BENCHMARKING ELECTRON CLOUD DATA WITH COMPUTER SIMULATION CODES

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Abstract

Saturated electron flux and time decay of the electron cloud are experimentally inferred using many electron detector datasets at the Relativistic Heavy Ion Collider (RHIC). These results are compared with simulation results using two independent electron cloud computer codes, CSEC and ECLOUD. Simulation results are obtained over a range of different values for 1) the maximum Secondary Electron Yield (SEY), and 2) the electron reflection probability at zero energy. These results are used to validate parameterization models of the SEY as a function of the electron energy.

INTRODUCTION

This paper uses two simulation codes (CSEC and ECLOUD) to reproduce the electron signal behaviour observed with the Electron Detector (ED) during a RHIC fill (#3460). The beam characteristics are listed in the first part of Table 1. Figure 1 shows, as an example, two snapshots of the electron signal collected in the ED (top plot) and the bunch intensity (bottom plot) as read by the WCM. Between $t = 1.8$ and 3.8μs, the bunch intensity decreases from 8×10^{10} to about 5.5×10^{10} protons/bunch, causing the electron signal to interrupt its build up. In the snapshot at 12:19:52 the signal stays more or less constant. At 12:20:00 a slightly decrease is noticeable. This is related to large ED noise [1]. Two quantities are reproduced using CSEC and ECLOUD: the peak to peak signal (or saturated flux, in case saturation occurs), and the decay time after the last bunch (inside-plot in Fig. 1). The signal goes from negative to positive voltage values because of the system electronics, yet both the peak to peak signal and the decay time are not affected [1]. The evolution of both the peak to peak signal and decay time throughout the fill is analyzed in the following. These values are compared with results obtained after running CSEC and ECLOUD simulations with two different Secondary Electron Yield (SEY) parameters: the maximum SEY, $\delta_{\max}$, and the SEY at zero electron energy, δ_0.

EXPERIMENTAL VALUES

Figure 1 shows an example of the fit to the experimental values for the snapshot at 12:20:00. The signal in the ED decays after the last bunch passage in the form:

$$V(t) = A_v e^{-(t-t_M)/\tau_d} - V_0 \,, \tag{1}$$

where the offset V_0 is produced by the system electronics, A_v is a fitting parameter, and τ_d indicates the decay time.

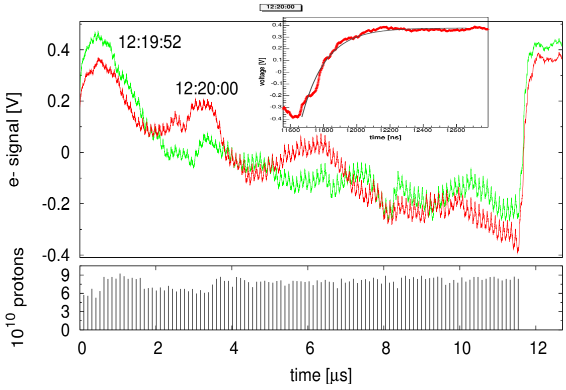

Figure 1: Two ED snapshots only 4 seconds apart (top plot) and bunch intensity (bottom plot) for a RHIC revolution (12.8 μs) during fill 3460. The inside-plot shows the fit to the experimental values at 12:20 using Eq. 1.

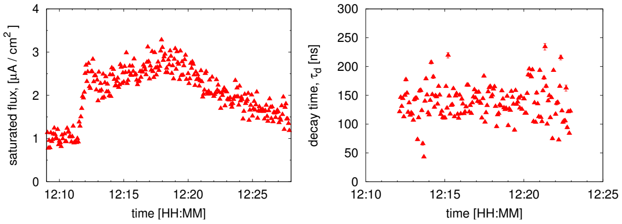

Figure 2: Evolution of the peak to peak electron signal (left) and decay time (right) during fill #3460.

Figure 2 (left) shows the evolution of the peak to peak value observed in the ED assuming a transparency of 5% [1]. The electron cloud triggers at about 12:12, the flux stays more or less constant ranging between ~ 2.5 and $\sim$3.5 μA/cm^2. However, two noise sources are present. In the absence of a multipacting (before 12:12), the noise level induced by the beam is about 1μA/cm^2. Secondly, the lack of knowledge of the electron energy spectrum indicates that the effective transparency can change by about a factor of 2 [1]). All in all, it is assumed that the saturated flux is reproduced within a factor of 2.

Reference [1] illustrates two different regimes in an electron cloud decay. In the first, the cloud decays quickly due to the space charge effects and the reminiscences of the bunch passage. In the second, the electrons move slowly and their dissipation rate depends mainly on the elastic reflection probability of the chamber surface for these low energies (i.e., parameter δ_0 in Eqs. 3 or 4). The decay time obtained using the ED refers to the first regime, since the second regime shows very low fluxes and very low energy electrons, which are hardly distinguishable from the ED noise. The time t_M corresponds to the last bunch passage, and it is obtained from the WCM data. The fitting is only performed for those snapshots showing a clear signal, between 12:12 and 12:23. The evolution of the calculated time decay throughout the fill is shown in Fig. 2, right. Similar to results at PSR [3], Fig. 3 shows the average and rms values for the decay time:

$$\tau_d = 140 \pm 30 \text{ ns} . \qquad (2)$$

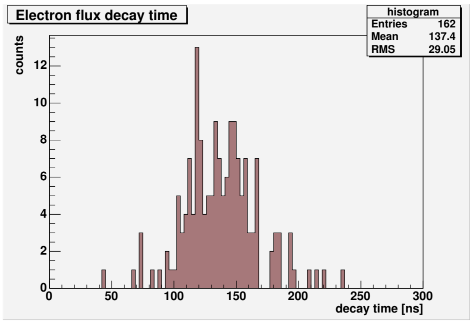

Figure 3: Histogram with the calculated decay times.

SIMULATION RESULTS

One of the main uncertainties in the electron cloud simulation codes stems from the SEY dependence on the electron energy $\delta(E)$, especially for low energy electrons (below $\sim$ 20 eV). The SEY parameterization used by the CSEC code is [2]:

$$\delta(E) = (\delta_0 - \delta_\infty) e^{-E/E_r} + \delta_\infty + \delta^*_{\max} \frac{sx}{s - 1 + x^s} , \qquad (3)$$

On the other hand, the SEY parameterization used with the ECLOUD code in this work is [5]:

$$\delta(E) = \delta_0 \left[\frac{\sqrt{E} - \sqrt{E + E_0}}{\sqrt{E} + \sqrt{E + E_0}} \right]^2 + \delta^*_{\max} \frac{sx}{s - 1 + x^s} , \qquad (4)$$

where $x \equiv E/E_{\max}$, and explanations of the parameters used in Eqs. 3 and 4 are shown in Table 1. Terms proportional to δ_0 and δ_∞ approximate the contribution of "reflected" electrons (whose emission energy equals the incident electron energy), while terms proportional to $\delta^*_{\max}$ indicate "true secondaries", emitted typically at low energies (around E_{sec} $\sim$5 eV). Inside the "true secondary" group, CSEC considers that electrons have a certain probability for "rediffusion", that is, electrons can be emitted by the chamber wall at intermediate energies (between the incident energy E and E_{sec}). The rediffusion process is not considered in the ECLOUD version used in this work. In the following, we fix the wall surface parameters to values similar to those obtained in the literature [4], and sweep the most significant ones, $\delta^*_{\max}$ and δ_0, comparing the calculated using simulations peak flux and the decay time obtained with the experimental values.

From the values in Table 1, we stress that for the CSEC parameterization (Eq. 3), the value of the maximum SEY is $\delta(E_{\max}) = \delta_{\max} \sim \delta_\infty + \delta^*_{\max}$. On the other hand, the maximum SEY using the ECLOUD parameterization (Eq. 4) is $\delta(E_{\max}) = \delta_{\max} \sim \delta^*_{\max}$.

Table 1: List of input parameters for the electron cloud CSEC and ECLOUD simulations.

parameter	CSEC	ECLOUD
bunch spacing, s_b[ns]	107	
number of bunches	110	
bunch population, $N_b[10^{10}$ p]	8.0	
rms beam radius, σ_r[mm]	2.4	
full bunch length, σ_l[ns]	15	
pipe radius, b[mm]	60	
SEY at $E \rightarrow 0$, δ_0	from 0.5 to 1.0	
max. SEY for true sec., $\delta^*_{\max}$	from 1.6 to 2.4	
SEY for $E \rightarrow \infty$, δ_∞	0.2	...
energy at max. SEY, $E_{\max}$[eV]	300	300
reflection energy, E_r[eV]	60	...
potential step, E_0[eV]	...	60

The left hand side plot in Fig. 4 shows three examples of the evolution of the simulated electron flux to the wall for three different $\delta^*_{\max}$. The data is numerically smoothed using a 10 MHz filter. Note that between 2 and 4 μs the build up is interrupted due to the lower bunch intensities, as it is observed in the experimental data (see Fig. 1, left). Figure 4, right, shows the decay time fit for the case corresponding to $\delta_0 = 0.6$ and $\delta^*_{\max} = 2.0$. Since the experimental observations can only measure the first decay regime (due to the ED noise), the fit is only performed for 400 ns after the last bunch passage.

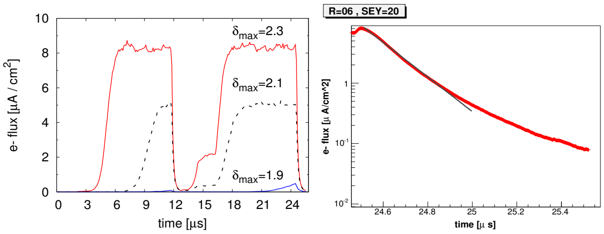

Figure 4: The left hand side plot shows the evolution of the electron flux as a function of time for three different $\delta^*_{\max}$, while keeping $\delta_0 = 0.6$. The right hand side plot depicts an example of the fit (black line) to the CSEC simulation results during 400 ns after the last bunch for $\delta^*_{\max}$=2.0, δ_0=0.6. The peak flux and the decay time are compared with the values of the experimental data (Fig. 2).

CSEC results

Figure 5 (left) shows the peak electron flux as a function of $\delta_{\max}$ for three different values of δ_0. The left hand side plot in Fig. 5 shows the calculated decay times for the same set of δ_0, and $\delta_{\max}$. To avoid large error bars, the decay time is only calculated if the peak electron flux is larger than 0.01 μA/cm^2. Note that for $\delta_{\max}$ <1.9, the calculated decay times (from CSEC simulations) are larger than those measured experimentally (see Fig. 3). For an easy comparison with the experimental values, these have been marked with a horizontal bold line in Fig. 5, while the limits of the error margin are marked with two dashed horizontal lines.

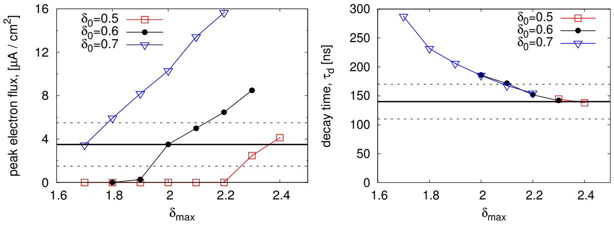

Figure 5: Peak flux (left) and time decays (right) calculated using CSEC simulations as a function of $\delta_{\max}$, and for different δ_0.

Combinations compatible with both the experimental peak fluxes and the decay times Fig. 2 are listed in Table 2. Parameterizations combining $\delta_0 \in [0.5, 0.6]$ and $\delta_{\max} \in [2.0, 2.3]$ are shown in literature SEY models [4]. However, it is worth mentioning that 1) the model in [4] fits (not measures) δ_0, and 2) that the value for δ_∞ in this work is larger than in [4]. It is interesting to observe (as it occurs with ECLOUD, see below) that in this range of parameters, the decay time is almost independent of δ_0. This shows that during the first regime of the cloud decay, the dissipation rate does not depend on δ_0 because the electrons energies are typically larger than ~20 eV.

ECLOUD results

ECLOUD simulations using the input parameters in Table 1 have been carried out. A scan in $\delta^*_{\max}$ and δ_0 is performed using the aforementioned procedure. The peak electron flux and the decay time as a function of $\delta_{\max}$ are shown in Fig. 6. Again, the decay time is only calculated if the peak electron flux is larger than 0.01 μA/cm^2.

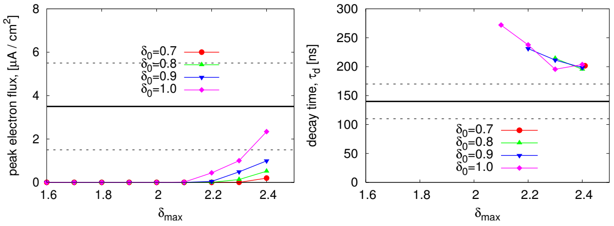

Figure 6: Peak electron flux (left) and time decays (right) calculated using ECLOUD simulations as a function of $\delta_{\max}$, and for different δ_0.

The experimental peak electron fluxes are only reproduced by ECLOUD if $\delta_{\max} > 2.3$ and $\delta_0 > 0.9$. The decay times calculated using the ECLOUD code are larger than the experimental results, but within twice the rms value found in Eq. 3. This is summarized in Table 2. This discrepancy is arguably related with the contribution of the "rediffused" electrons, which are not considered by this version of ECLOUD. This produces lower electron fluxes and, especially, lower electron cloud energies. Neglecting the self-electron cloud fields, the time decay for a monoenergetic electron jet with energy E such that $\delta(E) < 1$ is [1]

$$\tau_d = -\,2b/\ln\delta(E)\sqrt{2E/m_e}, \qquad (5)$$

where m_e is the electron mass and b is the beam pipe radius. It follows that lower energies and $\delta(E) \to 1$ produce large time decays.

Table 2: Combination of SEY parameters whose CSEC or ECLOUD output is compatible with observations in Fig. 2.

SEY at $E \to 0$, δ_0	maximum SEY, $\delta_{\max}$
CSEC	
0.5	2.2 – 2.5
0.6	1.9 – 2.3
0.7	1.5 – 1.9
ECLOUD	
0.9	2.4
1.0	2.3 – 2.4

SUMMARY

RHIC experimental data are benchmarked with different SEY parameterizations using CSEC and ECLOUD. Surface physics literature for unbaked stainless steel quotes $\delta_{\max} \sim 2.1$ [4, 6] and do not measure δ_0, but an extrapolation to 0.5 is performed in [4]. CSEC optimally reproduces the RHIC observations if $\delta_0 \sim 0.55$, and $\delta_{\max} \sim 2.1$. ECLOUD simulations reproduce the experimental results if $\delta_0 > 0.9$ and $\delta_{\max} > 2.3$, but its decay times remain larger by twice the experimental rms error. Although $\delta_{\max}$ is in the upper limit of the range in [4, 6], ECLOUD better matches the measurements for $\delta_0 \to 1$, shown in [5]. Results indicate that the influence of rediffused electrons in the modeling (neglected by ECLOUD) could be important to better fit RHIC electron cloud measurements.

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