ELECTRON CLOUD PARAMETERIZATION STUDIES IN THE LHC

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Abstract

During LHC beam commissioning with 150, 75 and 50-ns bunch spacing, important electron-cloud effects, like pressure rise, cryogenic heat load, beam instabilities or emittance growth, were observed. The main strategy to combat the LHC electron cloud, defined about ten years ago, relies on the surface conditioning arising from the chamber-surface bombardment with cloud electrons. In a standard model, the conditioning state of the beam-pipe surface is characterized by three parameters: 1. most importantly, the secondary emission yield δ_{max}; 2. the incident electron energy at which the yield is maximum, ε_{max}; and 3. the probability of elastic reflection of low-energy primary electrons hitting the chamber wall, R. Since at the LHC no in-situ secondary-yield measurements are available, we compare the relative local pressure-rise measurements taken for different beam configurations against simulations in which surface parameters are scanned. This benchmarking of measurements and simulations is used to infer the secondary-emission properties of the beam-pipe at different locations around the ring and at various stages of the surface conditioning. In this paper we present the methodology and first results from applying the technique to the LHC.

INTRODUCTION

Since almost 15 years photoemission and secondary emission had been predicted to build up an electron cloud inside the LHC beam pipe [1], similar to the "Ohmi effect" in positron storage rings [2, 3]. The possibility of "beam-induced multipacting" at the LHC had been recognized even earlier [4]. The electron cloud, at sufficiently high density, can cause both single and coupled-bunch instabilities of the proton beam [1, 5], give rise to incoherent beam losses or emittance growth [6], heat the vacuum chamber, or lead to a vacuum pressure increase by several orders of magnitude due to electron stimulated desorption [7]. From 1999 onward electron-cloud effects have been seen with LHC-type beams first in the SPS, then in the PS, and finally, since 2010, as expected, in the LHC itself. During the LHC beam commissioning with 150, 75 and 50-ns bunch spacing in the fall of 2010, important electron-cloud effects, such as pressure rise, cryogenic heat load, beam instabilities, beam loss and emittance growth, were observed [8, 9]. In response to these observations a series of machine study sessions has been scheduled to investigate, and combat, the electron-cloud build up in the LHC. The LHC mitigation strategy against electron cloud includes a sawtooth pattern on the horizontally outer side of the so-called

beam screen inside the cold arcs, a shield mounted on top of the beam-screen pumping slots blocking the direct path of electrons onto the cold bore of the magnets, NEG coating for all the warm sections of the machine, installation of solenoid windings in field-free portions of the interaction region, and, last not least, beam scrubbing, i.e. the reduction of the secondary emission yield (SEY) with increasing electron dose hitting the surface, i.e. as a result of the electron cloud itself. Beam scrubbing is the ultimate solution to mitigate the electron cloud effects of the LHC, and considered necessary to achieve nominal LHC performance [10].

In the absence of dedicated in-situ measurements for the LHC electron cloud density and the LHC vacuum-chamber surface properties, we are developing a method to determine the actual surface properties of the vacuum chamber related to secondary emission and to the electron-cloud build up (δ_{max}, ε_{max} and R [11]; see Fig. 1), and their evolution in time, based on benchmarking computer simulations of the electron flux on the chamber surface using the ECLOUD code against pressure measurements for different beam characteristics (e.g. for varying spacing between bunch trains). The new method will allow monitoring the effectiveness of LHC "scrubbing runs" and provide snapshots of the surface conditions around the LHC ring.
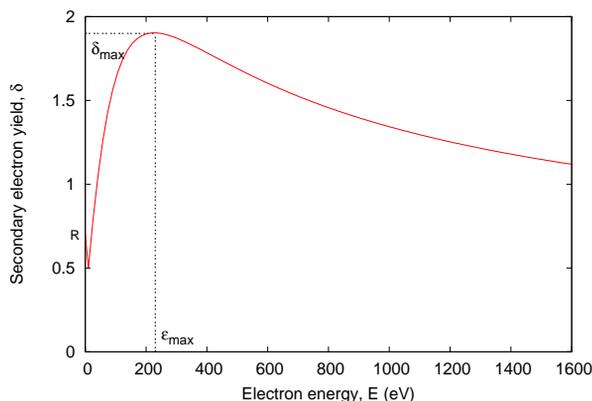

Figure 1: Secondary emission yield as a function or primary electron energy, defining the parameters δ_{max}, ε_{max} and R.

METHODOLOGY

At injection energy (450 GeV), the pressure inside the vacuum beam pipe has a strong impact on the speed of the electron-cloud build up, since the initial electrons are produced by gas ionization. However, if there is noticeable multipacting the rate of primary electrons does not affect significantly the final value of the saturated electron density, which is then determined by secondary emission

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(multipacting) and by the space-charge field of the electron cloud itself. In such case larger vacuum pressures just make the electron density reach its equilibrium value faster. This is due to the fact that the energy spectrum of electrons hitting the wall is insensitive to the pressure [12].

Nevertheless, in order to infer the best estimates of the beam-pipe characteristics, the steady-state vacuum pressure of the machine at each stage of the experiment has to be introduced as an input parameter in the simulations in order to correctly take into account the multiturn nature of the pressure evolution in a circular accelerator like the LHC. This is due to the fact that the time constant of the vacuum evolution is much longer than the revolution period, while the electron-cloud build-up simulations typically model only a fraction of a turn. This steady-state pressure is normally established some minutes after injecting the last bunch train for a given configuration.

Assuming that the pressure increase is proportional to the electron flux hitting the chamber wall, pressure measurements for different bunch train configurations (e.g. with changing spacing between trains or with a varying number of trains injected into the machine) can be benchmarked against simulations by comparing ratios of observed pressure increases and of simulated electron fluxes at the wall, respectively. The idea of the benchmarking using ratios goes back to an earlier study for the SPS (serving as LHC injector) where the electron-cloud flux could be measured directly [13]. In the LHC case, no electron-cloud monitor is available, but instead the measured increase in the vacuum pressure is taken to be a reliable indicator proportional to the electron flux on the wall.

We face a four-parameter problem. The steps followed in the benchmarking are the following: (1) We fix two of the parameters, namely the pressure (using the measured value) and ε_{max} (set to 230 eV, which seems to be a good first estimate according to past surface measurements and some previous simulation benchmarking). (2) We simulate the electron cloud build up for different bunch configurations using the ECLOUD code, scanning the other two parameters, δ_{max} and R, in steps of 0.1 and 0.05 respectively. Smaller steps introduce statistical noise which needs to be controlled by smoothing techniques. (3) For each bunch configuration we plot the simulated electron flux ϕ_i above a 2D grid spanned by δ_{max} and R; (4) We fit the flux simulated on the grid to a third order polynomial and then form the ratio of simulated fluxes (that is, dividing the polynomials) for two different bunch configurations [the fluxes and not their ratio are fitted in order to suppress the effect of statistical fluctuations]. (5) Comparing the latter ratio with the experimental ratio of measured pressure increases yields a curve in the δ_{max}-R plane (see Fig. 2). Different configurations yield different curves in that plane. (6) If the measurements contain sufficient information and the simulation model is reasonably accurate we expect to obtain a unique intersection between lines corresponding to different bunch configurations. This crossing point then defines the solution for δ_{max} and R.
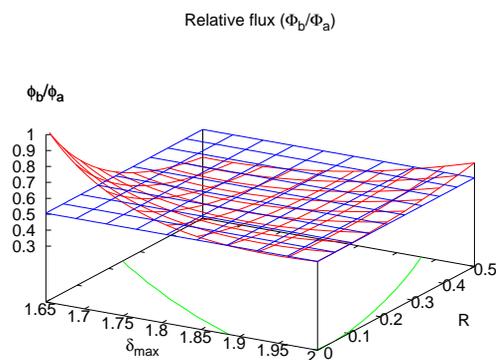
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Figure 2: Example of a 3D surface of simulated fluxes for the case ϕ_b/ϕ_a (red) cut by a plane surface (blue) at the value equal to the ratio of the corresponding measured pressures ($P_b/P_a = 0.5$). The bottom plane shows the contour of the intersection between both surfaces (green).

RESULTS

Until now we have processed 3 sets of measurements obtained during the conditioning of the machine through beam scrubbing. All of these have been recorded at a beam energy of 450 GeV with 50 ns bunch spacing. In the benchmarking simulations the geometry of the vacuum chamber is taken to be round (with 40 mm diameter), as in the modules hosting the pressure gauges. We only present results for one ionization gauge. Results for other gauges look similar. We have used two kinds of beam configurations, with varying spacing between batches and varying number of batches, respectively. Table 1 lists the parameters for the three sets of measurements.

Table 1: Parameters used in the simulations for the different sets of measurements. The value 225 ns for the batch spacing in sets 2 and 3 refers to the space between two or three trains of 36 bunches injected simultaneously.

	Set 1	Set 2	Set 3
# of bunches per batch	36	72 (2x36)	108 (3x36)
# of batches	variable	variable	variable
batch spacing (ns)	variable	225, 4850	225, 925
bunch population ($\cdot 10^{11}$ ppb)	1.1	1.21	1.15

At the beginning of a scrubbing run in April 2011, two experiments were carried out (both corresponding to set 1 listed above). In the first we injected batches in pairs with varying batch spacing (6 μs, 4 μs and 2 μs). In the second we injected an increasing number of batches at a batch-to-batch distance of 2.125 μs (up to 5). Figure 3 depicts the results obtained for both experiments. We could conclude that the solution is around $\delta_{max} = 1.9$ and $R = 0.2$. We have to take into account that there are large uncertainties in the measured pressure values as well as in the estimated

bunch population. According to simulations, such uncertainties can lead to a mismatch between lines and prevent a single unique intersection, as illustrated by this example.
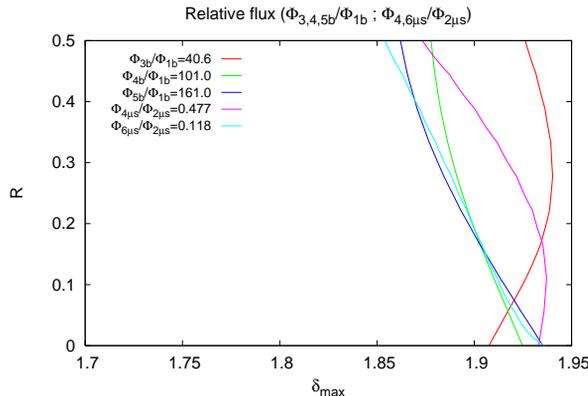

Figure 3: Combinations of δ_{max}-R values characterizing the chamber surface, obtained by benchmarking ratios of observed pressure increases against ratios of simulated electron fluxes, for measurements on 6 April 2011.

After a few days of surface conditioning, double batches of 36 bunches each separated by 225 ns were injected at a distance of 4.85 μs (up to 14). This corresponds to the set 2 of experimental data. A similar experiment (set 3) took place in mid May 2011 but using triple batches instead, again separated by 225 ns, at a distance of 925 ns (up tp 12). Figure 4 shows the results obtained in these cases. It is worth noting that for these last two cases we observe parallel lines instead of a clear cut between the lines. This is due to the loss of memory from the 225 ns gap between 36-bunch batches that appears when we inject the double (or triple) batches together. Indeed the lines should be the same in theory. The conclusion is that it is necessary to have two sets of measurements during the same experiment with different batch spacings in order to obtain lines of different slope which uniquely intersect. The intersection between sets of lines would yield the desired solution. A new measurement, with varying spacing, will be carried out as soon as dedicated machine time will again be allocated for electron cloud measurements.

Although we are not yet able to extract a unique value for δ_{max} and R, we can clearly see evidence for conditioning, as the later solution tends towards lower δ_{max} values. This fact instills some confidence in the method and supports its potential use as a tool for monitoring the surface conditioning through beam scrubbing.

CONCLUSIONS

A new method to monitor the LHC surface conditioning due to electron cloud by benchmarking simulations against experimental results is under development. The observable considered is the pressure increase resulting from the electron cloud, which is taken to be proportional to the electron flux impinging on the vacuum chamber walls. Benchmarking the ratios of experimental pressures and of simulated
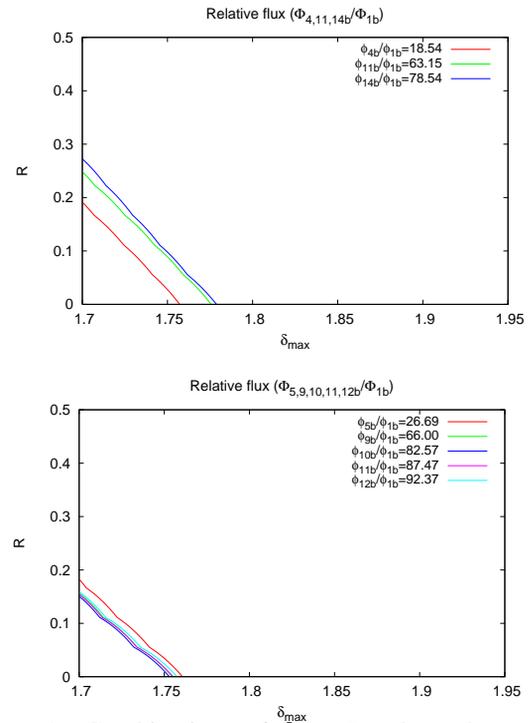

Figure 4: Combinations of δ_{max}-R values characterizing the chamber surface, obtained by benchmarking ratios of observed pressure increases against ratios of simulated electron fluxes, for measurements on 11 April (top) and 19 May 2011 (bottom).

electron fluxes for different beam configurations (e.g., for varying spacing between bunch trains or varying number of batches), we can pin down the value of the maximum secondary emission yield as well as the reflection probability for low-energy electrons. Doing this for each of the 3 measurement sets available so far provides clear evidence for surface conditioning, from an initial maximum secondary emission yield of about 1.9 down to about 1.7, with $R \approx 0.2$, as can be seen by comparing Figs. 3 and 4.

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