

HIGH-ACCURACY DIAGNOSTIC TOOL FOR ELECTRON CLOUD OBSERVATION IN THE LHC BASED ON SYNCHRONOUS PHASE MEASUREMENTS

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Abstract

Electron cloud effects such as heat load in the cryogenic system, pressure rise and beam instabilities are among the main limitations for the LHC operation with 25 ns spaced bunches. A new observation tool was developed to monitor the e-cloud activity and has been successfully used in the LHC during Run 1 (2010-2012). The power loss of each bunch due to the e-cloud can be estimated using very precise bunch-by-bunch measurement of the synchronous phase shift. In order to achieve the required accuracy, corrections for reflection in the cables and some systematic errors need to be applied followed by a post-processing of the measurements. Results clearly show the e-cloud build-up along the bunch trains and its evolution during each LHC fill as well as from fill to fill. Measurements during the 2012 LHC scrubbing run reveal a progressive reduction in the e-cloud activity and therefore a decrease in the secondary electron yield (SEY). The total beam power loss can be computed as a sum of the contributions from all bunches and compared with the heat load deposited in the cryogenic system. The plan to use this method in the LHC operation is also presented.

INTRODUCTION

At the beginning of the LHC Run 1, in 2011, e-cloud effects were limiting the LHC operation with beams with 50 ns bunch spacing, leading to an excessive heat load in the cryogenic system, a degradation of the vacuum, transverse instabilities, emittance growth, and particle losses [1–3]. Scrubbing with beam was proven to be effective for reducing the SEY below the e-cloud build-up threshold for 50 ns beams, although requiring a long time.

The e-cloud is currently considered to be the main limitation for operation of the LHC with beams having 25 ns bunch spacing and the deterioration of the beam quality can also cause a reduction of the luminosity delivered to the experiments. Future LHC operation relies on efficient scrubbing of the beam pipe surface to further reduce its SEY and observation tools are required for optimization of the scrubbing time [4].

In this paper we present a new method for e-cloud observation that uses synchronous phase measurements. The main advantage in respect to the available observations is that it shows the bunch-by-bunch structure of the e-cloud build-up in real time and with sufficient accuracy. A diagnostics tool based on this method will be available soon in

the LHC control room and will provide useful information for optimization of the scrubbing process. In addition, the SEY can be also estimated by comparing the synchronous phase measurements with particle simulations [5].

SYNCHRONOUS PHASE SHIFT

The e-cloud causes an energy loss of the proton beam since the electrons are accelerated by its electric field. The bunch energy loss per turn U depends on the e-cloud density and therefore the e-cloud build-up can be observed as an increasing bunch-by-bunch energy loss along the bunch trains. This energy loss is compensated by the RF system and is connected to a synchronous phase shift, $\Delta\varphi_s$:

$$U = N e V \sin(\varphi_s + \Delta\varphi_s), \quad (1)$$

where N is the bunch intensity, V is the RF voltage, and φ_s is the synchronous phase. Above transition ($\varphi_s = \pi$), a negative phase shift indicates an energy loss.

The synchronous phase was measured using the beam Phase Module (PM) from the LHC Low-level RF [6] as the phase shift between the beam and the vector sum of the voltage in the 8 RF cavities, as shown in the simplified scheme in Fig. 1. The effect of the beam loading is excluded by measuring the real voltage in the cavities with antennas.

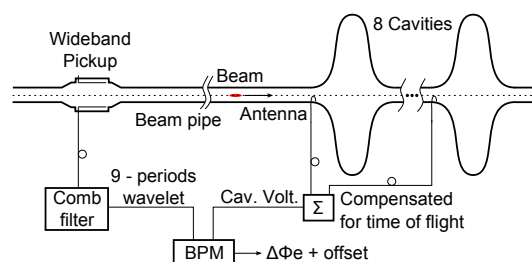


Figure 1: Simplified scheme of the RF phase shift measurement. A wavelet is generated from the wideband pick-up signal and in the beam Phase Module it is compared in phase with the vector sum of the voltages of the 8 RF cavities.

An example of the raw data obtained using the PM of Fig. 1 is presented in Fig. 2.

Bunch positions measured by the Beam Quality Monitor (BQM) [7] were also considered to extract the synchronous phase shift [8], but this method was finally rejected due to the lower accuracy and the fact that it also includes the phase shift from beam loading, which is comparable to that from the e-cloud effect (~ 1 deg).

In general, the synchronous phase shift is defined also by the contributions to the energy loss due to synchrotron

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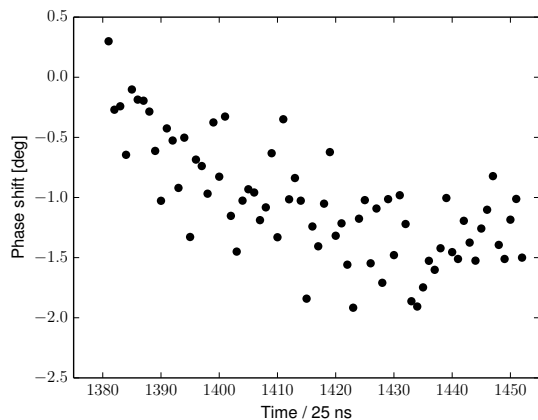


Figure 2: Raw data for the phase shift along a bunch train of 72 bunches averaged over 73 acquisitions. Measurements were taken at the beginning of the 2012 scrubbing run (25 ns spaced bunches).

radiation and resistive impedance. The former is the same for all bunches. The energy loss due to the resistive impedance depends on bunch length and distribution, but the energy loss difference from bunch to bunch is in general small compared to the one caused by e-cloud (less than 0.1 deg) [9]. These contributions to the bunch energy loss are taken into account by using as a phase reference the average phase of the first bunch train, which is shorter (12 bunches for beams with 25 ns spaced bunches) and has the Abort Gap in front (3 μ s without beam); thus, it is practically not affected by the e-cloud.

Despite the very high accuracy of the PM (around 1 deg at 400 MHz), the raw data is quite noisy (see Fig. 5) and an accuracy of ~ 0.1 deg is required. Two corrections were applied to the measurements to minimize systematic errors together with a post-processing which improves the precision and are presented below.

Measurement Corrections

Reflections in the cables affect subsequent bunch phase measurements after a bunch arrival. It is important to remove these perturbations. The transfer function of the cable, shown in Fig. 3, was measured with a single bunch and then applied for correction of the multi-bunch data.

Another correction is necessary to minimize a systematic error that is determined as the average value of the noise signal measured in the empty buckets (assuming white noise). The standard deviation of this noise can be used to estimate the remaining error of the phase shift measurements. For a bunch intensity of 1.1×10^{11} , the noise amplitude after corrections is $\sim 1/700$ of the bunch amplitude signal. In the worst case, which can happen when the angle between the noise and the bunch signal is 90 deg, it would lead to a phase error of ± 0.08 deg. The phase shift after these corrections can be observed in Fig. 5 (blue squares).

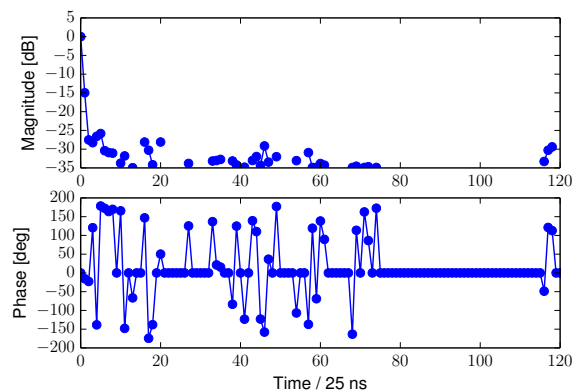


Figure 3: Transfer function of the cables were measured with a single bunch during 3 μ s. Note that the strongest reflection affects the following bunch. Reflections below 35 dB are neglected.

Data Post-Processing

Bunch amplitude and phase, phase shift, as well as cavity voltage amplitude V_{RF} are acquired for each bucket over the whole ring 73 times at an adjustable rate (memory limit of the PM), which is usually set to 5 turns (0.45 ms). A measurement therefore covers 33 ms, almost 2 synchrotron periods T_s at 450 GeV ($T_s = 18$ ms for $V_{RF} = 6$ MV).

First the variation of the phase in the 73 acquisitions for each bunch is checked. If it is smaller than ± 1 deg, we can assume that the bunch is not oscillating and the value of the phase shift can be calculated as the average of the 73 acquisitions. In this case, the maximum error would be $\pm 1 \text{ deg} / \sqrt{73} = \pm 0.12$ deg, which is acceptable compared to the typical phase shift due to e-cloud (in the order of 1 deg). If the variation of the bunch phase is larger than ± 1 deg, the phase shift is extracted from a sine-wave fit of the dipole synchrotron oscillations, as shown in Fig. 4.

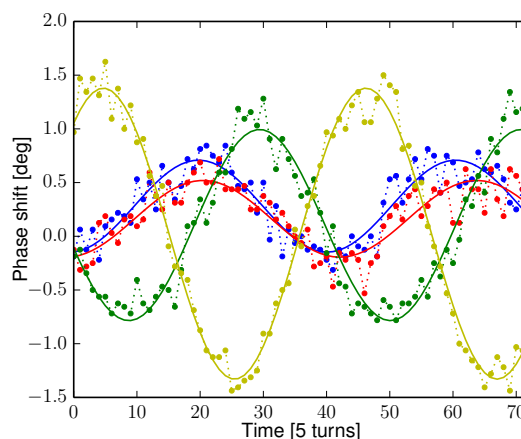


Figure 4: Sine-wave fit (solid lines) of the synchrotron oscillations for four different bunches (dots) used for extraction of its phase.

Then, as the synchronous phase is changing slowly compared to the time between measurements (usually ~ 10 – 15 s),

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the phase variation of each bunch is smoothed by applying a local linear regression with a moving window of 10 measurements. The resulting phase shift after corrections and post-processing is cleaner, as shown in Fig. 5 (red diamonds).

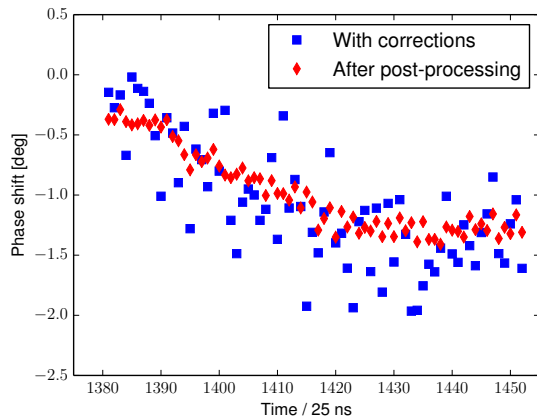


Figure 5: Phase shift along the bunch train after corrections for systematic errors (blue squares) and after post-processing (red diamonds), for the same measurements as in Fig. 2.

Experimental Results

The e-cloud build-up can be observed in Figs. 5 and 6 as a phase difference between the bunches at the beginning and at the end of the bunch trains for two fills during the 2012 scrubbing run with beams having 25 ns spaced bunches. The reduction of the SEY due to the scrubbing leads to a decrease of the phase shift variation along the bunch trains from about 1.2 deg at the beginning of the scrubbing run (Fig. 5) to 0.3 deg at the end (Fig. 6). Nevertheless, the e-cloud effect was still present for 25 ns beams after the scrubbing run in 2012.

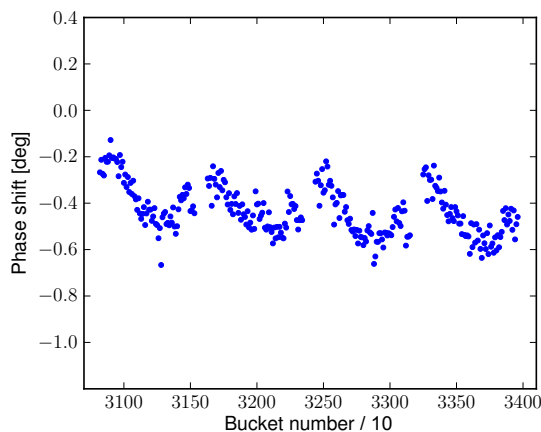


Figure 6: Bunch-by-bunch phase shift (corrected) immediately after the injection of four trains of 72 bunches. Measurements during a fill at the end of the 2012 scrubbing run with 25 ns beams.

A similar effect could be seen for beams with 50 ns spaced bunches in 2011 before the scrubbing run, but no e-cloud effect was observed for these beams after the surface condi-

tioning of 2011. In 2012, the phase variation along the bunch trains for 50 ns beams was smaller than the measurement resolution.

Another observation of the e-cloud build-up is shown in Fig. 7 as an increasing bunch-by-bunch power loss along the bunch trains. Note that the space between the first 72 bunches (green) and the next train (red) is long enough and the e-cloud can decay.

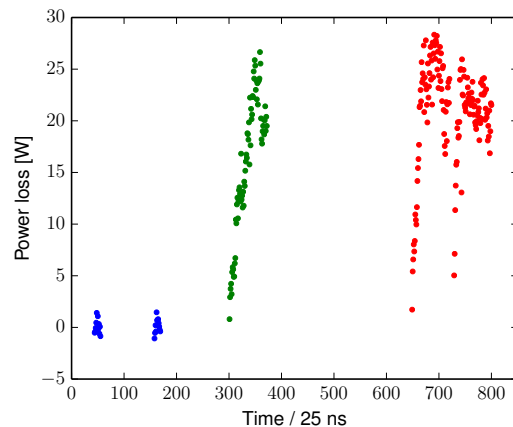


Figure 7: Bunch-by-bunch power loss for a fill with 25 ns beams before the 2012 scrubbing run. The first short bunch train (12 bunches, blue) is used as a reference for the phase.

The total beam power loss, found as the sum over all bunches, allows the time evolution of the e-cloud density in the ring during the cycle to be seen. An example of the total beam power loss during a fill with beams with 25 ns spaced bunches is shown in Fig. 8 (black line). Note that the heat load (HL) increases after each bunch train injection and then during the acceleration.

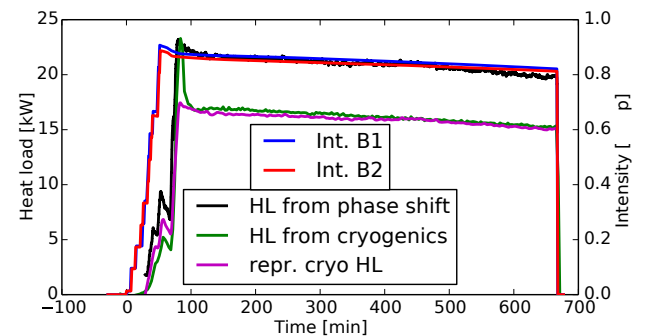


Figure 8: Total beam power loss found from the phase shift (black line) and the heat load measured by the cryogenic system (green line) [10, 11], for a fill with 25 ns beams accelerated to 4 TeV in December 2012. An estimation to the cryogenic heat load (magenta line) was calculated from the phase shift measurements as described in the text (scale factor 0.76 to fit the part at 4 TeV).

The maximum of the average power loss per particle gives some idea of the maximum e-cloud activity during one fill. A comparison of different fills during the 2012 scrubbing

run is shown in Fig. 9 and the decrease of this parameter is a clear indicator of the SEY reduction (scrubbing).

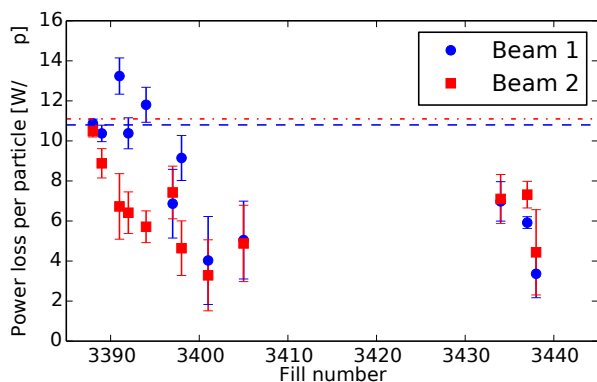


Figure 9: Evolution of the maximum power loss per particle at 450 GeV during the scrubbing run (25 ns beams) in 2012 for Beam 1 (blue circles) and for Beam 2 (red squares). The dashed lines represent the scrubbing level achieved in 2011 for both beams. Error-bars are calculated from the noise of the bunch-by-bunch phase measurements.

COMPARISON WITH OTHER OBSERVATIONS

Cryogenic Heat Load Measurements

The energy lost by the beam due to electron cloud is transferred to the electrons and it is finally deposited in the beam screens, where it has to be absorbed by the cryogenic system. Therefore, the beam power loss calculated from the phase shift can be compared with the heat load measured by the cryogenic system [10, 11]. However, the cryogenic system sees the heat load only in the superconducting magnets in the arcs. As the cryostat is shared by the two beam chambers, the contributions of both beams are added. Additionally, the cryogenic system has a slow time response (~ 5 min) due to its large thermal inertia. Note also that the calculated heat load due to image currents and synchrotron radiation should be subtracted from the total heat load to obtain the effect of e-cloud.

The heat load measurement can be reproduced from the measured phase shift by applying a moving average filter with a window of 5 min to the beam power loss, similar to the cryogenic system, and then applying a scale factor. An example of the estimation of the cryogenic heat load from the phase shift for a fill at 450 GeV is shown in Fig. 8. The scale factor giving the best agreement with the cryogenic heat load measurements found for several fills is ~ 0.79 at 4 TeV and ~ 0.7 at 450 GeV. This means that the dependence of the heat load on beam energy is stronger in the arcs than in the straight sections.

Simulations

The bunch-by-bunch power loss due to e-cloud has been calculated [5] from simulations performed with the code PyECLoud. Figure 10 shows that the details of the e-cloud

build-up can be reproduced in a very good agreement with phase shift observations using in simulations the measured beam parameters as filling pattern, bunch lengths and intensities.

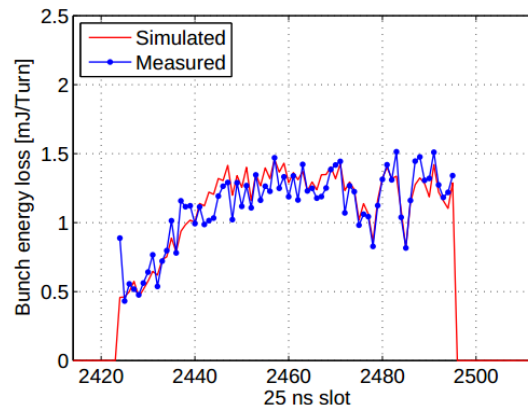


Figure 10: Bunch-by-bunch energy loss per turn calculated from synchronous phase shift measurements for a bunch train of 72 bunches spaced by 25 ns (blue circles) and comparison with simulations (red line) [5].

LHC OPERATION

A new diagnostic tool using the measured phase shift is planned to be implemented in the LHC control room for operational purposes. A practical application will be the monitoring of the e-cloud activity during the scrubbing run, with special importance for taking the decision on when to dump the beam and inject again (for time optimization). The decision would be based on the e-cloud activity seen in the bunch-by-bunch power loss.

Another possibility is to use this tool as a feedback signal for the cryogenic system. As it was mentioned above, the instantaneous heat load deposited in the cryogenic system can be seen much faster than the cryogenic heat load measurement so that necessary changes in the cryogenics can be anticipated. To improve the accuracy of the predictions, a calibration of the scale factor for the heat load estimation can be done regularly using the cryogenics measurement.

CONCLUSIONS

Bunch-by-bunch synchronous phase shift measurements have been proven to be a good diagnostic tool for the e-cloud effect. This novel method can be used to observe the e-cloud build-up along the bunch trains and to calculate the total beam power loss. Measurements of the heat load in the cryogenic system are well reproduced, although a scale factor that depends on the beam energy needs to be applied. Phase shift measurements have a very good agreement with simulations of the e-cloud build-up [5]. The use of this method in operation could ease the scrubbing run optimization and can be also used as an additional input for the cryogenic system feedback.

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