SIMULATION OF ELECTRON-CLOUD BUILD-UP FOR THE COLD ARCS OF THE LHC AND COMPARISON WITH MEASURED DATA

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Abstract

The electron cloud generated by synchrotron radiation or residual gas ionization is a concern for LHC operation and performance. We report the results of simulation studies which examine the electron cloud build-up, at injection energy, 3.5 TeV for various operation parameters In particular we determine the value of the secondary emission yield corresponding to the multipacting threshold, and investigate the electron density, and the heat load as a function of bunch intensity for dipoles and field-free regions. We also include a comparison between simulation results and measured heat-load data from the LHC scrubbing runs in 2011.

INTRODUCTION

The electron cloud in the LHC is generated by photoemission when synchrotron-radiation photons hit the surface of the beam pipe, by ionization of the residual gas and, especially, by secondary electrons emitted from the vacuum chamber walls. The electron-cloud effect reduces the beam luminosity and degrades the quality of the beam. During the second half of 2010, phenomena related to an electron cloud were observed for the first time in the LHC, during operation with a beam of 150 ns bunch spacing. Namely at this bunch spacing a pressure increase was detected in the common beam pipes of the experimental areas. Soon thereafter, with a shorter bunch spacing of 75 and 50 ns, a heat load induced by the electron cloud was measured in the cold parts of the LHC ring, where the beams pass through separate vacuum chambers.

SECONDARY ELECTRON YIELD

One of the most important parameters for the electron cloud build-up is the secondary emission yield (SEY). An electron cloud is produced if the SEY of the metallic surface is high enough for electron multiplication [1]. The SEY describes the average number of secondary electrons emitted per incident electron. It is a function of the energy of the primary incident electron. The SEY is often characterized by its maximum value as a function of primary electron energy, for perpendicular incidence, which is called δ_{Max}. The coefficient R designates the probability for an elastic electron reflection in the limit of zero primary energy ($0 < R < 1$).

ELECTRON-CLOUD HEAT LOAD

An electron-cloud related effect, which is expected to become relevant for future LHC performance at 25-ns bunch spacing, is the additional heat load on the beam screen inside the cold superconducting magnets due to the electrons, since this heat load, if sufficiently high, can provoke the quench of a superconducting magnet. The beam-screen heat load depends strongly on the energy, the bunch intensity, as well as the number and length of the circulating bunches [2]. An individual beam-screen cooling loop extends over 53 m (half an optical cell). Along this region there are dipoles, quadrupoles and short drifts sections. Due to some computing limitations, in this paper we report simulation results for dipoles and drift sections, i.e. we present average heat loads per unit length for a reduced half optical cell of 49.3 m length (that is, excluding the quadrupoles from the calculation).

SIMULATION METHODOLOGY

A first set of simulations, set A, was launched in order to determine the multipacting thresholds at injection and top energy for 50 ns bunch spacing. For this set we used the simulation parameters shown in Table 1. As basic filling pattern we considered a pair of 2 batches of 36 bunches each, with a batch spacing of 200 ns. This pattern was repeated up to 6 times, with a different, larger spacing between batch pairs. The reflectivity R was varied from 0.2 to 0.6. All the simulations were performed for a Gaussian bunch profile.

Table 1: Summary of Simulation Parameters for Set A

Parameter	450 GeV	3.5 TeV
Bunch intensity	1.2×10^{11} p/b	
SEY	1.6 – 2.4	
Primary photoelectron emission yield	---	0.0001233
Bunch length	11.8 cm	9 cm
$\sigma_x = \sigma_y$	1.2 mm	0.3 mm
Pressure	4.3×10^{-6} Pa	---

During the scrubbing run in 2011 at 50 ns bunch spacing some data were received from the cryogenic system about the heat load due to the electron cloud. This motivated a second set of simulations, set B at 3.5 TeV beam energy, with the same parameters as for the previous one, but with the scan of over the reflectivity *R* extended up to a value of 0.9. In addition, for this set, we changed the filling scheme from the previous one and we simulated the bunch filling pattern of LHC fill no. 1704 (13/4/2011 – 12:16 to 16:47) with the following filling scheme (for both beams): 228 bunches per beam with an average intensity of 1.22×10^{11} protons per bunch. We omitted the pilot bunches and the small intermediate 12-bunch batches, which are not expected to contribute to the electron build up, and we simulated the last 6 batches of 36 bunches of this scheme. Between a pair of batches there was a batch spacing of 200 ns and between pairs a spacing of 1.1 µs. The measured data are shown in Figure 1, which presents the total electron-cloud heat load per half cell. To obtain the heat load per beam and per meter the values shown have to be divided by about a factor of 100. Then, from Fig. 2, the peak heat load due to electron cloud is of order 40-50 mW/m/beam. The measurement resolution is estimated to be about 5-10 mW/m/beam.

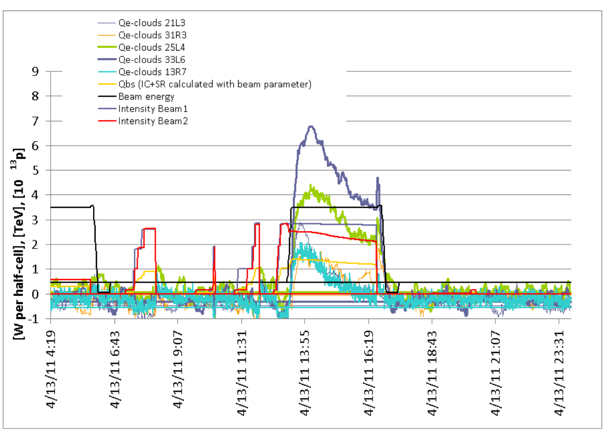

Figure 1: Measured heat load due to the electron cloud during the scrubbing process at 50 ns on April 13th, 2011.

Table 2: Summary of Simulation Parameters for Set C

Parameter	**Energy: 3.5 TeV**
Bunch intensity	1.15×10^{11} p/b
SEY	1.0 – 3.0
Primary photoelectron emission yield	0.0001233
Reflectivity	0.0, 0.25, 0.5, 0.75, 1.0
Bunch length	9 cm
$\sigma_x = \sigma_y$	0.3 mm
Bunch spacing	25 ns, 50 ns, and 75 ns

The third simulations, set C, were a study of the multipacting thresholds as a function of the reflectivity *R* and the bunch spacing. In Table 2, we list the parameters used for these calculations. The filling patterns for each bunch spacing are illustrated in Figure 2.

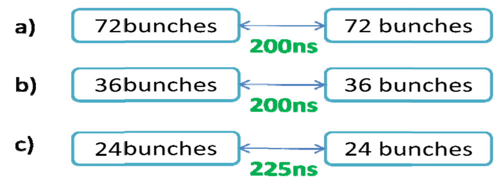

Figure 2: Filling patterns used in simulations for a bunch spacing of a) 25 ns, b) 50 ns and c) 75 ns.

Finally, the last simulations, set D, were a bunch intensity scan for different secondary emission yields at 25 ns bunch spacing and 7 TeV. We considered a LHC nominal filling pattern (2 batches of 72 bunches each one, with a 200 ns batch gap). The intensity was varied from 2×10^{10} until 2×10^{11} and we considered only a dipole section.

RESULTS

Table 3 shows the multipacting thresholds found from the simulations of set A and B. We notice that there is not a very big difference in the thresholds between the 450-GeV injection energy and 3.5 TeV beam energy, except for a slightly earlier start of multipacting for the higher energy.

Figure 3 presents the heat load obtained for simulation set A (averaged over first two batches). We again remark that the difference between the two beam energies is not dramatic.

Table 3: Summary of Multipacting Thresholds for a Dipole Section of Sets A and B

Energy	**Reflectivity**	**SEY**
450 GeV	0.2	2.5
	0.3	2.4
	0.4	2.3
	0.5	2.2
	0.6	2.1
3500 GeV	0.2	2.4
	0.3	2.3
	0.4	2.2
	0.5	2.1
	0.6	2.0
	0.7	1.9
	0.8	1.8
	0.9	1.7

We observe a nice correlation between the reflectivity and the multipacting thresholds, i.e., if we increase the reflectivity by 0.1 the SEY thresholds decrease by the same amounts, i.e. by 0.1. Figure 4 shows a contour plot of the heat load for simulation set B (averaged over all 6 batches). We can infer that to get a heat load of 50 mW/m/beam below *R*~0.35 a maximum secondary emission yield δ_{max} above 2.4 is needed. In Figure 5 we plot the multipacting thresholds for different bunch-spacing values as a function of the reflectivity. We can conclude that for the present 50-ns bunch spacing, multipacting no longer occurs if the maximum secondary emission yield δ_{max} decreases below about 2.2 (at a realistic value of R~0.25), while at 25-ns bunch spacing a δ_{max} value below 1.4 is required to stop multipacting.

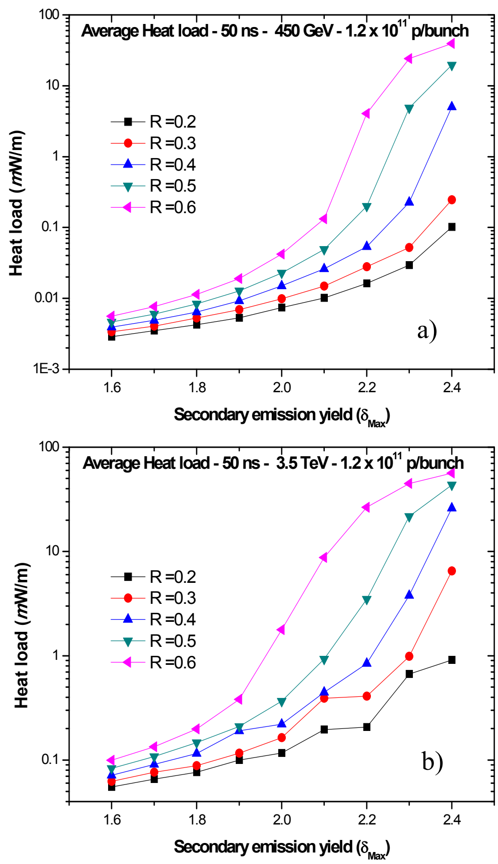

Figure 3: Simulated average arc heat load for 50 ns bunch spacing at a) injection energy and b) top energy.

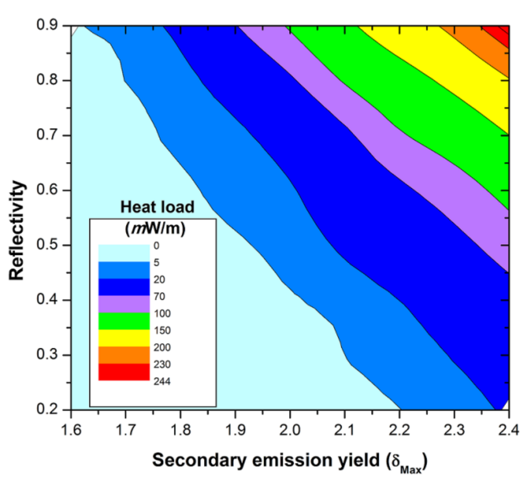

Figure 4: Heat load contour plot for 3.5 TeV beam energy.

In Figure 6 we can see the results of the set D. As we can notice there is an increment of the electron volume density, (the central density computed inside a transverse circle of radius 1 mm and averaged over the whole simulation time) and after a decrement for high bunch intensities, except for a δ_{max} =1.1, this latter seems to reach a saturation level after a bunch intensity of $8x10^{10}$.

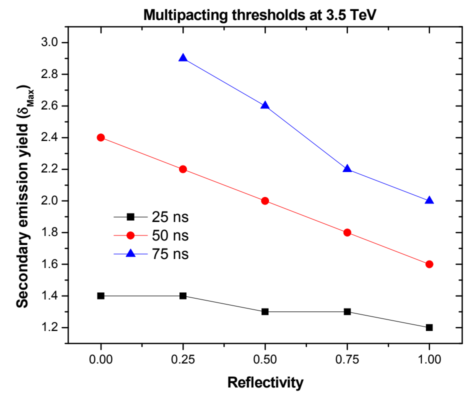

Figure 5: Simulated multipacting thresholds as a function of the electron reflectivity at 3.5 TeV beam energy for three different values of bunch spacing.

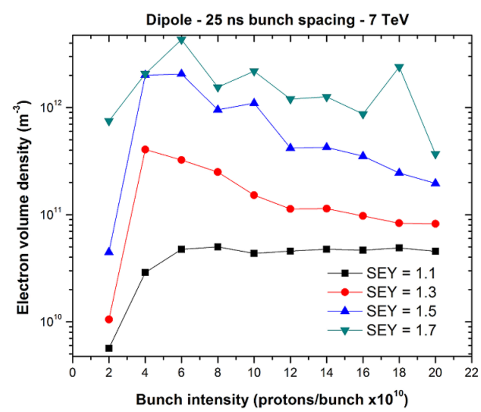

Figure 6: Average electron volume density for a dipole at 25 ns bunch spacing and 7 TeV.

CONCLUSIONS

Simulated multipacting thresholds, heat loads, and central electron densities were reported for the LHC, considering different bunch spacings, filling patterns, and beam energies, as well as a varying maximum secondary emission yield δ_{Max} and electron reflectivity *R*. The results can be used to deduce actual vacuum-chamber surface parameters, δ_{Max} and *R*, from observations, such as the onset of multipacting-induced vacuum degradation, heat loads in the cold arcs, and beam instability thresholds, and to make predictions for future LHC operation.

REFERENCES

[1] A. Kuzucan, "Secondary Electron Yield on Cryogenic Surfaces as a Function of Physisorbed Gases," CERN-THESIS-2011-057, Vienna, Tech. U., 2011.

[2] LHC Design Report, Vol. 1, Chapter 11, CERN-2004-003-V-1 (2004).