacuum system is bakeable and is evacuated by a turbomolecular pump. After bake out the pressure reached in the system is in the low 10^{-10} Torr region.

In EPA[1,3] the second system used was based on the same principle as the laboratory system, the measurement procedure (beam optimisation, current pulses and data handling) was identical.

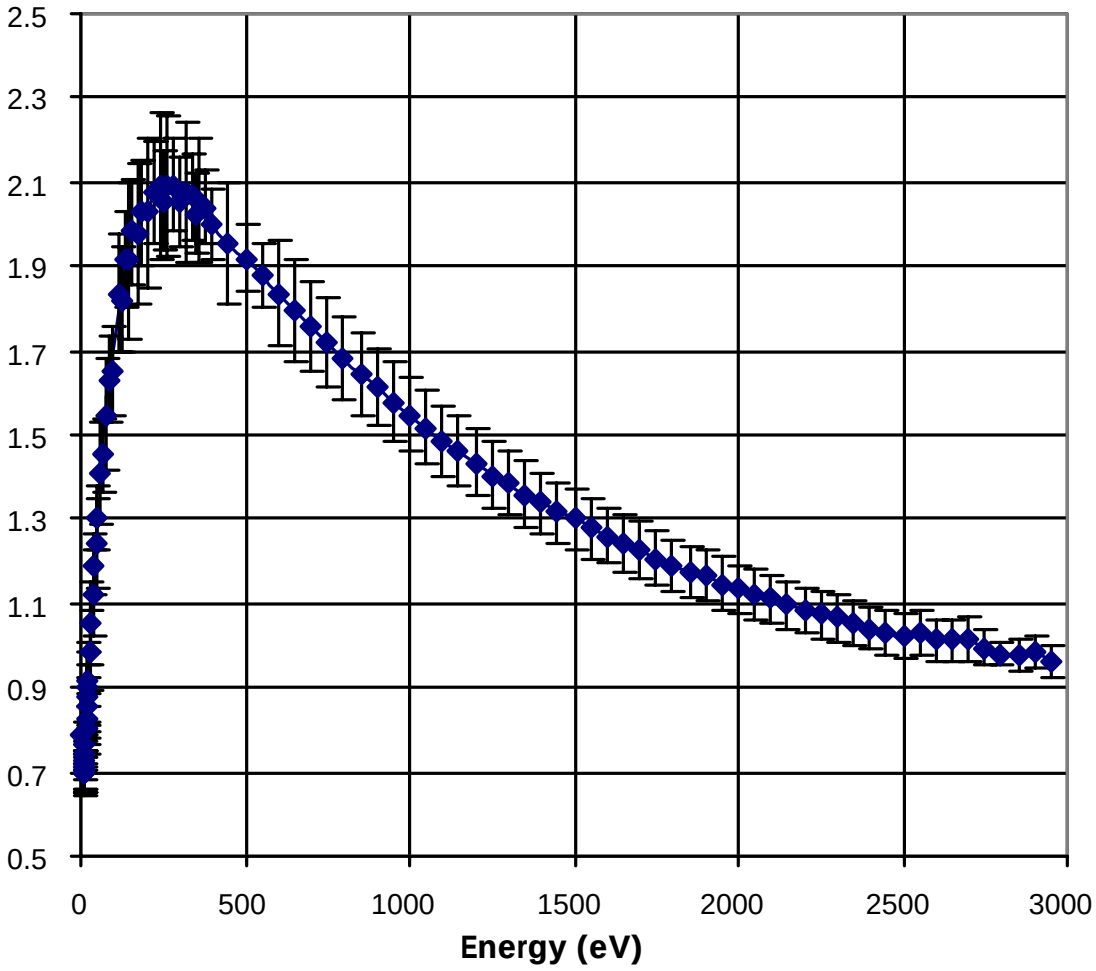

Figure 1: Variation of the average secondary electron yield versus electron energy for 25 as received copper samples

For the energy measurements, a 4 grids hemispherical energy analyser has been used. Its energy resolution is limited to some eV and the energies given do not take into account any correction of contact potential between the filament gun and the sample. The dose effect was studied using various procedures. Initially (1978) the electron dose was delivered to the sample using the measurement gun. The yield was continuously measured at the bombardment energy. Because of the rapid destruction of the expensive gun filament, this method was abandoned and a rustic flood gun was added to the laboratory system allowing to irradiate completely the sample

surface. In EPA the electron dose was accumulated by biasing the sample to a variable positive voltage that attracted the photoelectrons created by the synchrotron light.

A change in the bias voltage modifies the mean energy of the incident electrons as well as their amount. As the sample bias voltage changes the collection efficiency of the sample, the photon dose needed to condition the sample are not directly comparable when the sample bias is modified. The dose is determined by integrating the current collected on the sample. The main difference between these two methods to accumulate the dose is that in EPA any artefact linked to the presence of a hot filament for the production of the impinging electron has been eliminated.

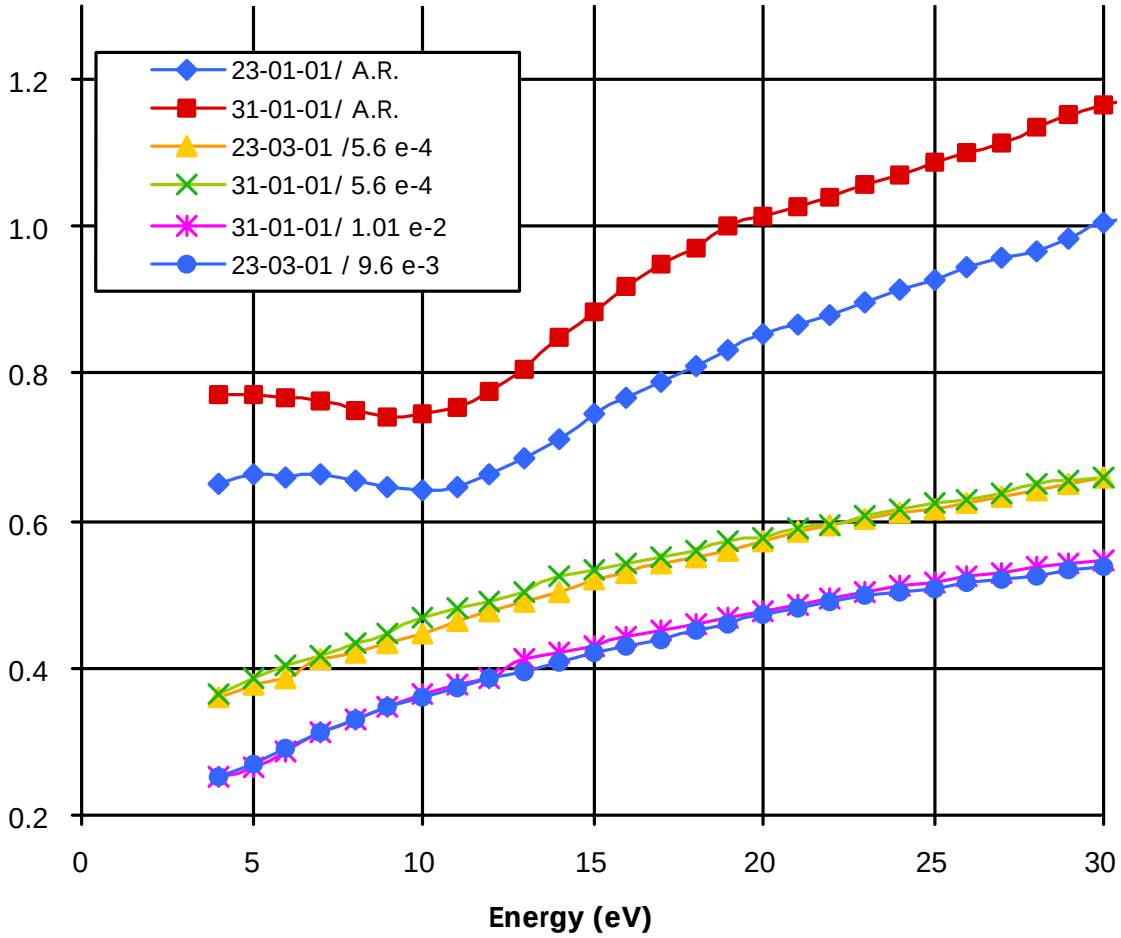

Figure 2: Variation of the average secondary electron yield versus electron energy for copper samples and energies lower than 30 eV

2 THE VARIATION OF THE SECONDARY ELECTRON YIELD OF COPPER VERSUS THE PRIMARY ELECTRON ENERGY

Figure 1 shows the mean secondary electron yield (S.E.Y.) measured on 25 as received copper samples cleaned following the LHC recipe. The average maximum is 2.06 (σ = 0.16) for an energy of 271 eV (σ = 25). The bars are used to display the spread between the minimum and maximum S.E.Y. at each energy for these 25 samples. The low energy part of the δ (E) curves was measured recently and is displayed in Figure 2 for various electron doses (cf. next section). The two curves labelled 23/03 AR and 31/01 AR show the SEY as a function of the energy for electron energies between 4 eV and 30 eV. The SEY at 4 eV lies between 0.6 and 0.8. Below 10 eV the as received curves tend to indicate a constant value of the SEY, independent of the electron energy.

3 THE CHANGE OF THE SECONDARY ELECTRON EMISSION WITH THE INCIDENT ELECTRON DOSE

The variation of the SEY with the electron dose is an effect leading, when not properly taken into account, to underestimated secondary electron yield. This brought us to modify the experimental set up and procedure in order to decrease as much as possible the electron dose received by the sample during the measurements[4]. In Chamonix X [1] it was proposed to take profit of this effect to obtain the decrease of the copper SEY necessary to operate LHC without "electron cloud effect".

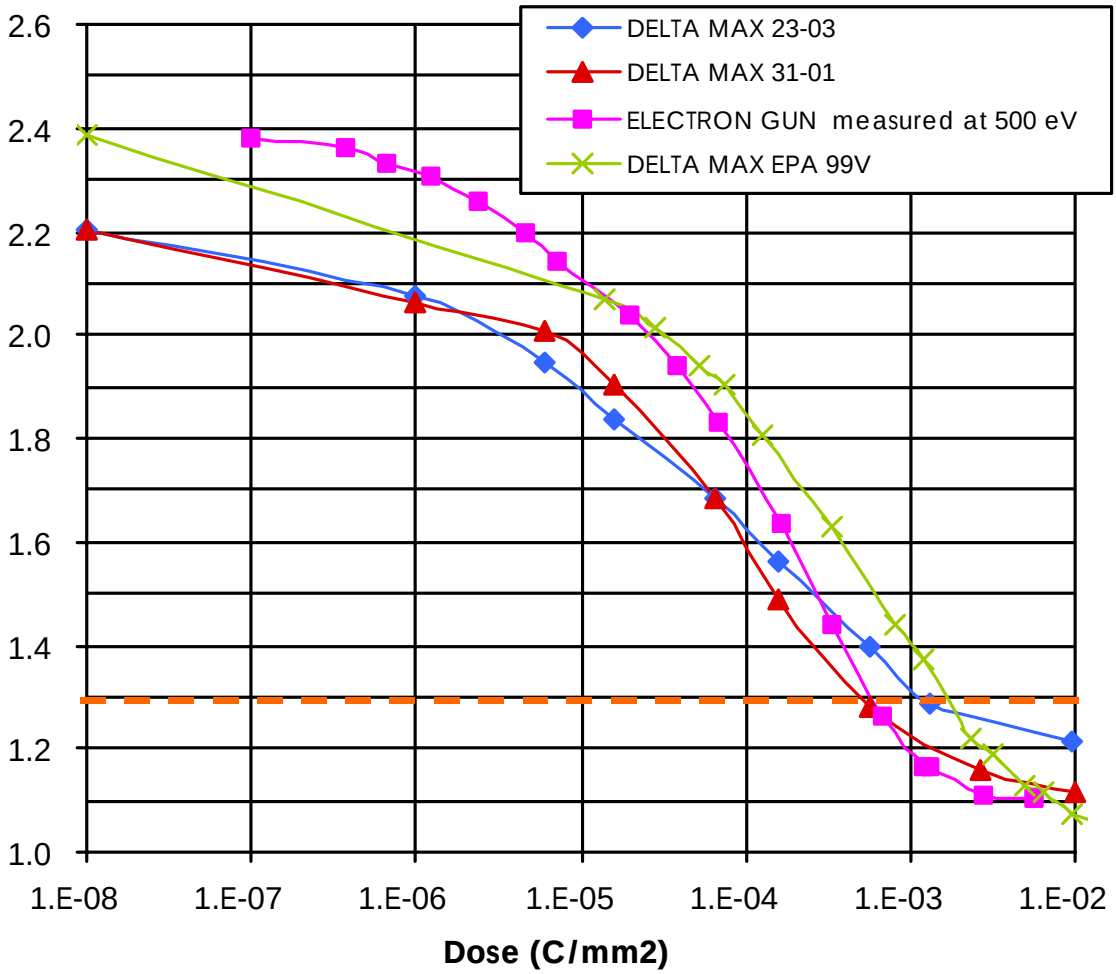

Figure 3: The variation of the secondary electron yield with the incident electron dose

In Figure 3, the variation of the SEY of as received copper is plotted against the incident electron dose for various measurements made using various procedures and under various experimental conditions:

- The curve noted electron gun was obtained in 1979 using an electron gun on a copper sample. It gives the SEY of copper *at 500 eV energy* versus the electron dose. The impinging electrons had an energy of 500 eV. The area irradiated by the beam was a circle of approximately 2 mm diameter.
- The curve note "delta max EPA" gives the variation of the *maximum SEY* against the dose of electron collected with a bias of 99 V (i.e. 99 eV impinging electron energy).
- The 2 curves noted 'delta max 23-03" and "delta max 31-01" were obtained this year using a flood gun irradiating the whole sample with an electron energy of 500 eV.

These curves show that an electron dose between 8x 10^{-4} and 2x 10^{-3} C/mm^2 is necessary to reach a SEY lower than 1.3. The minimum of the SEY (close to 1.1) is obtained for an electron dose close to 10^{-2} C/mm^2 (fully conditioned sample).

In Figure 2 the low energy part of the two later curves (23-03 and 31-01) are also shown. The reproducibility is very good, the SEY are continuously decreasing below 10 eV and are close to 0.2 at an energy of 4 eV.

4 THE ENERGY DISTRIBUTION OF THE SECONDARY ELECTRONS, EXPERIMENTAL RESULTS AND CURVES REFLECTED/TRUE SECONDARIES VERSUS INCIDENT ELECTRON ENERGY

The preceding measurements have shown the peculiar behaviour of the SEY as the primary electron energy decreases. These peculiarities could be related to the change in the shape of the secondary electron energy distribution. This distribution was studied using a 4 grids hemispherical energy analyser. The energy axis is shifted by an unknown amount (< 3eV) due to the unknown contact potential between the filament and the sample. It must be emphasised that, because of the large amount of incident electrons needed for this type of measurement, the data presented here are related to a copper close to the "conditioned state".

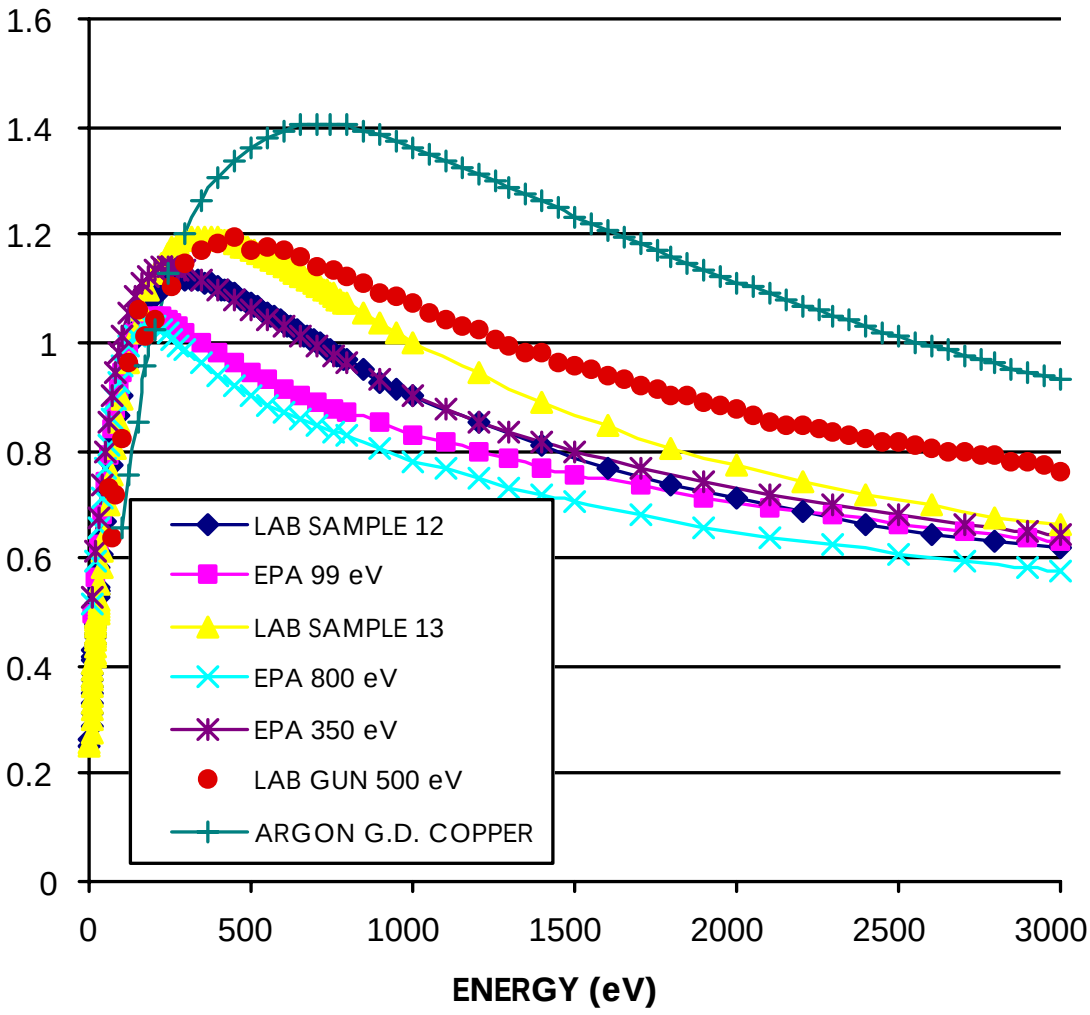

Figure 4: Variation of the secondary electron yield versus the primary electron energy for 6 fully conditioned (10^{-2} C/mm^2) copper

In Figure 5 the energy distribution of secondary electrons emitted by a copper sample are shown using two normalised axis: the abscissae are normalised to 1 at the incident electron energy, the ordinates are normalised to 1000 for the maximum emitted intensity. On this graph the increased importance of the reflected electrons at low primary electron energy is striking when the curves measured at 10 eV and 550 eV are compared. A second fact, also reported in the literature[5], is illustrated in Figure 6 which shows a slight shift towards lower energy in the position of the "true" secondary electron peak when the incident electron energy is raised.

The "true"secondary electron peak is found around an energy of 2 eV. Using the data partially presented in Figure 5 the ratio between the number of reflected electrons and the total number of emitted electrons has been calculated for the five energies considered (10, 30, 100, 300, 550 eV). This ratio is given in Figure 7 as a function of the primary electron energy.

5 NUMERICAL EXPRESSIONS FOR THE RELATION BETWEEN THE SECONDARY ELECTRON YIELD AND THE INCIDENT ELECTRON ENERGY

Usual expressions given by M. Furman[6] or J.J. Scholtz[7] can be used to numerically express the variation of the true secondary electron yield δ_s with the primary electron energy (E_p). Both formulae give good fits to the measured curves for a given energy range. The simple expression given by M. Furman produces a reasonable fit in the low primary energy part (E_p< 1000 eV) which is the most interesting for LHC. In the low energy region (<100 eV) the importance of the reflected electrons becomes more important as it can be deduced from Figure 5. For this reason the fit formula proposed here uses the Furman formula corrected for the contribution of reflected electrons. The reflected electron contribution has been assessed from the previously shown experimental data on the secondary electron energy distribution for copper. Furman's relation for the true secondary electron yield is:

$$\delta_s = \delta_{MAX} \frac{s \times \left(\frac{E_p}{E_{MAX}}\right)}{s - 1 + \left(\frac{E_p}{E_{MAX}}\right)^s}$$

δ_{MAX}, s and E_{MAX} are 3 parameters used to obtain the best fit to the experimental.

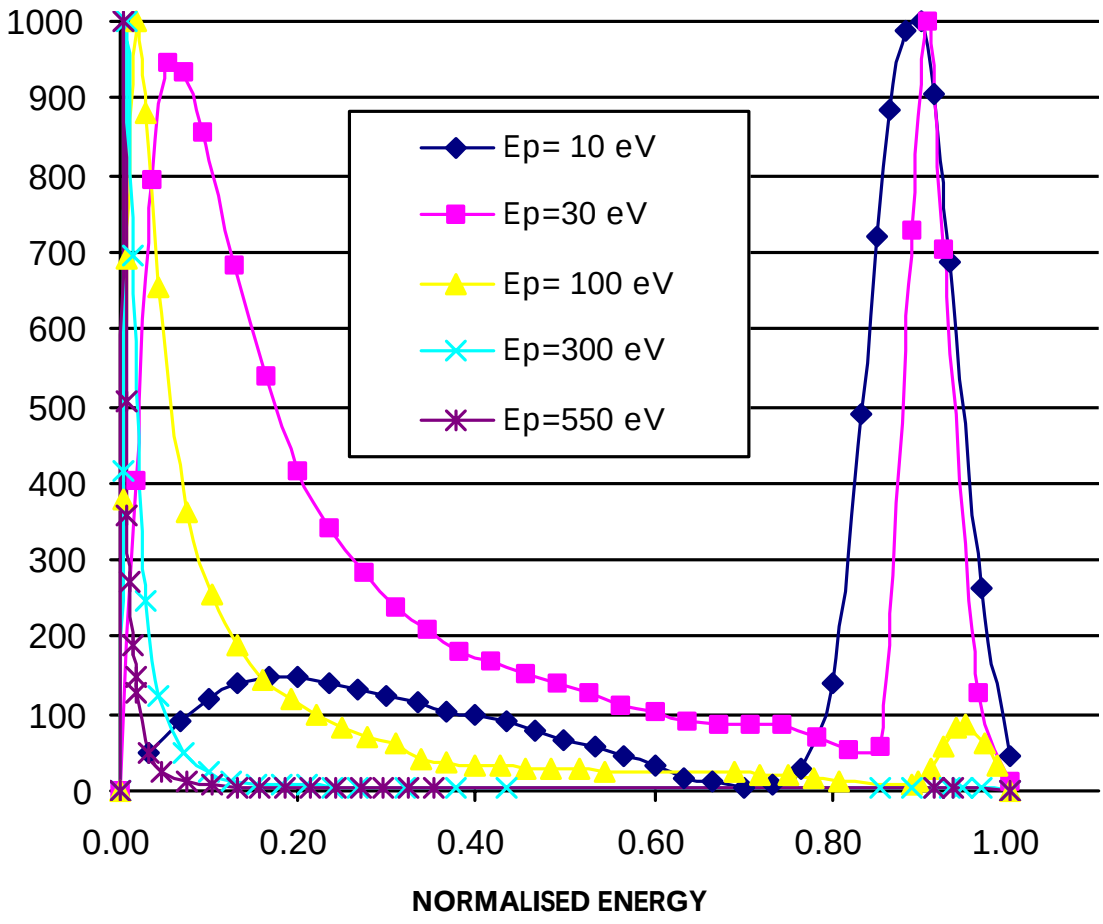

Figure 5: Normalised secondary electron energy distribution for conditioned copper

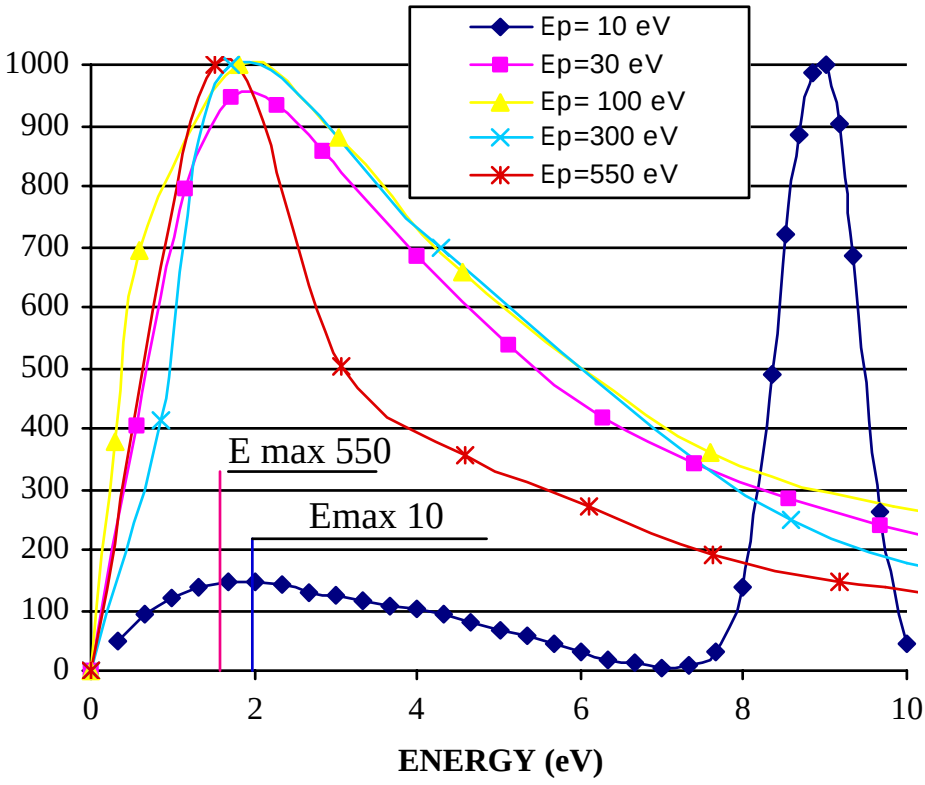

Figure 6: Secondary electron energy distribution for copper (below 10 eV)

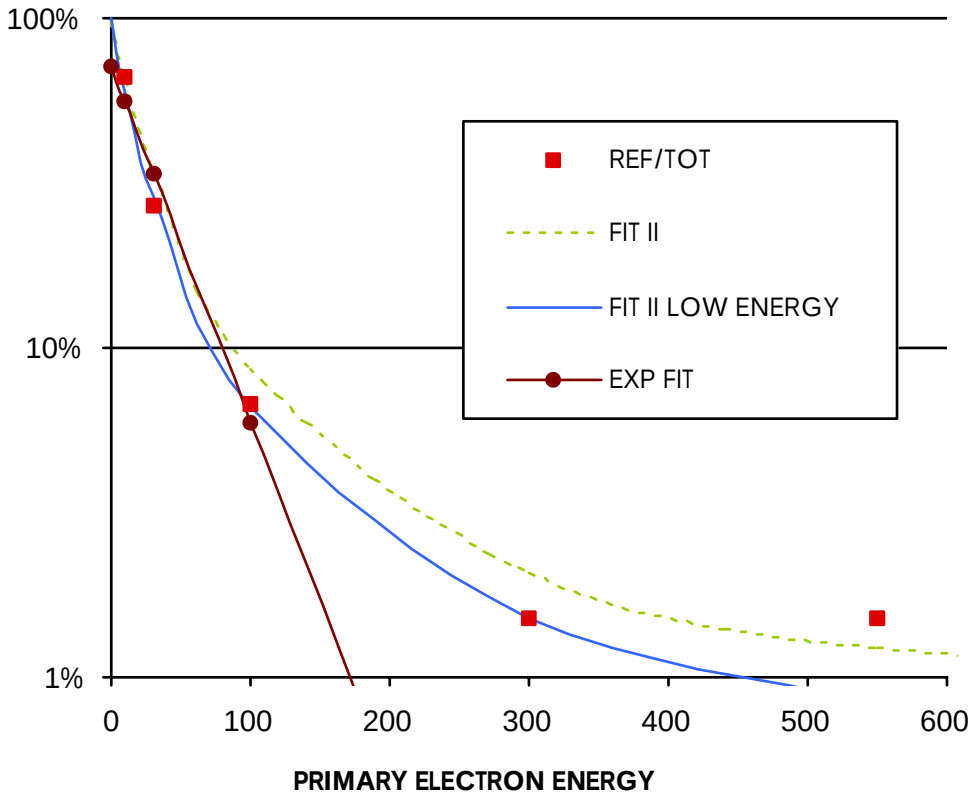

Figure 7: The ratio between the reflected and the total number of re-emitted electrons in the case of copper

The numerical value used to fit the experimental data presented in Figure 1 are given in Table 1.

Table 1: **Fit parameters for the true secondary yield (M.Furman formula**)

SAMPLE STATE	AS RECEIVED	FULLY CONDITIONED
δ_{MAX}	2.03	1.13
E_{MAX}	262	318
s	1.39	1.35

To introduce the correction due to the reflected electrons two approximations could be made depending on the accuracy needed. Of course as it appears in Figure 7, the correction for reflected electrons is only significant at energy lower than 300 eV and amounts to more than 10% for energies below 100 eV. A relation [7] allows to fit the experimental curve given in Figure 7:

$$\ln(f) = A_0 + A_1 \times (\ln(E_p + E_0)) + A_2 \times (\ln(E_p + E_0))^2 + A_3 \times (\ln(E_p + E_0))^3$$

To obtain the best fit in the low energy part (below 300 eV), the following constants has been used:

A_0 = 20.699890, A_1= -7.07605, A_2= 0.483547, A_3= 0, E_0=56.914686
(Curve labelled FIT II low energy).

For use up to higher primary electron energy (2000 eV), the following coefficients should be used:

A_0 = 0.300207076, A_1= 0.044915014, A_2= -0.155498672, A_3= 9.50318 x 10^{-4}, E_0=0
(Curve labelled FIT II)

A simplified exponential relation of the form:

$$f = R_0 \times \exp(-E_p / w)$$

can also be used below 100 eV using the following numerical constants:

R_0= .64438713, w=43.2268304. (Curve labelled EXP FIT)

The accuracy of the various approximations can be appreciated from Figure 7.

The various formulae used to account for the reflected electron contribution at low energy combined with Furman's formula have been checked against the measured value of the total secondary electron yield (δ_t) in the two cases of as received copper and fully conditioned copper (dose = 10^{-2} C/mm^2). To calculate δ_t, the following formula was considered:

$$\delta_t = \delta_S + \delta_R ,$$
$$\delta_R = f \times \delta_t \Rightarrow \delta_t = \delta_S + f \times \delta_t$$
$$\text{Hence: } \delta_t = \delta_s \times \frac{1}{(1-f)}$$

The results of the two fits are compared to the experimental results on the two Figures 8 (as received case) and 9 (fully conditioned case). In both cases the agreement with the measured secondary electron yield is good between 1000 and 100 eV incident energy. For energies greater than 300 eV, the contribution of the reflected electrons can be neglected and M. Furman formula used without correction. The low energy part (E_p < 100 eV) of the two graphs 8 and 9 is expanded on the two graphs 10 and 11 to compare the results of the two fitting formulae to the experimental results. Above 20 eV incident energy, both formulae give the same results. Below 20 eV (i.e. when the reflected contribution accounts for more than 25% of the total number of secondary electrons) the exponential fit gives increasingly underestimated value.

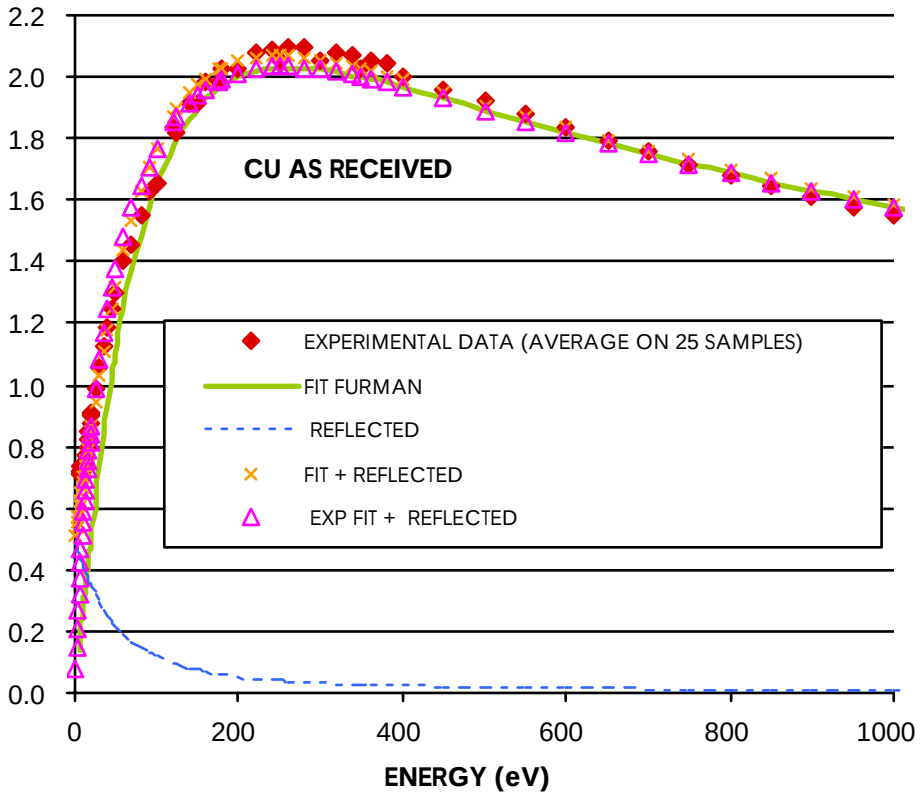

Figure 8: The numerical expressions for the various contributions to the secondary electron yield compared to the experimental measurements in the case of as received copper.

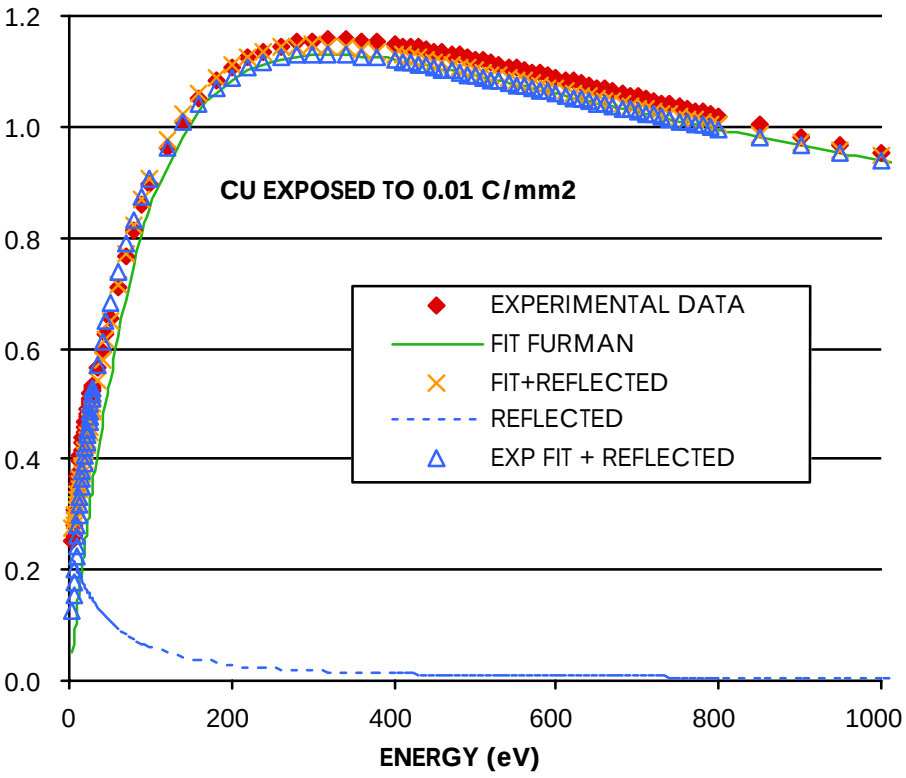

Figure 9: The numerical expressions for the various contributions to the secondary electron yield compared to the experimental measurements in the case of fully conditioned copper

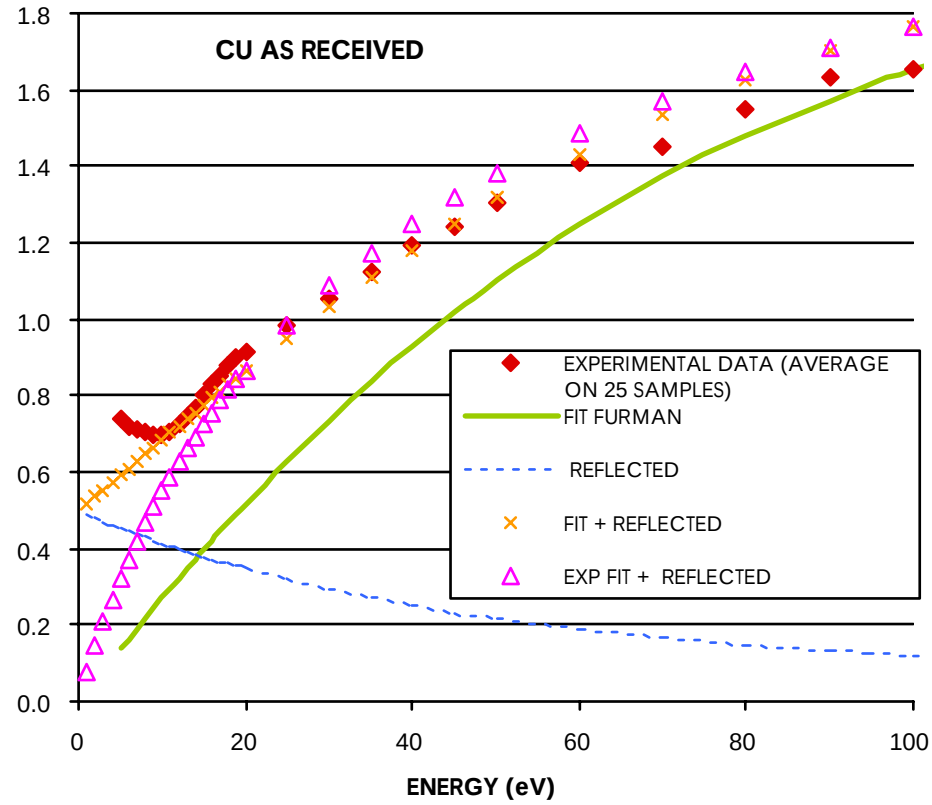

Figure 10: The numerical expressions for the various contributions to the secondary electron yield compared to the experimental measurements in the case of as received copper (Ep < 100 eV)

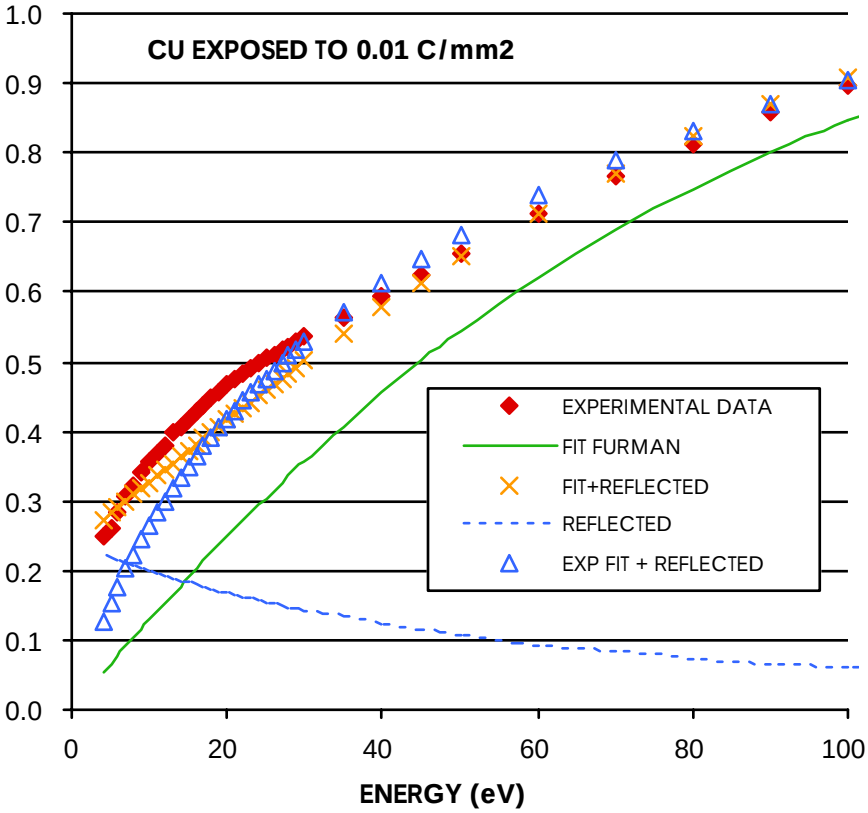

Figure 11: The numerical expressions for the various contributions to the secondary electron yield compared to the experimental measurements in the case of fully conditioned copper (Ep < 100 eV)

6 COMPARISON WITH OTHER PUBLISHED DATA

Measurements of the secondary electron yield of as received copper have been published in references [8,9]. They are compared to the results obtained at CERN for as received copper in Figure 12. The agreement between CERN measurement and Hopman measurements is good. The measurements made at SLAC gives a maximum secondary electron yield, which is significantly smaller than those obtained in the two other labs. The different measurements obtained for a primary electron energy in the vicinity of 1000 eV are close to each other.

A dose dependence curve has also been given in reference [8]. This curve is compared with a typical curve obtained at CERN in Figure 13. As noticed in Figure 12, the initial yield is much smaller than what is measured at CERN and the yield decrease proceeds at a slower rate. The fully conditioned state was apparently not obtained in that reference [8].

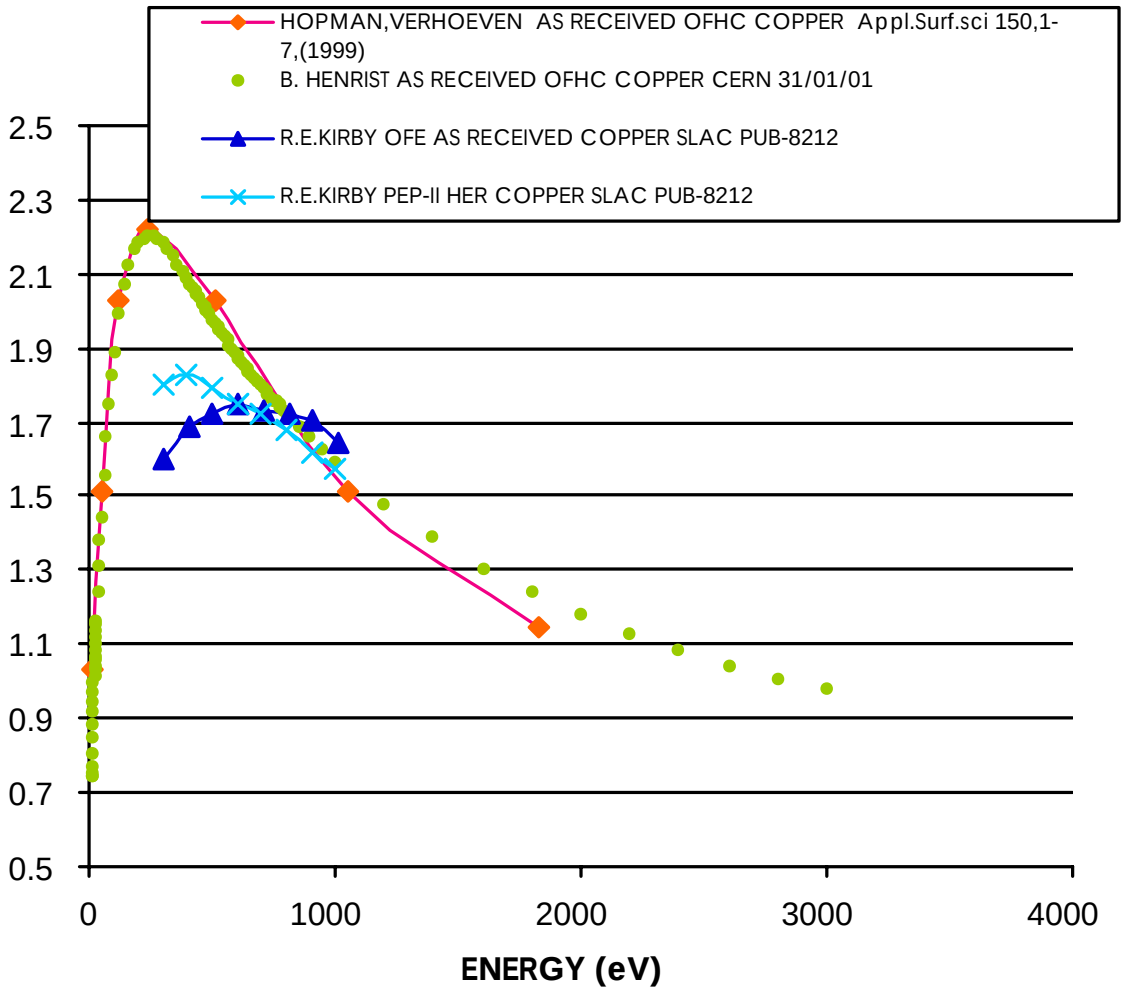

Figure 12: The variation of the secondary electron yield versus the primary electron energy as obtained in three different laboratories

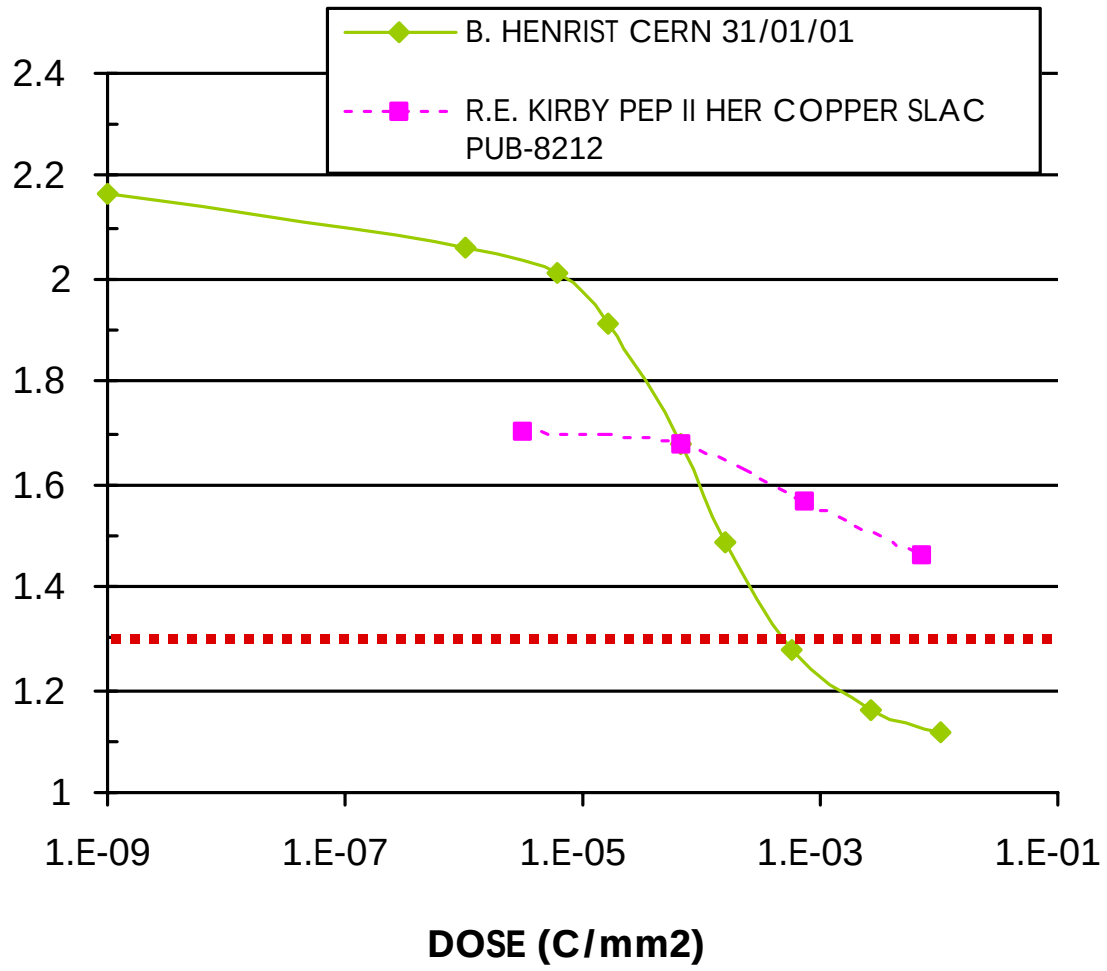

Figure 13: Comparison of the dose dependence of the secondary electron yield as measured at CERN and at SLAC

7 ESTIMATION OF THE QUANTITY OF GAS RELEASED DURING THE CONDITIONING.

During the electron bombardment of a surface, leading to the above mentioned decrease of the secondary electron yield, a significant decrease of the electron induced desorption yield is also observed[10,11]. The desorption yields data, obtained in a separate system, on an as-received copper sample, are presented together with the data concerning the secondary electron yield in Figure 14 as a function of the number of electrons impinging per unit area. To allow a better comparison, both data are normalised to 1 in the initial non-bombarded state. These data allow the calculation of the amount of gas released during the conditioning of a copper surface by integrating the product of the desorption yield and the electron dose.

Table 2: Total number of molecules released per unit area during processing for the main desorbed gases

GASES	H_2	CH_4	CO	C_2H_6	CO_2	H_2O
QUANTITY (cm^{-2})	$6x10^{16}$	$8x10^{14}$	$8x10^{15}$	$8x10^{14}$	$8x10^{15}$	$3x10^{14}$

Figure 15 shows as a function of the total number of molecules released per unit surface area, the secondary electron yield ratio and the desorption yield ratio for three molecular species. These were chosen (for the sake of clarity) to represent the main desorbed gases of the two types: hydrogen and carbon containing gases, (H_2, CO and C_2H_6).

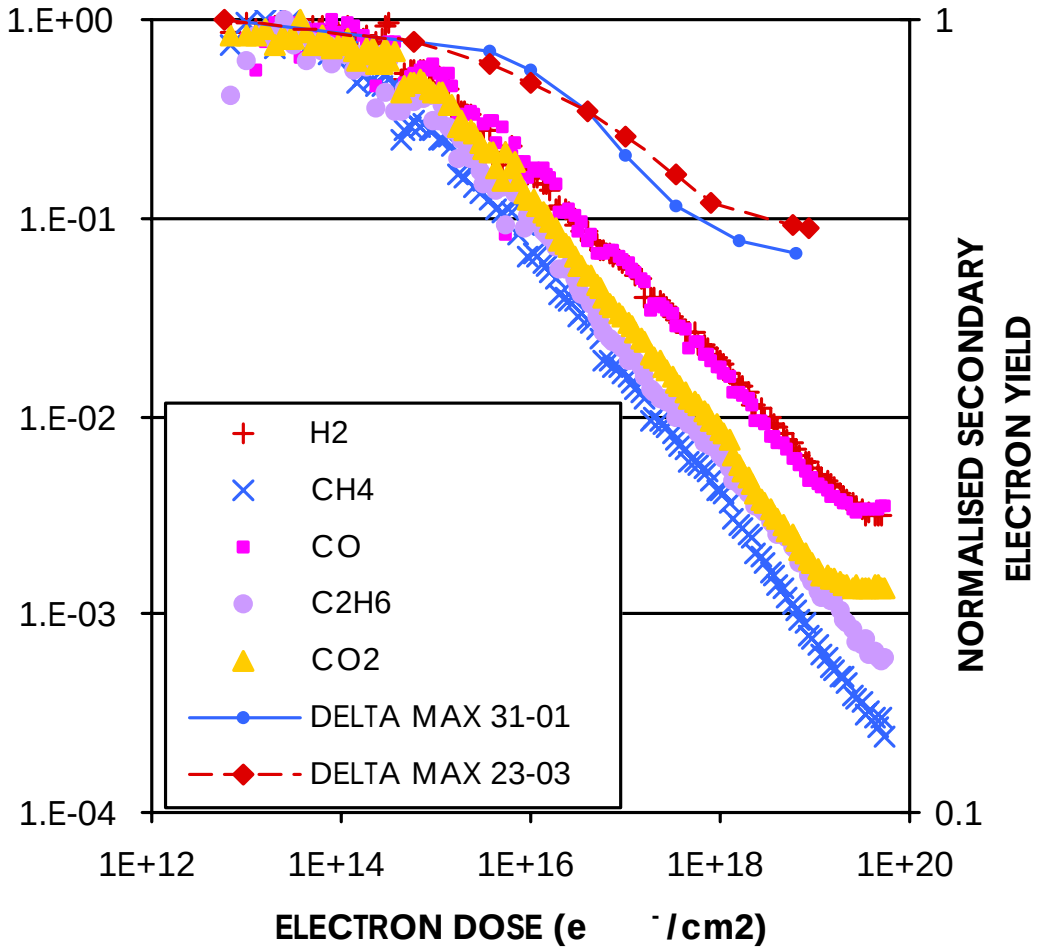

Figure 14: The variation of the normalised desorption and secondary electron yields with the electron dose

These data show that the reduction of both the secondary electron yield and the desorption yield are two processes evolving in parallel during the irradiation of a surface by electrons. The upper limit of the total number (the mantissa being rounded to the next integer) of molecules released during the conditioning of a copper surface is given in Table 2 for the main desorbed gases. Hydrogen is the main released gas, its predominance is established during the initial part of the conditioning when desorption yields are the highest and hydrogen the most abundant species, carbon monoxyde and dioxyde come in second position. These results are in good agreement with those concerning desorption yields published in the reference [11].The total number of molecules removed from an as-received copper surface during its conditioning is smaller than 10^{17} molecules per cm^2 i.e. less than 100 monolayers. The number of molecules released per unit surface area during the conditioning process is given in Figure 16 as a function of the final secondary electron yield achieved. Although both the desorption yield and the secondary electron yield evolve in parallel under electron bombardment, it should not be concluded that the cleaning of the surface is the origin of the decrease of the secondary electron yield. For example a clean copper surface (e.g. in situ glow discharge cleaned) has a secondary electron yield higher than a conditioned surface (see Figure 4, curve labelled: “Argon G.D. Copper”).

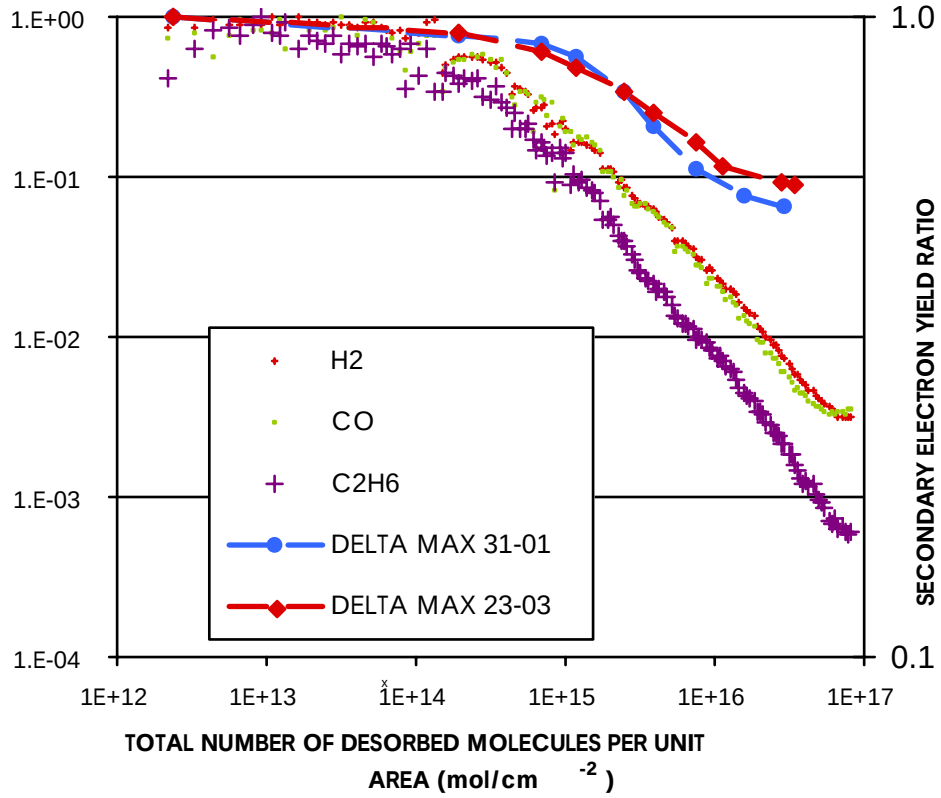

Figure 15: The normalised desorption and secondary electron yields as a function of the total number of desorbed molecules

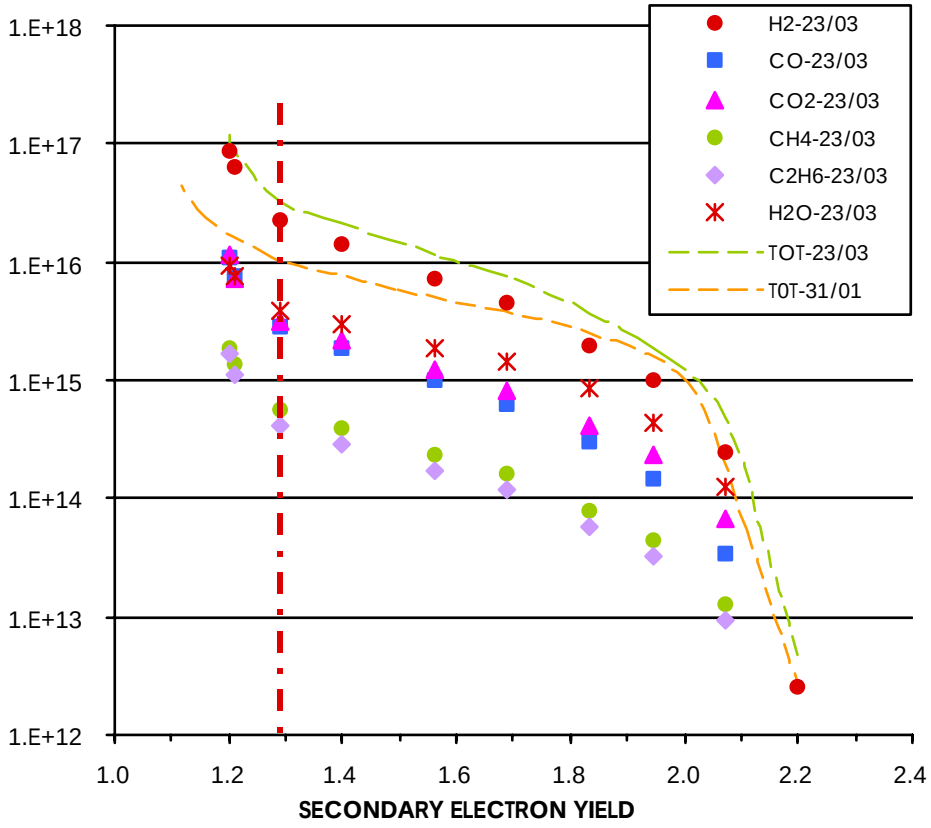

Figure 16: The quantity of desorbed molecules per unit area as a function of the final secondary electron yield

8 CONCLUSIONS

The conditioning of as received copper surfaces has been studied in various experimental set-ups and coherent results have proved its efficiency to reduce the secondary electron yield. Based on measurements of the secondary electron energy distribution, a numerical expression has been given which allows to calculate the fraction of reflected electrons with a good agreement to the experimental data between 4 and 500 eV. The Furman's expression has been used and the relevant parameters are given to calculate the true secondary electron yield as a function of the primary electron energy. Combining both formulae permits to compute the total number of electrons emitted when the energy of the incident electrons is given. Using data obtained for electron induced desorption it has been shown that the quantity of molecules removed from a surface during processing is smaller than 10^{17} molecules.cm^{-2}. Using these data, it is now possible to better estimate the amount of gas released during the beginning of the LHC operation when multipacting can occur because of the electron cloud effect. Although the phenomenon of conditioning has been obtained reproducibly on many samples, in different experimental set-ups, the exact mechanism leading to this effect is not properly understood. This is of course not a comfortable situation as the LHC operation at nominal intensity relies on this effect. Further studies are going on to try to elucidate the main physical parameters responsible for this beneficial effect.

---

[1] V. Baglin, B. Henrist, N. Hilleret, E. Mercier, C. Scheuerlein: Proceedings of the X workshop on LEP-SPS performance Chamonix , 130, 2000.

[2] V. Baglin, J. Bojko, O. Gröbner, B. Henrist, N. Hilleret, C. Scheuerlein, M. Taborelli: 7th Europen Accelerator Conference, Vienna, 217-220, 2000.

[3] V. Baglin, I.R. Collins, O. Gröbner, C. Grünhagel, B. Henrist, N. Hilleret, B. Jenninger: Proceedings of the XI workshop on LEP-SPS performance Chamonix , 141, 2001.

[4] G. Arnolds-Mayer, N. Hilleret: Advances in Cryogenic Engineering Materials, 28, 611-621, 1982

[5] R. Bindi, H. Lanteri, P. Rostaing, J. Phys. D: Appl.Phys. 13,267, 1980.

[6] M. A. Furman, CERN LHC Project Report 180, 1998.

[7] J.J. Scholtz, D. Dijkkamp, R.W.A. Schmitz, Philips J. Res. 50, 375-389, 1996.

[8] R. E. Kirby, F. K. King SLAC-PUB-8212, 2000.

[9] H.J. Hopman, J. Verhoeven: Applied Surface Science, 150, 1-7, 1999.

[10] F. le Pimpec: Thèse Université de Paris VI, 2000.

[11] J. Gomez-Goni, A.G. Mathewson, J. Vac. Sci.Technol. A 15, 6, 3093-3103, 1997