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DETAILED INVESTIGATION OF THE LOW ENERGY SECONDARY ELECTRON YIELD OF TECHNICAL Cu AND ITS RELEVANCE FOR THE LHC[*]

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Abstract

The detailed study of the low energy Secondary Electron Yield (LE-SEY) of technical Cu for very low electron landing energies (from 0 to 30 eV) is very important for electron cloud build up in high intensity accelerators and in many other fields of research. However, LE-SEY has been rarely addressed due to the intrinsic experimental complexity to control very low energy electrons. Furthermore, several results published in the past have been recently questioned for allegedly suffering from experimental systematics. Here, we critically review the experimental method used to study LE - SEY and define more precise energy regions, in which the experimental data can be considered valid. E-cloud simulations are than performed to address the impact of such results on electron cloud predictions in the LHC.

INTRODUCTION

Low energy electrons in accelerators are known to interact with the circulating beam, giving raise to the formation of a so called e^- cloud [1]. Such an e^- cloud may cause detrimental effects on the accelerated beam quality and stability.

Low energy electrons can be produced either by the synchrotron radiation hitting the accelerator walls or by direct ionization of residual gases. Once the primary electrons are produced, they are accelerated by the electric field of the bunch creating secondary electrons at the accelerator walls. If the bunch charge and the bunch spacing satisfy certain conditions, an avalance multiplication effect, called "multipacting", can be established. Clearly, one of the most important parameters is the number of electrons produced by the accelerator walls when hit by other electrons. This quantity, called Secondary Electron Yield (SEY), is defined as the ratio of the number of emitted electrons to the number of incident electrons (also called primary electrons), and is commonly denoted by δ. Its value, its time stability and its dependence on primary electron dose and energy are indeed a crucial issue and an essential ingredient to correctly predict and mitigate e^- cloud effects (ECE) . Here we would like to discuss and confirm the detailed behavior of SEY at very low impinging electron energy ($E_p < 20$ eV). The LE-SEY can play a major role in determining ECE onset and effectiveness [1,2], since it has been shown that the electrons in the e^-cloud are of very low energy in nature [1,3], and have shown to have peculiar properties in terms of scrubbing [1,4,5]. In recent years, a series of publications [2,6] on the detailed study of SEY from Cu technical surfaces presented new observation reporting, for the first time, the tendency of SEY not only to reach 1 as E_p approaches 0 eV, but also to stay significantly above 0 for a quite extended energy region, having a minimum SEY of about $0.5 \div 0.7$ at E_p as high as $10 \div 20$ eV. This low energy behavior was clearly stated to be relative to the actual technical Cu surface studied and a strong warning was given against the extrapolation of such results as being a general property of SEY. More recently, Kaganovich and others [7], put this observation into question suggesting instead that the measured SEY is somehow due to experimental artifacts, since the SEY value at zero impinging energy is and must be zero or close to zero and the SEY curve should nearly monotonically decrease to this value. The authors corroborate such statement with experimental findings taken from the literature [8,9].

Scope of the present work is than to analyze the LE-SEY of LHC Cu technical surface and to investigate its effects on e^- cloud simulation prediction.

EXPERIMENTAL

Experimentally, dealing with very low electron energies is intrinsically difficult since, space charge, spurious residual electromagnetic fields, beam energy resolution etc. may act on the very low energy electron beam potentially affecting any detailed experimental SEY determination [10,11]. In the design of the set-ups used to perform such experiments and presently in operation at the Material Science INFN-LNF laboratory of Frascati (Roma), great care has been taken to eliminate spurious effects affecting the determination of LE-SEY. The experimental setup, described in details elsewhere [1,2], can operate in UHV (background pressure below 10^{-10}mbar). The use of a μ-metal chamber reduce to less than 5 mG the residual magnetic field at the sample position. Various sample preparation (Ar sputtering, evaporators, fast entry lock, etc.) and sample spectroscopic characterization techniques (LEED-Auger, XPS, XPS, SEY) are then available in "situ".

In order to measure low-energy impinging primary electrons, a negative bias voltage of V_b = -75 eV, was applied on the sample. Such bias not only allow us to eliminate space

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charge problems on the sample, but, even more importantly, allows us to work with landing energies close to zero still using the e^-gun in an energy region where it is stable and focused onto a transverse cross-sectional area which can be precisely determined and varied between around 0.25mm^2 for to 3mm^2 for all energies. The e^-gun used produce e^- by thermionic emission due to the variable current applied to the e^- source. Such e^- beam will show an intrinsic broadening due to the temperature at which the emitter is set and that can range, in our set up from 0.5 to 1 eV in FWHM.

SEY ($\delta(E)$), is defined as the ratio of the number of electrons leaving the sample surface, $I_{out}(E)$, to the number of incident electrons, $I_p(E)$, per unit area. $I_{out}(E)$ is the number of electrons emitted from the surface but also the balance between the current flowing from the sample $I_s(E)$ minus the current impinging on the sample, $I_p(E)$, so that:

$$\delta(E) = 1 - I_s(E)/I_p(E). \tag{1}$$

The SEY measurement is then performed by two subsequent operation: a) collect the sample electron current $I_s(E)$ as a function of the intensity and energy of the landing primary electron beam E_p; b) collect the e-gun emitted current $I_p(E_g)$ by using an "ad hoc" designed Faraday cup described elsewhere [1]. The SEY value can be considered valid within 5%, taking into account the experimental uncertainties and the intrinsic differences among nominally identical samples.

Energy Reference

We clarify here the energy scale of the presented spectra, since this is essential to understand the measured data. As clearly discussed by [12], in all spectroscopic experiments the energetic alignment between the different metals and systems (detectors, samples, guns etc) is their Fermi Energy (E_F), while each kinetic energy of any emitted electron is referenced to the Work Function of the material from which it has been emitted, if metal, or to its Electron Affinity plus the Energy Gap ($\chi_s + E_G$) if semiconductor or insulator. Electrons emitted by the gun will reference their kinetic energy to the cathode work function, (W_g) plus additional, when present, gun lents voltages applied, while electrons interacting with the sample, will reference their energy to the sample reference energy (W_s for metals or $\chi_s + E_G$ for semiconductor and insulators), and obviously additional, when present bias voltages applied. Here we refer all e^- energies to the Fermi Energy level E_F, which is the common and sample-independent reference for the entire system. With this energy reference, the minimum energy of a primary electron interacting and producing a measurable $I_s(E)$, with an atomically clean polycrystalline Cu will be the Work Function (W_{Cu}) of such sample, which is known from literature to be 4.65 eV [13]. Scaling this spectrum (as well as all the others) in this way, eliminates systematic errors linked to the absolute estimate of V_b , E_g and W_g. In most if not all SEY experiments [1] the landing energy of the impinging electron has been referenced to the sample work function (W_s) (or $\chi_s + E_G$), regardless the fact that it changes among different and differently treated surfaces. Actually, this would not significantly alter the conclusions of those papers.

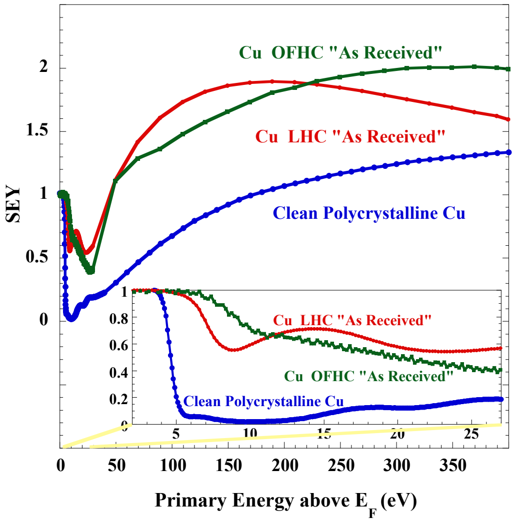

Figure 1: Experimental SEY curves of an OFHC "as received" Cu; a LHC "as received" Cu and of a clean polycrystalline Cu in the energy region between 0 and 400 eV above E_F. In the inset we zoom on the LE-SEY region between 2 and 27 eV above E_F.

Results

Here we analyze some experimental results that allow us to confidently validate our experimental technique, confirm previous literature results and certify a method to obtain reliable LE-SEY to be used in E-e^- cloud buildup simulations. To address this point we show in Fig. 1 the SEY of a representative Cu surface from LHC dipole beam screen [1] and we compare it with similar SEY results of an Oxygen-free high thermal conductivity (OFHC) "as received" Cu technical surface and with the reference clean polycrystalline Cu obtained after having atomically cleaned by ion sputtering both surfaces, as checked by XPS analysis. The inset of Fig. 1 shows the LE-SEY of the 3 different surfaces. The geometry and all other experimental conditions were kept constant during the acquisition of the different data sets. All SEY spectra shows a δ_{max} consistent with literature data [1], and the differences between the "as received" LHC Cu and the "as received" OFHC one is representative of the fact that "as received" surfaces are not in a well defined chemical state, and can differ significantly one from the other, consequently having different SEY. A closer look at the inset of Fig. 1 reveals a series of very interesting issues. We clearly show that we are able to see difference in work functions (W_s) and Electron affinities plus Energy Gap ($\chi_s + E_G$), and to measure their changes as referenced to the clean polycrystalline Cu sample which occurs at W_{Cu}= 4.65 eV [13]. Our technique is clearly able to measure SEY at landing energies just above the different W_s ($\chi_s + E_G$) and the only region, as shown for clean Cu, in which our technique is "blind" is the one very close to W_{Cu} where the LE-SEY goes from 1 to nearly zero. Such "blind" region originate from the experimental broadening of our e^- beam and actually measure it to be less than 1 eV. Our technique is "blind" in this small energy region since, due to the e^- beam broadening, not all of the impinging electrons contributing to $I_p(E)$, as measured by the Faraday, contribute to the measured $I_s(E)$, (some of them has energy lower than V_b so they are repelled by the surface). Hence δ_E in this small region can not be confidently measured with our method. Despite this small blind region, the diferences between clean metal and "as received" surfaces are significant and reproducible. While the LE-SEY of the clean Cu goes and stays close to zero showing no electron reflectivity up to less than 1 eV from W_{Cu}, our data on "as received" Cu surfaces confirm the ability of contaminated surfaces to reflect electrons at very low landing energies and that their δ stay above 0.5 - 0.7 eV for the entire LE-SEY energy region.

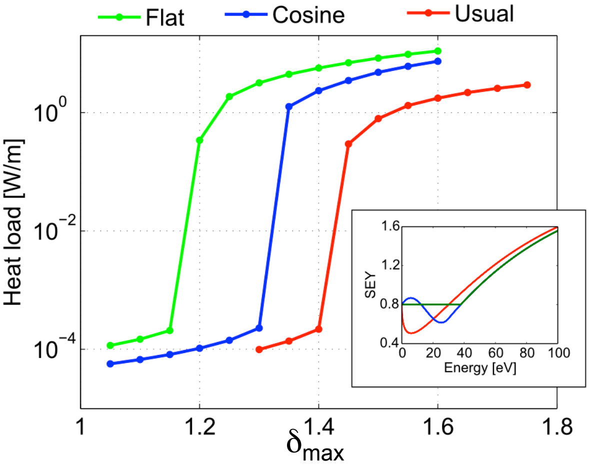

Figure 2: Simulated heat load for an LHC dipole for nominal beam parameters as a function of the δ_{max} for the different LE-SEY behaviors shown in the inset.

SIMULATIONS

In order to get a first hint on the impact of the LE-SEY region on the e^- cloud buildup [1], PyECLOUD simulations [14] have been performed considering three different LE-SEY behaviors, as shown in the inset of Fig. 2, on an otherwise identical SEY curve. Figure 2 shows the simulated EC induced heat load for an LHC dipole and nominal beam parameters [15] as a function of the δ_{max} parameter for the three cases. The simulations confirm a significant impact of the LE-SEY on the e^- cloud buildup behavior. In particular the δ_{max} threshold becomes significantly lower for a constant LE-SEY at 0.8 rather than for the SEY distribution generally adopted, and heat load above threshold gets significantly enhanced. Note that in all three cases the SEY at 0 energy has been set to 0.8 suggesting that, more than the actual SEY at 0 eV, it is the overall behavior of the LE-SEY which can significantly influence ECE predictions for the LHC.

CONCLUSION

We show here that it is possible to measure LE-SEY with great confidence and without experimental artifacts above less than 1 eV from sample W_s (in case of metallic surfaces) and EA (in case of semiconductors and insulators) and that the discrepancies recently discussed in literature were manly due to the different sample studied rather than to any experimental artifact. On the other hand, our preliminary calculations show that the LE-SEY detailed knowledge is indeed important to correctly simulate and predict ECE effects so that a more detailed campaign aimed to measure LE-SEY vs. Scrubbing and temperature, and to seed those results into simulations is a mandatory issue to analyze in details LE-SEY effects on ECE.

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