MEASUREMENTS OF THE LHC LONGITUDINAL RESISTIVE IMPEDANCE WITH BEAM

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Abstract

The resistive part of the longitudinal impedance contributes to the heat deposition on different elements in the LHC ring including the beam screens, where it has to be absorbed by the cryogenic system and can be a practical limitation for the maximum beam intensity. In this paper, we present the first measurements of the LHC longitudinal resistive impedance with beam, done through synchronous phase shift measurements during Machine Development sessions in 2012. Synchronous phase shift is measured for different bunch intensities and lengths using the high-precision LHC Beam Phase Module and then data are post-processed to further increase the accuracy. The dependence of the energy loss per particle on bunch length is then obtained and compared with the expected values found using the LHC impedance model.

MOTIVATION

The heat load in different elements in the LHC can be a practical limitation for the maximum beam intensity. In particular, the heat load in the injector kickers (MKIs) was excessive for the current nominal intensities and an increase in bunch lengths was required to reduce the heating. This circumstance motivated the study of the longitudinal impedance.

Additionally, very successful electron cloud observations through synchronous phase shift measurements were done in the LHC in 2011 [1]. In some cases, the electron cloud density was so high that it generated particle losses, resulting in a large distribution in bunch lengths and intensities. In that cases, the knowledge of the longitudinal impedance would be very useful in order to take its effect into account to improve the measurements.

ENERGY LOSS DUE TO RESISTIVE IMPEDANCE

The interaction of the beam with the longitudinal resistive impedance results in an energy loss per particle and per turn that can be written as:

$$U = -q^2\, N_b\, k_{\parallel}, \tag{1}$$

where q is the elementary charge, N_b is the bunch intensity, and $k_{\parallel}$ is the longitudinal loss factor, defined as:

$$k_{\parallel} = \frac{\omega_0}{\pi} \sum_{p=0}^{\infty} \Re\{Z_{\parallel}(p\,\omega_0)\}\, h(p\,\omega_0), \tag{2}$$

where ω_0 is the revolution frequency, $Z_{\parallel}(\omega)$ is the longitudinal impedance, and $h(\omega)$ is the power spectral density of the bunch [2].

The energy loss caused by the impedance is compensated by the RF system by a synchronous phase shift. To achieve this, in the absence of acceleration, the phase shift ϕ_s from the synchronous phase should be:

$$\sin\phi_s = \frac{U}{qV}, \tag{3}$$

where U is the energy loss per turn and per particle and V is the RF voltage amplitude.

From Eq. 1 and Eq. 2 it is apparent that the particle energy loss is directly proportional to the bunch intensity and it has also a dependence on bunch lengths through the power spectral density. Combining Eq. 1 and Eq. 3, and for small phase shifts ($\sin\phi_s \approx \phi_s$), we conclude that the synchronous phase shift is proportional to the bunch intensity. We will measure the dependence of synchronous phase on bunch intensity for different bunch lengths to determine the longitudinal resistive impedance of the LHC. This method has been applied successfully in many accelerators at CERN, for example in the SPS [3].

There are two other main sources of beam energy loss in the LHC, the synchrotron radiation and the interaction with an electron cloud, but they can be taken into account. The energy loss per particle by synchrotron radiation does not depend on the total intensity, but on the energy of the particle and its bending radius, resulting in a constant phase offset for any bunch. The electron cloud effect can be avoided by measuring a small number of bunches, as they are not affected by the electron cloud.

MEASUREMENTS

Method

The synchronous phase shift dependence on bunch intensity was measured for 8 bunches spaced by one ninth of the LHC circumference (9.9 μs). We chose 8 bunches as a compromise to calculate precisely the dependence and to neglect any interaction between bunches.

Bunch intensities were in the range $0.7 - 2.4 \times 10^{11}$ p, achieved by scraping in the SPS to preserve the longitudinal emittance and distribution, and therefore obtain uniform bunch lengths within the same fill.

Two MD sessions were devoted in 2012 to these measurements, the first one comprising three fills with different injected longitudinal emittances, and the second one in-

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ISBN 978-3-95450-118-2

cluding one long fill with small injected longitudinal emittances.

Measurements were done at injection energy (450 GeV) and with an RF voltage of 6 MV, acquiring continuously for a long time to have a natural longitudinal emittance growth. This provided us with data for a wide range of bunch lengths, covering all values that are used in operation.

Very accurate synchronous phase measurements are required due to the small energy loss resulting from the relatively low longitudinal resistive impedance of the LHC. The method is described below.

Synchronous Phase Measurement

A simplified schematic of the setup is shown in Fig. 1. To measure very precisely the synchronous phase and to separate the synchronous phase shift due to resistive impedance from beam loading effects, the Beam Phase Module (BPM) [4] from the LHC Low Level RF was used. This module measures the synchronous phase as the difference in phase between the beam and the vector sum of the voltage in the 8 cavities. This signal is called phase error and is used by the Phase Loop to damp coherent dipole mode synchrotron oscillations.

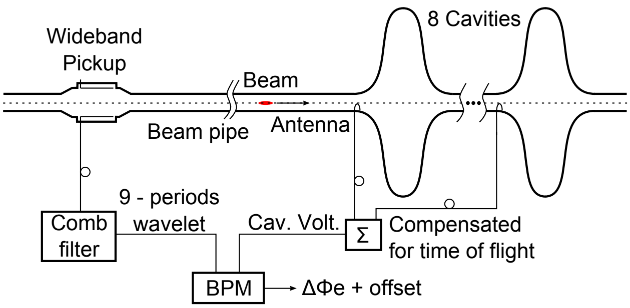


Figure 1: Simplified scheme of the phase error measurement. A wavelet is generated from the wideband pickup signal and is compared in phase with the vector sum of the 8 cavities voltages in the Beam Phase Module (BPM).

Bunch position measurements were also acquired from the Beam Quality Monitor (BQM) [5], but the precision is not enough for our requirements.

Data Analysis

Figure 2 shows three measurements of the dependence of phase shift on bunch intensity done for different bunch lengths. From Eq. 3 we determine that the slope of the fitted lines is proportional to the energy loss per turn and per particle, normalized to the bunch intensity. We will refer to it as *normalized energy loss*.

Only Beam 1 measurements are presented here because Beam 2 measurements are much more noisy.

Although the measurements are very accurate, the Beam Phase Module introduces a dependence on the bunch intensity which was corrected to further increase the accuracy. The reason is that the BPM calculates the bunch phase from the IQ components of the beam signal at 400 MHz, but there is an offset in the origin of the IQ plane. The IQ plane was reconstructed from the bunch magnitude and phase signals and the origin offset was measured from the noise in the empty buckets. The bunch phase was recalculated and used to correct the phase error, improving appreciably the accuracy. In Fig. 3 is shown the same measurements as in Fig. 2 after applying this correction.

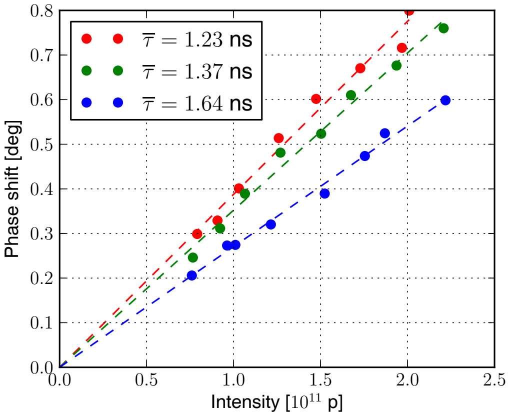


Figure 2: Example of phase shift with respect to bunch intensity measured for 3 different bunch lengths for Beam 1 and the linear fit applied to remove the phase offset.

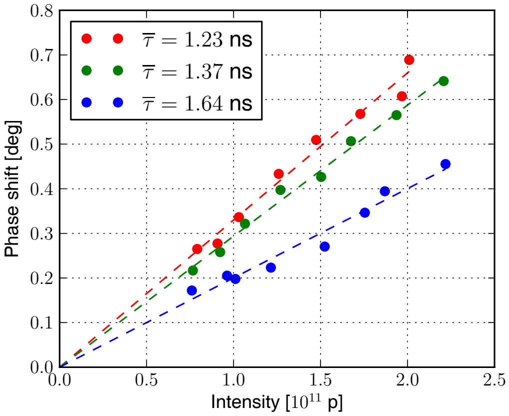
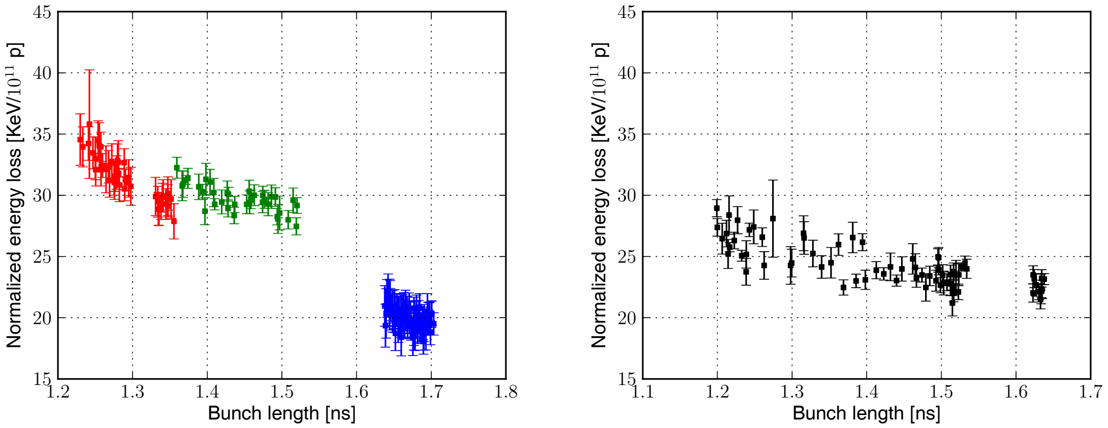


Figure 3: Example of phase shift with respect to bunch intensity measured for 3 different bunch lengths for Beam 1 and the linear fit applied to remove the phase offset after IQ-origin correction.

Then the phase offset coming from the energy loss due to synchrotron radiation and the systematic offset of the measurements is removed by extrapolating to zero intensity the phase shift with respect to the bunch intensity.

Bunch lengths are obtained from the BQM. They are calculated from the full width at half maximum (FWHM) of the bunch profile, scaled to Gaussian, and correspond to 4-σ bunch lengths.



(a) MD 1

(b) MD 2

Figure 4: Normalized energy loss with respect to bunch lengths for Beam 1. Each color corresponds to a fill with different injected longitudinal emittance.

Normalized Energy Loss vs Bunch Length

Figure 4 shows the dependence of the normalized energy loss on bunch lengths for Beam 1, measured during four dedicated LHC fills in 2012. The average bunch length of the 8 bunches has been considered. Measurements for different fills reach a good agreement and show that the energy loss is higher for shorter bunches. The small discrepancies between the fills are probably related to the difference in bunch distributions.

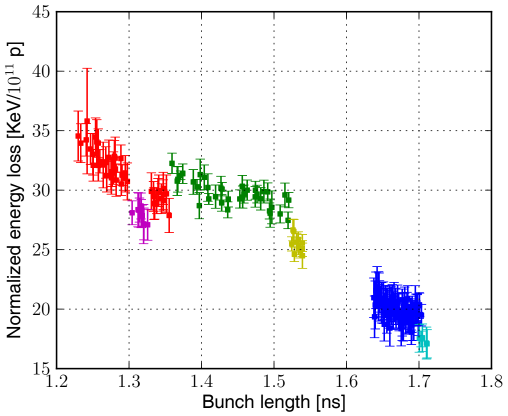


Figure 5: Normalized energy loss with respect to bunch lengths measured during 3 different fills for Beam 1. In red, green, and blue, with the TDI in. In magenta, yellow, and cyan, with the TDI retracted at the end of the same fills.

TDI Impedance

The LHC injection beam stopper (TDI) is a protection element that has two movable jaws which are inside the machine at injection energy and they are retracted before the acceleration. There are two TDI, one per beam, and they give a substantial contribution to the longitudinal resistive impedance.

Synchronous phase shift measurements were done during three LHC fills while moving the TDI jaws in and out to quantify the effect of the TDI jaws impedance. In Fig. 5 it can be seen that the TDI jaws are responsible of 5-10 % of the total energy loss.

Comparison with the LHC Impedance Model

The normalized energy loss due to the longitudinal resistive impedance was calculated using the LHC impedance model [6] for different bunch distributions. The comparison with the measurements is shown in Fig. 6.

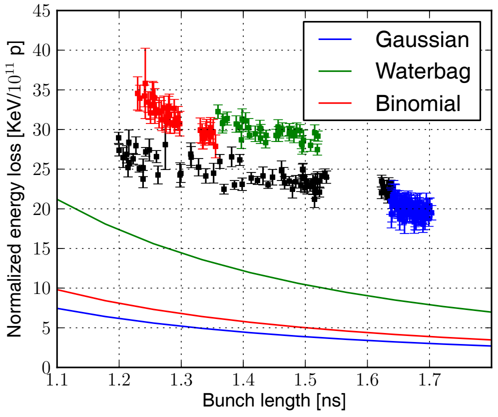


Figure 6: Normalized energy loss with respect to bunch lengths measured during 4 different fills for Beam 1. Solid lines are the normalized energy loss calculated from the LHC impedance model for three different bunch distributions.

The bunch distribution chosen for the calculation has a large impact on the result. However, measurements show an energy loss higher than the values predicted by the model even for the worst case. This discrepancy can be probably caused by two reasons:

- Some impedances in the model could be underestimated. For example, the model predicts that the TDI jaws impedance produce a 3% of the total energy loss instead of the 5 % to 10 % that we measured.
- Measurements could be exaggerated by an additional amplitude dependence of the Beam Phase Module. This is under investigation and will be verified in the near future.

CONCLUSIONS

The first attempt to measure the longitudinal resistive impedance of the LHC done in 2012 has been presented. This has required very precise synchronous phase measurements (in the order of 0.1 deg), an especially designed filling pattern, and a complex data post-process.

Single bunch energy loss in the LHC was estimated from synchronous phase shift as a function of bunch intensity.

Contribution of the TDI jaws to the total energy loss due to the longitudinal resistive impedance was determined.

Comparison with the LHC impedance model show discrepancies that are under investigation, including improvements on the measurements accuracy and on the impedance model.

ACKNOWLEDGMENT

We would like to thank the LHC and SPS operators for their kind assistance during all the measurements.

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ISBN 978-3-95450-118-2