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COMPARISON OF ELECTRON CLOUD BUILD-UP SIMULATIONS AGAINST HEAT LOAD MEASUREMENTS FOR THE LHC ARCS WITH DIFFERENT BEAM CONFIGURATIONS

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Abstract

Electron cloud effects are among the main performance limitations for the operation of the Large Hadron Collider (LHC) with 25 ns bunch spacing. A large number of electrons impacting on the beam screens of the cold magnets induces significant heat load, reaching values close to the full cooling capacity available from the cryogenic system. Interestingly, it is observed that parts of the machine that are by design identical show very different heat loads. We used numerical simulations to investigate the possibility that these differences are induced by different surface properties, in particular maximum Secondary Electron Yield (SEY) for the different cryomagnets. Using the PyECLOUD code, the electron cloud build-up was simulated assuming different values of SEY in the LHC cold magnets. Comparing the measured heat loads to the simulation results for the 25 ns beams at 450 GeV we have identified the SEY values that match the observations in these conditions. These SEY values were found to be in good agreement with the heat loads measured with different beam configurations (changing the bunch pattern, the bunch intensity and the beam energy).

HEAT LOAD OBSERVATIONS

During Run 2 (2015-2018) the Large Hadron Collider (LHC) has been operated with the design bunch spacing of 25 ns. In these conditions, large heat loads are observed on the beam screens of its superconducting magnets [1, 2].

The heat loads measured in the eight cryogenic arcs of the machine during a typical luminosity fill with 25 ns beams are shown in Fig. 1. The heat loads are much larger than expected from impedance and synchrotron radiation (dashed line) and vary a lot from arc to arc. These differences are not expected as the eight arcs are by design identical. It is possible to identify two groups: a group of four consecutive high-load sectors (including S78, S81, S12, S23) and a group of four consecutive low-load sectors (including S34, S45, S56, S67).

The LHC arc is built of practically identical 53.4 m long half-FODO-cells, accommodating three main dipoles and one main quadruple. Large differences in heat load are observed also among half-cells within each sector. A small set of half-cells has been equipped with additional temperature sensors, which have allowed observing that differences are present also among magnets installed in the same half-cell.

The most characteristic features of the observed heat loads are the following [3]:

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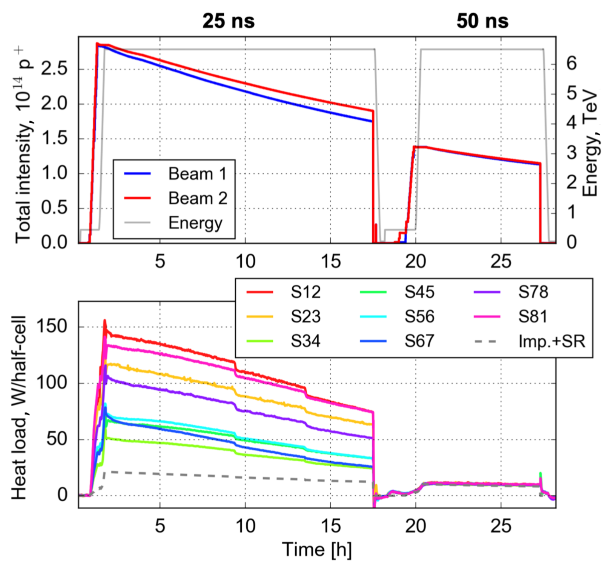

Figure 1: Heat loads (bottom) measured during a regular luminosity fill with 25 ns bunch spacing and during a subsequent test fill with 50 ns bunch spacing, both with 1.1×10^{11} p/bunch. Heat loads are per half-FODO-cell. The total intensity of the corresponding fill is shown on the top figure.

- The heat loads are significantly larger than impedance and synchrotron radiation estimates and differ significantly among the eight sectors. These differences are very pronounced during operation with the 25 ns bunch spacing but disappear when the 50 ns bunch spacing is employed (as shown in Fig. 1).
- Heat load measurements taken with 25 ns beams at different bunch populations show a threshold around 0.4×10^{11} p/bunch.
- For a fixed bunch population the heat loads are proportional to the number of circulating bunch trains.
- Large heat loads and differences among sectors are already present at injection energy (450 GeV) and increase only moderately during the energy ramp.

Based on these features and on the analysis of the heat load measurement technique, it is possible to exclude that the observed differences result from measurement artifacts [3].

Differences among sectors, half-cells and magnets are very reproducible and were observed in all 25 ns fills over the entire Run 2. Nevertheless, these differences were not

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observed during the LHC Run 1 (2010-2013), even when operating with beam configurations similar to Run 2 [4].

UNDERLYING MECHANISM

It is possible to show that the power deposited in the form of the heat load ultimately comes from the beam. To do so, the power lost by the beam can be inferred from RF stable phase measurements and it is found to be consistent with heat load measurements from the cryogenics [2].

Experimental observations, both from physics fills and from dedicated tests, provide important information on the source of the heat loads and, in particular, on the observed differences among sectors [3]:

- **Beam losses:** the hypothesis that the differences in heat loads are generated by protons lost on the beam screen, can be easily discarded since the total power associated to beam losses (calculated from beam intensity measurements) only amounts to less than 10% of the measured heat loads.
- **Synchrotron radiation:** the possibility that the observed heat loads are deposited by photons radiated by the beam can also be excluded. In fact, power from synchrotron radiation is proportional to the beam intensity and independent of the bunch spacing, which is inconsistent with the experimental observations.
- **Beam coupling impedance:** the hypothesis that the energy is transferred through electromagnetic coupling between the beam and the surrounding structures is incompatible with the observations as well. The measured dependence of the heat load on the bunch intensity is not quadratic and impedance heating cannot justify the large differences observed between 25 ns and 50 ns beams.
- **Electron cloud (e-cloud) effects**: the hypothesis that the energy deposition comes from e-cloud (electrons impacting on the beam pipe) is not in conflict with any of the mentioned observations. It can be further investigated by numerical simulations, as discussed in the following.

COMPARISON AGAINST E-CLOUD SIMULATIONS

In order to compare the measured heat loads against e-cloud simulations, we assume that the differences observed among sectors and among half-cells are caused by non-identical surface properties resulting in a different Secondary Electron Yield (SEY) parameter (defined as δ_{max} in [5]).

The e-cloud build-up process has been simulated using the PyECLOUD code [6] as a function of the SEY parameter for all the elements of the LHC arc half-cell. The simulation model is described in detail in [7]. The total simulated heat load as a function of the SEY is shown in Fig. 2 (left) for the two circulating 25 ns beams at 450 GeV built of trains of 48 bunches. Figure 2 (right) shows the corresponding measured heat loads in the eight arcs. By comparing the two graphs, the SEY parameter corresponding to the average heat load in each arc can be determined, as illustrated in Fig. 2 for the sectors having the largest and the lowest heat loads. Likewise, based on the heat loads measured at each half-cell, the SEY distribution within the sectors can be found as shown in Fig. 3.

The SEY model defined in this way can be cross-checked against independent measurements. Using the obtained SEY parameters, we simulate the expected heat load as a function of the bunch population for different beam configurations (changing the bunch pattern and the beam energy). Figure 4 shows the expected dependence of the heat load on the bunch population at 6.5 TeV for one of the arcs with the largest heat load (S81). The results for the operational bunch pattern (trains of 48 bunches) and for the *8b4e* scheme [8] (trains of eight bunches separated by gaps of four empty slots) are shown in different colors. The dashed curves are calculated assuming uniform SEY along the arcs, estimated as described above using data collected at 450 GeV. The continuous curves, instead, are calculated assuming for each half-cell the SEY shown in Fig. 3. Measured data for both

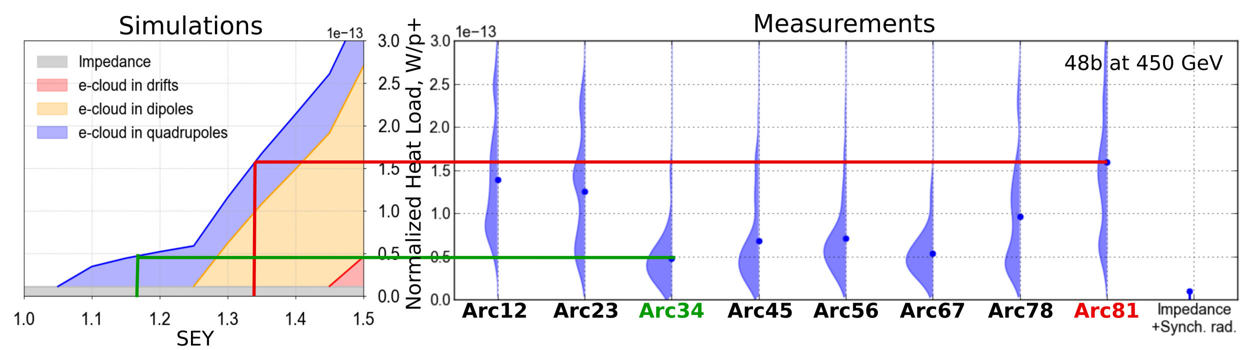

Figure 2: Left: simulated heat load per half-cell as a function of the SEY parameter for two circulating beams at 450 GeV (different contributions are shown in different colors). Right: Corresponding measured heat loads. The curves represent the distribution among half-cells within each arc, the dots represent the average for each arc. The expected load from impedance and synchrotron radiation is shown on the right.

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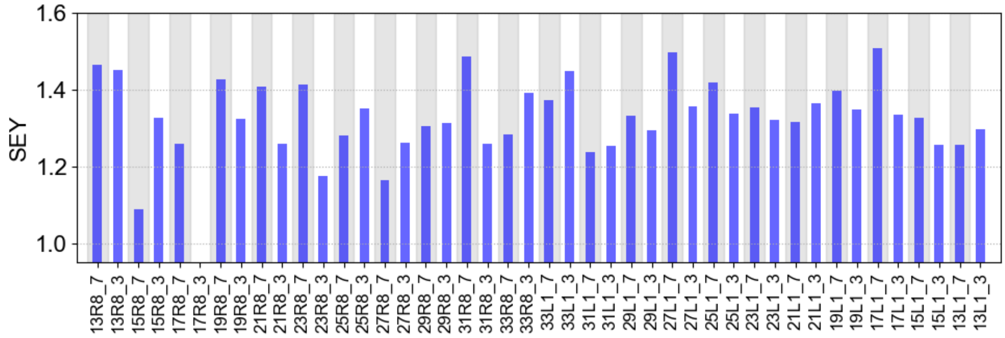

Figure 3: SEY parameter estimated for all cells in one of the sectors showing the highest heat load (S81).

beam configurations is shown by the markers in Fig. 4. The agreement between measurements and simulations is found to be very good, especially for the sectors showing the highest heat load [9].

The High-Luminosity LHC project [10] aims at increasing the circulating bunch population up to $2.3{\times}10^{11}$ p/bunch. The SEY models defined above predict a relatively mild increase of the heat load generated by e-cloud for bunch populations above 1.2×10^{11} p/bunch (see Fig. 4). Due to intensity limitations in the LHC injectors, direct experimental checks on the dependence of the heat loads on the bunch populations were possible only for up to 1.2×10^{11} p/bunch with long bunch trains. The results of these measurements are shown by the blue dots in Fig. 5. They are compared against the prediction from our SEY models, showing a very good agreement. Towards the end of 2018 it was possible to test higher bunch populations (up to 1.9×10^{11} p/bunch) using short trains of 12 bunches (12b) at injection energy. The

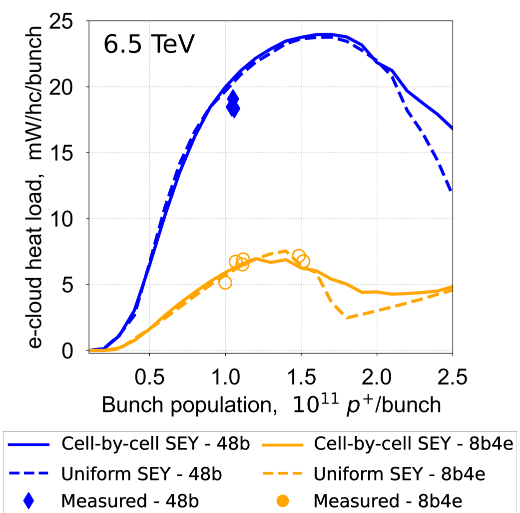

Figure 4: Heat loads per half-cell at 6.5 TeV as a function of the bunch intensity for one of the sectors showing the highest heat load (S81). Simulation results are represented by lines (continuous for the model assuming a different SEY in each half-cell, dashed for the simpler model assuming uniform SEY over the entire arc). Different filling patterns are shown in different colors.

collected data displayed in Fig. 5 clearly shows that the heat loads from e-cloud tend to saturate above 1.5×10^{11} p/bunch. Again a good agreement is found when comparing the measured heat loads with the 12b beam against our models.

In general, it is possible to conclude that, not only is e-cloud heating the only identified mechanism that cannot be excluded based on the available observations, but it also allows achieving a good quantitative agreement between measurements and models, when assuming that the root cause of the differences in heat load is a difference in SEY.

Efforts are ongoing to identify possible causes that could alter the surface SEY. A laboratory measurement campaign has been launched by the CERN vacuum and surfaces team [11]. The history of the beam-screen manufacturing, preparation, installation and operation is also being analyzed in detail searching for possible causes of degradation, but no correlation has been found so far.

During the LHC Long Shutdown 2 (2019-2020) selected beam-screens from high-load and low-load half-cells will be extracted and analyzed in order to identify possible surface alterations.

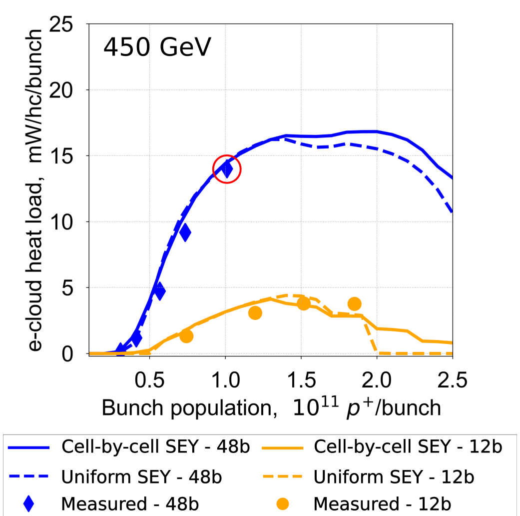

Figure 5: Heat loads at 450 GeV per half-cell as a function of the bunch intensity for one of the sectors showing the highest heat loads (S81). The data point used to infer the SEY is circled in red.

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REFERENCES

[1] G. Iadarola, B. Bradu, P. Dijkstal, L. Mether, and G. Rumolo, "Impact and Mitigation of Electron Cloud Effects in the Operation of the Large Hadron Collider", in *Proc. 8th Int. Particle Accelerator Conf. (IPAC'17)*, Copenhagen, Denmark, May 2017, pp. 2085–2088. doi:10.18429/JACoW-IPAC2017-TUPVA019

[2] G. Iadarola, G. Rumolo, P. Dijkstal, and L. Mether, "Analysis of the beam induced heat loads on the LHC arc beam screens during Run 2", CERN, Geneva, Switzerland, Rep. CERN-ACC-NOTE-2017-0066, Dec. 2017.

[3] G. Iadarola, "e-cloud and heat load in the LHC arcs", presented at the Accelerator and Beam Physics Forum, CERN, Geneva, Switzerland, Jul. 2018, unpublished. https://indico.cern.ch/event/740046/

[4] G. Iadarola, "Head loads in run 1 and run 2", presented at the LHC Machine Committee, CERN, Geneva, Switzerland, Sep. 2018, unpublished. https://indico.cern.ch/event/756722/

[5] R. Cimino *et al.*, "Can Low-Energy Electrons Affect High-Energy Physics Accelerators?", *Phys. Rev. Lett.*, vol. 93, p. 014801, 2004. doi:10.1103/PhysRevLett.93.014801

[6] G. Iadarola, E. Belli, K. S. B. Li, L. Mether, A. Romano, and G. Rumolo, "Evolution of Python Tools for the Simulation of Electron Cloud Effects", in *Proc. 8th Int. Particle Accelerator Conf. (IPAC'17)*, Copenhagen, Denmark, May 2017, pp. 3803–3806. doi:10.18429/JACoW-IPAC2017-THPAB043

[7] P. Dijkstal, G. Iadarola, L. Mether, and G. Rumolo, "Simulation studies on the electron cloud build-up in the elements of the LHC Arcs at 6.5 TeV", CERN, Geneva, Switzerland, Rep. CERN-ACC-NOTE-2017-0057, Oct. 2017.

[8] H. Bartosik, G. Rumolo, "Beams from the injectors", in *Proc. 7th Evian Workshop on LHC beam operation*, Evian-Les-Bains, France, Dec. 2016, p. 233–238.

[9] G. Skripka, "Scaling of ecloud effects with bunch population", presented at the 143th HiLumi WP2 Meeting, CERN, Geneva, Switzerland, Mar. 2019, unpublished. https://indico.cern.ch/event/800615/contributions/3327144/

[10] G. Apollinari *et al.*, "High-Luminosity Large Hadron Collider (HL-LHC): Technical Design Report V. 0.1", *CERN Yellow Reports: Monographs*, CERN, Geneva, Switzerland, Rep. CERN-2017-007-M, Apr. 2017.

[11] V. Petit, "Characterisation of beam screens extracted from LHC magnets", presented at the ECLOUD'18 workshop, La Biodola Bay, Isola d'Elba, Italy, Jun. 2018, unpublished. https://agenda.infn.it/event/13351