

# ELECTRON-CLOUD SIMULATION RESULTS FOR THE SPS AND RECENT RESULTS FOR THE LHC\*

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## Abstract

We present an update of computer simulation results for some features of the electron cloud at the Large Hadron Collider (LHC) and recent simulation results for the Super Proton Synchrotron (SPS). We focus on the sensitivity of the power deposition on the LHC beam screen to the emitted electron spectrum, which we study by means of a refined secondary electron (SE) emission model recently included in our simulation code.

## 1 INTRODUCTION

The electron-cloud effect (ECE) is of considerable interest for the LHC, the main issue being the magnitude of the power deposition by the electrons on the vacuum chamber beam screen. A great deal of simulation work has been devoted to estimating the power deposition under various assumed conditions, in particular its sensitivity to the peak value  $\delta_{\max}$  of the secondary emission yield (SEY)  $\delta(E_0)$  of the copper layer of the beam screen, and its value at zero incident electron energy,  $\delta(0)$  [1] (here  $E_0$  is the incident electron energy).

For some time now we have been studying the ECE by means of multiparticle simulations with our code “POSINST” that includes a detailed probabilistic model of the secondary emission process [2]. Application of this simulation tool to the LHC [3] exhibited a strong sensitivity to the backscattered-electron and rediffused-electron components of the SEY, which dominate  $\delta(0)$ . This issue has attracted increased attention by recent measurements of the SEY at low energy for Cu [4] and other materials [5], that show values for  $\delta(0)$  in the range  $\sim 0.4 - 0.6$ , which is significantly higher than earlier assumptions [6, 7]. One goal of this article is a better explanation of this sensitivity. For this purpose, we have carried out detailed fits of the SEY and the emitted-energy spectrum  $d\delta/dE$  to particular sets of measurements for Cu and stainless steel (St.St.) [8]. A key, and fortuitous, feature of these sets of data is that the SEY curve for Cu is almost identical to that for St.St., as shown in Fig. 1a, but that the secondary emission spectra is quite different, as seen in Fig. 1b for the case of  $E_0 = 300$  eV.

Our model takes into account the three main components of electron emission. Each of these components contributes an amount  $\delta_i$  to the SEY, where  $i = 1, 2, 3$  corresponds to true secondary, rediffused and backscattered electrons,

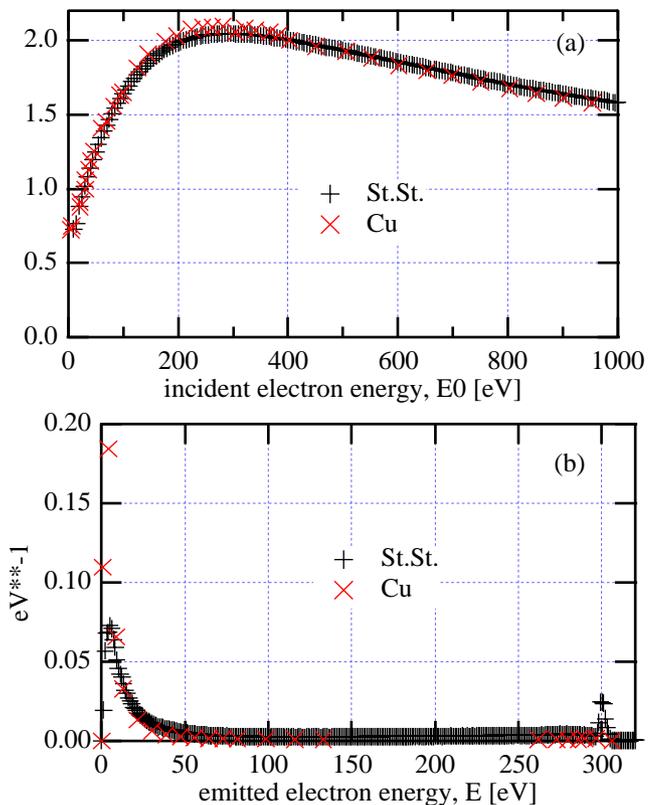


Figure 1: Top: SEY at normal incidence as a function of incident electron energy  $E_0$  for Cu (data courtesy N. Hilleret) and St.St. (data courtesy R. Kirby). Bottom: secondary emission energy spectrum  $d\delta/dE$  for  $E_0 = 300$  eV. The samples were measured by different apparatuses, and were in different states of surface conditioning.

respectively, so that  $\delta = \delta_1 + \delta_2 + \delta_3$ , where

$$\delta_i = \int_{E_i}^{E_{i+1}} dE \frac{d\delta}{dE} \quad (1)$$

For the data at  $E_0 = 300$  eV shown in Fig. 1b, we set  $E_1 = 0$ ,  $E_2 = 50$  eV,  $E_3 = 295$  eV, and  $E_4 = 305$  eV (the value for  $E_2$  of 50 eV is somewhat arbitrary, but conventional). Table 1 shows the three components as percentages of the total  $\delta$  corresponding to this case. It is seen that  $\delta_2 + \delta_3$  contributes substantially more to  $\delta$  for St.St. than for Cu. These percentages vary with  $E_0$ , although the general trend persists away from 300 eV. Our model does take this variation into account [8].

We stress that the Cu and St.St. samples for which this data was taken were in different states of surface condition-

\* Work supported by the US DOE under contract DE-AC03-76SF00098 and by the SNS project (ORNL).

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Table 1: Secondary components ( $E_0 = 300$  eV).

	$\delta_1$	$\delta_2$	$\delta_3$
Cu	84%	15%	1%
St.St.	57%	37%	6%

ing, and neither is representative of what is expected for the LHC beam screen in normal operation. In particular, the value  $\delta_{\max} \simeq 2.05$  in this data is significantly higher than what has been obtained by adequate conditioning of Cu samples of the LHC beam screen [4]. Of course, only the case of Cu is relevant to the LHC; we carry out here the simulation for both cases only for the purposes of exhibiting and explaining the sensitivity of the results to the details of the emitted energy spectrum.

We also present results for simulations for the SPS in a dipole magnetic field. As we are interested in benchmarking the code against measurements, we focus on the electron distribution, which exhibits characteristic peaks on either side of the center of the chamber.

## 2 MODEL

In this article we consider only the dominant sources of electrons. For the LHC, the dominant source is the photoelectrons arising from the synchrotron radiation striking the walls of the vacuum chamber. For the SPS, it is electrons from ionization of the residual gas. In addition to these “seed electrons,” we consider the secondary electrons, emitted when the electrons strike the vacuum chamber walls under the action of successive bunch passages. Although our code accommodates other sources of electrons, we have turned them off for the purposes of this article.

For the simulation we take bunch length effects into account by dividing the bunch into a number of kicks  $N_k$  in the longitudinal direction. Space-charge forces of the electron cloud on itself are computed by means of a transverse grid, and are applied at every kick during the bunch passage and at every step during an empty bucket (empty buckets are divided up into  $N_e$  steps). The main parameters are specified in Table 2. Further details of the simulation are described in Ref. 3.

## 3 POWER DEPOSITION IN LHC

We have estimated the power deposited on the vacuum chamber of an LHC arc dipole by simulating a train of 50 bunches injected into an empty chamber followed by a 10-bunch long gap, for a total of  $1.5 \mu\text{s}$  of beam time. We assume nominal parameters for the LHC bunch population and spacing, beam energy and beam sizes, listed in Table 2. We also assume a quantum efficiency per penetrated photon  $Y' = 0.05$ , with an effective photon reflection coefficient of 10%. This means that 90% of the photoelectrons

Table 2: Assumed parameters for the SPS and LHC.

Parameter	Symbol	SPS	LHC
Proton beam energy	$E$ , GeV	26	7000
Dipole field	$B$ , T	0.2	8.4
Bunch population	$N_p \times 10^{11}$	0.8	1.05
Bunch spacing	$\tau_g$ , ns	25	25
Bunch length rms	$\sigma_z$ , cm	30	7.7
Trans. bunch size	$\sigma_x, \sigma_y$ , mm	3, 2.3	0.3, 0.3
Pipe semi-axes	$a, b$ , mm	77, 22.5	22, 18
Kicks/bunch	$N_k$	101	51
Steps/empty bucket	$N_e$	25	41
Photon reflectivity	$R$	-	10%
Quantum efficiency	$Y'$	0	0.05
Peak SEY	$\delta_{\max}$	1.9	2.05
Peak SEY energy	$E_{\max}$ , eV	260	270
Sp. charge grid size	$h_x, h_y$ , mm	7.7, 2.25	2.5, 2.5

are emitted on the outward “edge” of the chamber, where the synchrotron radiation strikes the chamber, and 10% uniformly around the rest of the chamber as a result of multiple photon reflections. The results for the instantaneous power deposition per unit length,  $dE_a/dsdt$ , are shown in Fig. 2 in units of J/m/s (here  $E_a$  is the energy absorbed by the wall). Preliminary results were presented in Ref. 9.

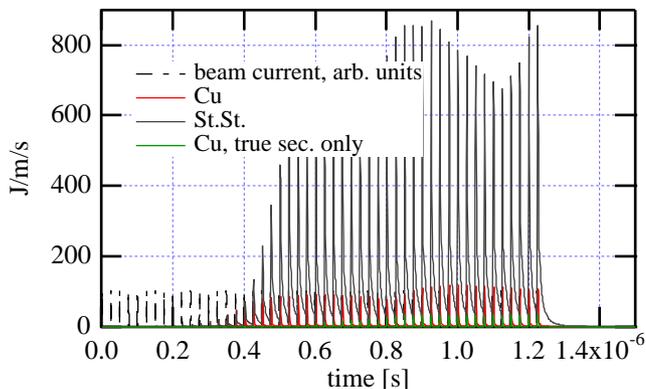


Figure 2: Simulated instantaneous electron-cloud power deposition in an LHC arc dipole for Cu, St.St., and for Cu in which only the true secondary emission is considered (see text).

The average power deposition in steady state (time interval  $0.5 \leq t \leq 1.2 \mu\text{s}$  in Fig. 2) are 11 W/m for Cu and 152 W/m for St.St. In addition to these two cases, we computed a third case in which we artificially eliminated the rediffused and backscattered components of the emitted spectrum, retaining only the true secondary electrons, and rescaled the SEY to  $\delta_{\max} = 2.05$ . In this case, the average power deposition is 2.1 W/m. If we average  $dE_a/dsdt$  over the whole run ( $0 \leq t \leq 1.5 \mu\text{s}$  in Fig. 2), the aver-

age power deposition is roughly half of the above-quoted values. The origin of this large sensitivity is explained in Sec. 5 below.

## 4 SPS SIMULATION

In the case of the SPS, we are primarily interested in reproducing a feature of the electron-cloud spatial structure, namely the position of the “vertical stripes,” or regions of high electron density, which appear in the presence of a dipole magnetic field. The vertical stripes are reproduced by the simulations, as seen in Fig. 3, which shows a histogram of the horizontal projection of the time-averaged electron cloud density (simulation parameters are listed in Tab. 2). In this case, the results are quite similar for Cu and St.St., showing stripes at  $\sim \pm 18$  mm, in agreement with CERN simulations [10], and in disagreement with the measured location at  $\sim \pm 9$  mm [11]. The peaks at  $\pm 2$  mm in Fig. 3 are mostly due to an artifact of our time-averaging procedure; indeed, instantaneous snapshots of the distribution show these peaks much reduced.

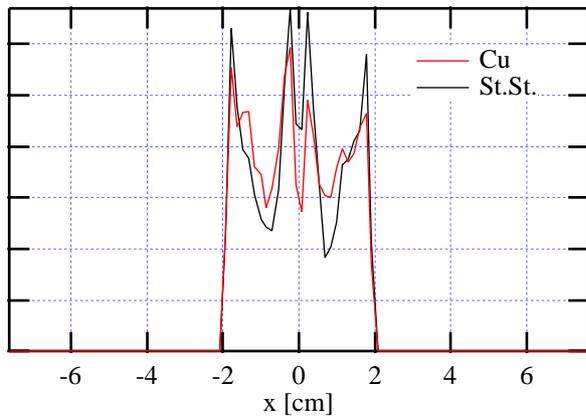


Figure 3: Histogram of the horizontal projection of the time-averaged electron-cloud density in a dipole magnet at the SPS. Although the electron density is quite different for Cu and St.St, we have normalized the two histograms to unity in order to emphasize the similarities of the distributions.

## 5 CONCLUSIONS

The large sensitivity of the power deposition in the LHC chamber to the composition of the emitted-energy spectrum can be explained as follows: When an electron strikes the chamber it is much more likely to emit high-energy secondaries when the rediffused plus backscattered component is large, as in the case of St.St., than when it is small, as for Cu. As a result, the second-generation electrons will create more secondaries in the former case than in the latter. Consequently, in the time interval between bunches, not only does the electron cloud dissipate at a lower rate for St.St. than for Cu, but also the average electron-wall col-

lision energy is higher, and so is the effective SEY. These results can be clearly observed in related output of the simulation, not shown here [12].

We emphasize that our estimated value for the electron-cloud power deposition, computed in Sec. 3 for  $\delta_{\max} = 2.05$ , is significantly larger than what can realistically be expected once the Cu surface of the beam screen becomes sensibly conditioned, whereupon a value  $\delta_{\max} = 1.3$  may be achieved [13]. Our results underscore the need for reliable data on the SEY and emitted-energy spectrum in order to improve the estimate of the magnitude of the power deposition in the LHC.

For the SPS dipole simulation, the agreement between the simulated stripe locations with experiment is off by a factor of  $\sim 2$ . We do not at present have an explanation for this discrepancy, which merits further investigation.

## 6 ACKNOWLEDGMENTS

We are indebted to R. Kirby and N. Hilleret for supplying us with data and many discussions. We are grateful to I. Collins, R. Cimino and F. Zimmermann for valuable discussions. We are grateful to NERSC for supercomputer support.

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