Nature of the Decrease of the Secondary-Electron Yield by Electron Bombardment and its Energy Dependence

R. Cimino,[1] M. Commisso,[1] D. R. Grosso,[1] T. Demma,[2] V. Baglin,[3] R. Flammini,[1,4] and R. Larciprete[1,5]

[1]*LNF-INFN, Via E. Fermi 40, 00044 Frascati (Roma), Italy*

[2]*Laboratoire de l'Accélérateur Linéaire, CNRS-IN2P3, Université Paris-Sud 11, Orsay, France*

[3]*CERN, Geneva, Switzerland*

[4]*CNR-IMIP Istituto Metodologie Inorganiche e Plasmi, Via Salaria Km. 29.300, 00019 Monterotondo Scalo (RM), Italy*

[5]*CNR-ISC Istituto dei Sistemi Complessi, Via Fosso del Cavaliere 100, 00133 Roma, Italy*

(Received 26 April 2012; published 10 August 2012)

We performed a combined secondary electron yield (SEY) and x-ray photoelectron spectroscopy study as a function of the electron dose and energy on a Cu technical surface representative of the LHC accelerator walls. The electron bombardment is accompanied by a clear chemical modification, indicating an increased graphitization as the SEY decreases. The decrease in the SEY is also found to depend significantly on the kinetic energy of the primary electrons. When low-energy primary electrons are employed ($E \leq 20$ eV), the reduction of the SEY is slower and smaller in magnitude than when higher-energy electrons are used. Consequences of this observation are discussed mainly for their relevance on the commissioning scenario for the LHC in operation at CERN (Geneva), but are expected to be of interest for other research fields.

DOI: 10.1103/PhysRevLett.109.064801 PACS numbers: 29.20.−c, 79.20.Hx, 07.30.−t, 29.27.Bd

An extremely vast range of research spanning from detectors, photon or electron multipliers, high power microwave tubes, systems for satellite applications [1], and radio frequency cavities [2] to optics for extreme ultraviolet lithography [3] base some of their essential functionalities on the number of electrons produced by a surface when hit by other electrons. This quantity, called secondary electron yield (SEY), is defined as the ratio of the number of emitted electrons (also called secondary electrons) to the number of incident electrons (also called primary electrons) [4], 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 in the design of many devices.

In particular, for particle accelerators with intense and positively charged beams and/or vacuum chambers of small transverse dimensions, electrons can be produced either by the synchrotron radiation hitting the accelerator walls [5,6] or by direct ionization of residual gases. Once the primary electrons are produced, they are accelerated by the electric field of the bunch in the direction perpendicular to the beam direction, creating secondary electrons at the accelerator walls. If the bunch charge and the bunch spacing satisfy certain conditions, a resonance phenomenon called multipacting can be established. When the effective SEY at the chamber is larger than unity, the electron population grows rapidly in time with successive bunch passages. This can lead to a high electron density, and, hence, to detrimental effects such as a rapid vacuum pressure rise resulting in beam loss. This phenomenon is called electron cloud (EC) buildup, and has been identified as source of limitations of accelerator performances in the positron rings at the B (Beauty) factories PEP-II and KEKB [7–11]. It is now clear that the best performance of present and future accelerators can be achieved if EC effects are understood, predicted, and finally mitigated. The only way to control and overcome such effects is to ensure a low SEY. At the Large Hadron Collider (LHC), SEY reduction (scrubbing or conditioning) is expected to occur during commissioning and is considered necessary to reach nominal operation [7–9,12].

In this Letter, we present the results of SEY and x-ray photoelectron spectroscopy (XPS) measurements of a Cu prototype of the beam screen adopted for the LHC, which is presently under commissioning at CERN. The target surfaces have been conditioned by electron bombardment (scrubbing). We have studied the variation of the SEY versus both the dose of the impinging electrons as well as their energy. Particular attention has been paid to low-energy primary electrons ($E < 20$ eV) which have been shown to have peculiar behavior in terms of reflectivity [13,14] and have been suggested to be the dominant species in the ring [15].

The experiment has been performed at the Material Science INFN-LNF Laboratory of Frascati (RM), with a dedicated experimental apparatus which is described elsewhere [5]. Briefly, the UHV system includes a μ-metal chamber (background pressure below 10^{-10} mbar), with less than a 5 mG residual magnetic field at the sample position, dedicated to XPS analysis and a second chamber for *in situ* sample preparation. Photoemission spectra have been acquired with an Omicron EAC125 electron analyzer. Nonmonochromatic Mg K_α radiation ($h\nu = 1253.6$ eV) has been used to induce photoemission. The samples studied (Cu, Al, TiN, a-C, stainless steel, etc.) have been used or are going to be used as technical surfaces in accelerators. The data here shown have been collected from parts of the final production of colaminated Cu for the LHC beam screen.

In order to measure low-energy impinging primary electrons, a negative bias voltage of -75 eV was applied on the sample. The *e*-gun was stable and focused onto a transverse cross-sectional area of around 0.25 mm^2 for all energies. The SEY measurement is then performed collecting the sample electron current produced as a function of the intensity and energy of the primary-electron beam. The SEY (δ) is then defined as $\delta = I_e/I_0 = (I_0 - I_S)/I_0$ where I_e is the current due to electrons emitted by the sample; I_0 is the impinging electron current as measured by a positively biased Faraday cup (75 V); I_s is the drain current measured on the sample. The SEY value can be considered valid within 5%, taking into account the experimental uncertainties and the intrinsic differences among the "as received" samples coming from the same batch.

The electron dose is defined as $D = Q/A = I_0 t/A$, where Q is the total charge incident per unit area on the sample surface, I_0 is the impinging beam current (generally on the order of a few nanoamperes while measuring δ in order not to perturb or scrub the surface during data acquisition, and some microamperes while dosing the sample), and t is the time during which the sample was exposed to the beam. A rastering procedure was chosen to ensure that all the SEY and XPS measurements were done on a uniformly irradiated area at each bombarding electron energy. Given some uncertainty on the irradiated spot and on the adopted rastering procedure doses are considered accurate to within 20% of their quoted values.

All SEY curves as a function of the incident beam energy are characterized by a maximum value ($\delta_{\max}$) reached in correspondence of a certain energy $E_{\max}$. The $\delta_{\max}$ values measured on the LHC samples bombarded with different electron doses at various impinging energies ranging from 10 to 500 eV are shown in Fig. 1. All the "as received" surfaces are characterized by a maximum value of $\delta_{\max} \approx 2.1$ at the corresponding energy $E_{\max} \approx 200$ eV.

As clearly shown in Fig. 1, the irradiation causes a decrease of the $\delta_{\max}$ values. We clearly notice how the behavior of the SEY at fixed doses varies as a function of the kinetic energy of the primary electrons. The curve obtained while conditioning the sample at 500 eV agrees well with results available in the literature [13,14,16,17], and shows that, for this energy, an electron dose up to 10^{-3} C mm^{-2} is indeed necessary to reduce the yield of the LHC samples from $\delta_{\max} = 2.1$ to $\delta_{\max} = 1.1$. Samples that do not show any further modification of their $\delta_{\max}$ value with increasing electron dose are considered "fully scrubbed." The reduction of $\delta_{\max}$ versus dose is quite similar for primary-electron energies between 500 and 50 eV. In contrast, when the scrubbing energy is 20 or 10 eV, the reduction of $\delta_{\max}$ not only proceeds with a slower rate but never reaches values lower than 1.35 even for doses of 3×10^{-2} C mm^{-2}. This evidence clearly indicates that the scrubbing process causing a SEY reduction at low incident electron energy is different from the one occurring while bombarding with higher-energy electrons and that the electron induced surface modifications do depend on the electron energy of the impinging beam. This observation has significant implications, which will only be partially discussed here.

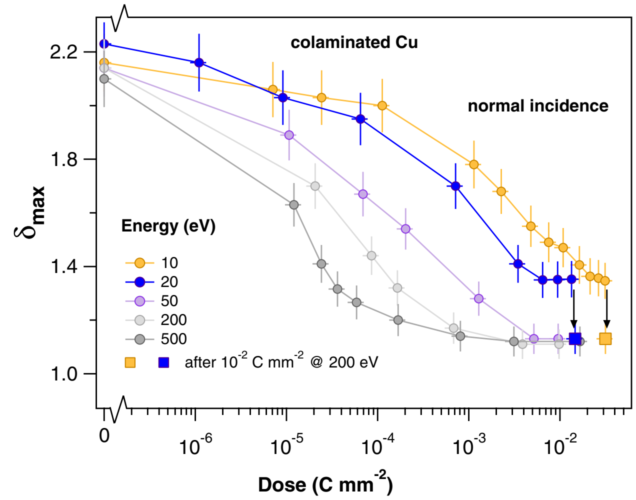

FIG. 1 (color online). $\delta_{\max}$ as a function of the dose for different impinging electron energies at normal incidence on colaminated Cu of the LHC beam screen. The squares represent the $\delta_{\max}$ values measured after an additional electron dose of 1.0×10^{-2} Cmm^{-2} at 200 eV.

Finally, we have bombarded with an ulterior dose of 1.0×10^{-2} C mm^{-2} electrons of 200 eV kinetic energy the samples showing a stable final value of $\delta_{\max} = 1.35$ (squares in Fig. 1). This has lowered $\delta_{\max}$ to the expected value of 1.1, as a further confirmation of the ability of high-energy electrons to efficiently reduce the SEY value.

While it is clear that changing primary energy between 50 and 20 eV changes the scrubbing efficiency and its final value, it is not possible, from our data, to analyze in detail the nature of this transition. Further investigation is needed to infer if this is a smooth or a sharp transition, and in the latter case, its value and chemical origin. For this reason, we consider 20 eV a conservative estimate of this threshold value.

We characterized the surface state of the LHC samples by acquiring XPS spectra as a function of dose and bombarding energy in order to clarify the detailed chemical mechanism at the base of the scrubbing process and its dependence on the energy of the impinging electrons. The most striking changes occurring at the surface, as seen by XPS, are exhibited by the C 1*s* core level spectra. In Fig. 2 (left panel) we report the C 1*s* spectra, and (right panel) the relative SEY curves, for the three representative cases:

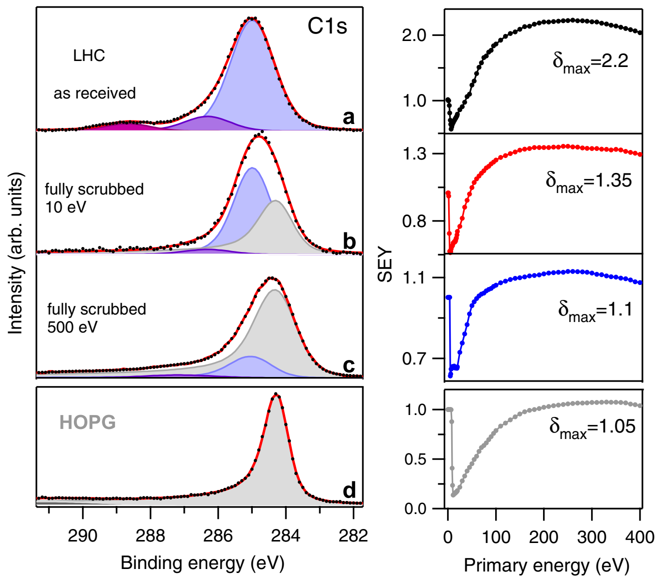

FIG. 2 (color online). C 1s XPS spectra and SEY curves measured on the LHC Cu sample: (a) "as received," (b) after a dose of 3×10^{-2} C mm^{-2} at 10 eV, (c) after a dose of 3×10^{-2} C mm^{-2} at 500 eV, and (d) on a freshly cleaved HOPG surface.

(a) the "as received" surface, and the surface fully scrubbed at (b) 500 eV and (c) 10 eV. Also, at the bottom panels of Fig. 2(d), we show the C 1s core level spectrum measured on a freshly cleaved highly oriented pyrolytic graphite (HOPG) surface, together with its SEY curve. All the SEY curves at low primary-electron energies, show a value lower than 1, which is independent of δ_{max} and on the electron dose received, in agreement with previous experimental results [13,14,16]. These measurements have been performed reproducibly on different LHC Cu beam screen samples.

All C 1s spectra were best fitted with Doniach-Šunjić functions [18] convoluted with Gaussians. The C 1s core level spectrum measured on HOPG consists of a single component at a binding energy (BE) of 284.3 eV and a FWHM of 0.95 eV, the broadening with respect to the value lower than 0.3 eV typically measured for HOPG [19] being due to the limited energy resolution of our experimental setup. In the analysis of the spectra taken on the LHC sample the graphitic component was fixed to have the same line shape as HOPG but with a broader Gaussian width, left as a free fit parameter to account for the presence of disorder sp^2 bonds. The best-fit results summarized in Fig. 2 indicate that in the "as received" sample the C 1s spectrum can be decomposed into a main peak at BE of 285.0 eV, which can be attributed to sp^3 hybridized C atoms in C—C [20] and C—H bonds [21] and two weak components at 286.3 and 288.6 eV ascribed to single or double C—O bonds [22], respectively, in partly oxidized aliphatic and/or aromatic compounds. Electron beam irradiation removes the peak at 288.6 eV after the decomposition of weakly bound species and converts the sp^3 hybridized C atoms into a network having predominantly sp^2 bonds, as it is indicated by the appearance of the graphitic component at 284.3 eV [20]. The C 1s spectra reveal that whereas the sp^3-sp^2 conversion is limited for the sample scrubbed at 10 eV, electron irradiation at 500 eV modifies the chemical state of almost all the contaminating C atoms producing a graphitelike layer coating the copper surface [17,23].

Analogue SEY reduction has also been obtained by bombarding several "as received" substrates of different nature like TiN and stainless steel. The C 1s spectra, taken in similar conditions as those described in the case of Cu, do show nearly identical behavior in terms of the increase of the component attributed to the sp^2 bonds and SEY reduction, and will be presented elsewhere. This general trend shows, as far as we know, at least one relevant exception represented by Al. Upon the scrubbing of Al samples, in fact, the SEY increases and the carbon graphitization does not take place. This has been ascribed to the exceptional oxygen reactivity of the Al surface [24]. From the set of data on Cu, stainless steel, TiN, and probably for a more vast class of industrial materials, it comes out that the formation of a graphitic film is the fingerprint and the actual chemical origin of the SEY reduction, and that the energy of the electrons needed to promote such effect should be higher than a certain value here estimated to be about 20 eV.

It is widely accepted that the LHC can reach its final operating parameters only when the majority of the Cu surfaces in the ring reach $\delta_{\mathrm{max}} < 1.3$ [7–9,12]. This requires a more detailed study to evaluate the consequences of our experimental findings and their implications for the optimization of the LHC commissioning sequence. As an example, we have calculated the real energy of the electrons of the EC hitting the walls. Calculations were performed using the ECLOUD code version 4.b [25–27], developed at CERN to study such effects. The code tracks electrons grouped in macroparticles, taking into account all the forces acting upon them. Both the bunch and interbunch gaps are divided in time steps. At each time step, while the bunch is passing, up to 1000 macroelectrons are generated whose charge is determined by the primary photoemission yield. As the macroparticles hit the vacuum chamber surface their total charge is changed according to the secondary emission properties of the material. The macroelectrons hitting the walls are binned in 500 uniform intervals extending between 0 and 800 eV. The calculations have been performed assuming $\delta_{\mathrm{max}} = 2.1$, which roughly corresponds to the maximum SEY of an "as received" Cu surface.

In Fig. 3, the energy distribution curve (EDC) of electrons hitting the LHC dipole inner chamber is shown for the 50 ns bunch filling pattern as listed in Table I. The number of electrons with energy $E < 20$ eV is orders of magnitude higher than the high-energy ones, so that the

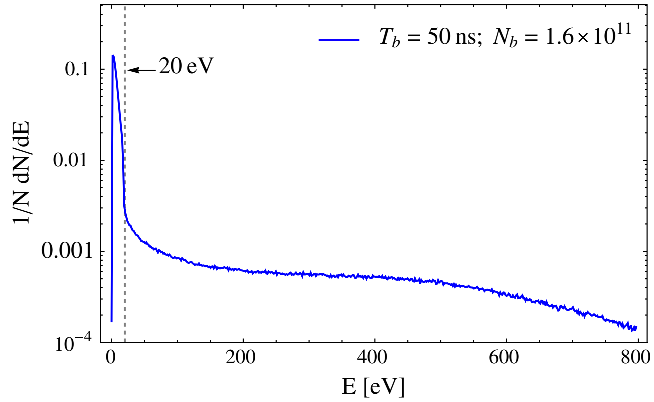

FIG. 3 (color online). Calculated electron energy distribution at the LHC accelerator wall. The number of electrons below and above 20 eV (dotted line) is nearly equal.

20 eV separation line divides the plot into two nearly equally populated regions. This notion may be extremely relevant to calculate the commissioning time of the different machines (like LHC) counting on scrubbing as an e-cloud mitigation scheme. Such a commissioning time does not only depend on the total electron flux, but mainly on the number of "scrubbing" electrons (i.e., with energy $E > 20$ eV) hitting the accelerator walls. Of course, the ratio between the total number of electrons in the cloud and the number of electrons with energy $E > 20$ eV, varies with beam properties and surface conditions of the vacuum chamber. This knowledge suggests that it will be possible to reduce the duration of the commissioning time by optimizing the beam parameters in a way to maximize the high-energy component of the electron EDC.

In conclusion, Cu technical surfaces representative of the Large Hadron Collider accelerator inner walls have been monitored by XPS and SEY measurements during conditioning by electron bombardment (scrubbing). Our findings show that the surfaces undergo a graphitization process causing a decrease of the SEY value. It is also shown that full graphitization, hence the effective reduction of the SEY, is not reached if the kinetic energy of the scrubbing electrons is $E < 20$ eV. We suggest that the commissioning time of the LHC could be significantly reduced if the beam parameters were set to maximize the higher-energy part of the EDC of the electrons hitting the accelerator walls. Our results provide a strong motivation to launch a high quality spectroscopic campaign to detail the physical phenomena which are the basis of our observations. This would provide a better understanding of what actually determines the SEY of technical surfaces in operational conditions. Such knowledge is necessary for the design of intrinsically low SEY surfaces for accelerators and may also be of interest to the broader community where the SEY of surfaces has significant impact.

The authors are indebted to J. M. Jimenez and G. Rumolo for support and useful discussions. This work was supported by INFN-NTA and Group V. We acknowledge the staff of DAΦNE-Light for technical assistance.

TABLE I. Parameters used for ECLOUD simulations.

Parameter	units	value
Beam particle energy	TeV	3.5
Bunch spacing	ns	50
Bunch length	m	0.1
Bunch transverse size ($\sigma_x = \sigma_y$)	mm	0.3
Number of bunches per train	⋯	36
Bunch gap at the end of each train	⋯	4
Number of trains in a batch	⋯	4
Number of particles per bunch N_b	10^{11}	1.6
Bending field B	T	4.2
Vacuum screen half height	mm	18
Vacuum screen half width	mm	22
Primary photoemission yield	10^{-4}	3
Maximum SEY δ_{max}	⋯	2.1
Energy for maximum SEY E_{max}	eV	230
Macroelectrons generated per bunch	⋯	1000
Number of time steps per bunch	⋯	200
Number of time steps per interbunch	⋯	20 000

[1] S. T. Lai, *Fundamentals of Spacecraft Charging: Spacecraft Interactions with Space Plasmas* (Princeton University, Princeton, NJ, 2011).
[2] A. Variola in *Proceedings of LINAC 2006* (JACoW, Knoxville, 2006), p. 531.
[3] J. Chen, E. Louis, J. Verhoeven, R. Harmsen, C. J. Lee, M. Lubomska, M. van Kampen, W. van Schaik, and F. Bijkerk, Appl. Surf. Sci. **257**, 354 (2010).
[4] H. Seiler, J. Appl. Phys. **54**, R1 (1983).
[5] R. Cimino, Nucl. Instrum. Methods Phys. Res., Sect. A **561**, 272 (2006).
[6] R. Cimino, I. R. Collins, and V. Baglin, Phys. Rev. ST Accel. Beams **2**, 063201 (1999).
[7] CERN Report No. CERN-2002, edited by G. Rumolo and F. Zimmermann, 2002.
[8] The 31st ICFA Advanced Beam Dynamics Workshop on Electron-Cloud Effects ECLOUD'04, Napa, California 2004, edited by M. Furman, http://icfa-ecloud04.web.cern.ch/icfa-ecloud04/ and references therein.
[9] Proceedings of International Workshop on Electron-Cloud Effects (ECLOUD '07) Daegu, Korea, April 2007, http://airex.tksc.jaxa.jp/pl/dr/AA0063628000/en and references therein.
[10] Proceedings of the International Workshop on Multibunch Instabilities in Future Electron and Positron Accelerators, Tsukuba, Japan, 1997, edited by Y. H. Chin.
[11] Proceedings of the International Workshop on Two-Stream Instabilities in Particle Accelerators and Storage Rings, Tsukuba, Japan, 2001, http://conference.kek.jp/two-stream/.
[12] F. Zimmermann, CERN Report No. CERN-SL-2001-003 DI, 2001.

[13] R. Cimino, I. R. Collins, M. A. Furman, M. Pivi, F. Ruggiero, G. Rumolo, and F. Zimmermann, Phys. Rev. Lett. **93**, 014801 (2004).
[14] R. Cimino and I. R. Collins, Appl. Surf. Sci. **235**, 231 (2004).
[15] G. Rumolo and F. Zimmermann, CERN Yellow Report CERN-2002-001, 2002, p. 97.
[16] V. Baglin, I. Collins, B. Henrist, N. Hilleret, and G. Vorlaufer, CERN, LHC Project Report No. 472, 2001.
[17] M. Nishiwaki and S. Kato, Vacuum **84**, 743 (2009).
[18] S. Doniach and M. Šunjić, J. Phys. C **3**, 285 (1970).
[19] F. Sette, G. K. Wertheim, Y. Ma, G. Meigs, S. Modesti, and C. T. Chen, Phys. Rev. B **41**, 9766 (1990).
[20] J. Díaz, G. Paolicelli, S. Ferrer, and F. Comin, Phys. Rev. B **54**, 8064 (1996).
[21] A. Nikitin, L. Näslund, Z. Zhang, and A. Nilsson, Surf. Sci. **602**, 2575 (2008).
[22] R. Larciprete, S. Fabris, T. Sun, P. Lacovig, A. Baraldi, and S. Lizzit, J. Am. Chem. Soc. **133**, 17315 (2011).
[23] M. Nishiwaki and S. Kato, J. Vac. Soc. Jpn. **48**, 118 (2005).
[24] D. R. Grosso, M. Commisso, R. Cimino, R. Flammini, R. Larciprete, and R. Wanzenberg, Proceedings of IPAC2011, San Sebastin, Spain, 2011, Vol. 1533, http://accelconf.web.cern.ch/accelconf/IPAC2011/papers/tups009.pdf.
[25] F. Zimmermann, CERN, LHC Project Report No. 95, 1997.
[26] G. Rumolo and F. Zimmermann, CERN Report No. SL-Note-2002-016, 2002.
[27] Tech. Report No. CERN-SL-Note-2002-016; see also The ECLOUD Program, http://wwwslap.cern.ch/collective/electron-cloud/Programs/Ecloud/ecloud.html.