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REFINING THE LHC LONGITUDINAL IMPEDANCE MODEL*

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Abstract

Modelling the longitudinal impedance for the Large Hadron Collider (LHC) has been a long-standing effort, especially in view of its High-Luminosity (HL) upgrade. The resulting impedance model is an essential input for beam dynamics studies. Increased beam intensities in the HL-LHC era will pose new challenges like RF power limitations, beam losses at injection and coupled-bunch instabilities throughout the acceleration cycle. Starting from the existing longitudinal impedance model, effort has been made to identify the main contributing devices and improve their modelling. Loss of Landau damping (LLD) simulations are performed to investigate the dependence of the stability threshold on the completeness of the impedance model and its broad-band cut-off frequency. Plans to perform beam measurements to estimate the cut-off frequency, by investigating the LLD threshold in operation, are also discussed.

INTRODUCTION

In the design phase of the Large Hadron Collider (LHC), first estimations for its impedance were performed [1] to ensure beam stability in the transverse and longitudinal planes. In the longitudinal plane, the main limitation is single-bunch loss of Landau damping. Coupled-bunch instabilities have not been observed so far [2, 3]. Following design changes of several devices, the impedance was re-evaluated and the final estimations were published in the the LHC Design Report [4]. After the construction phase of the LHC, the impedance model has been continuously updated with more accurate calculations and measurements of the numerous accelerator components [5, 6] while beam measurements were performed to verify the validity of the model [7, 8].

The present impedance model of the LHC is implemented using the *Python Wake and Impedance Toolbox (PyWIT)* [9] and the *Impedance Wake 2D (IW2D)* code [10]. This model is built considering the devices that have a high impact on the impedance in the transverse planes. As the beam intensities are being increased, especially in view of the High-Luminosity (HL) LHC, the longitudinal impedance can affect the stability of the beam. For instance, undamped injection oscillations have been observed to lead to losses for single bunches at injection [11]. Thus, a realistic longitudinal impedance model is crucial to study the dynamics of the beam in simulations.

An important parameter for all the broad-band (BB) contributions is the cut-off frequency. In the model, the cut-off frequency is chosen to be at 50 GHz, to stay conservative for instability predictions at high chromaticity in the transverse planes. In the longitudinal plane, this cut-off frequency led to artificial beam losses observed in tracking simulations at injection [12]. Beam-based measurements are proposed to estimate the effective cut-off frequency of the BB impedance in the longitudinal plane, through the loss of Landau damping (LLD) mechanism [13].

In this contribution, the present longitudinal impedance model will be briefly presented and some ongoing improvements will be discussed. First LLD simulation results will be shown comparing a constant BB impedance with the full impedance model. The proposed method to estimate the BB cut-off frequency with beam measurements of the LLD threshold will be introduced.

PREVIOUS AND REFINED IMPEDANCE MODEL

Since the conceptual design of the LHC, its impedance model has seen several iterations and refinements. It includes most of the relevant LHC devices, e.g., collimators, vacuum chambers, beam screens with their pumping holes, Y-chambers, experimental chambers, as well as RF cavities with their higher-order modes (HOMs), and the design BB impedance [4], containing the BB contributions from collimators, pumping slots, Y-chambers, BPMs, bellows, etc. The model was built prioritizing the elements with the largest impact on transverse beam stability.

Figure 1 shows the complete and the BB models of the longitudinal impedance, Z, divided by the harmonics of the revolution frequency, $n = f/f_{\mathrm{rev}}$, as a function of the frequency, f. In the longitudinal plane, the real part of the impedance produces energy losses, while the imaginary part can cause instabilities. Many HOM impedances that could potentially lead to coupled-bunch instabilities are observed in the range of about 1 GHz. For lower frequencies there is a resistive-wall behavior, while for higher frequencies a BB behavior is observed. The comparison with a BB resonator with $Q = 1$, $Z/n = 0.076\,\Omega$ and a cut-off frequency of f_c = 5 GHz shows very good agreement, as indicated in Fig. 1. This BB behavior has often been used as an approximation for analytical estimations and simulations [7].

The relevant beam spectrum in the LHC is about 1 GHz wide. The main impedance contributions in this frequency range for the present model, normalized to unity, are illustrated in Fig. 2a. The dominant device for this frequency appears to be the beam screen that contributes about 50 % of the total impedance. The design BB impedance and the

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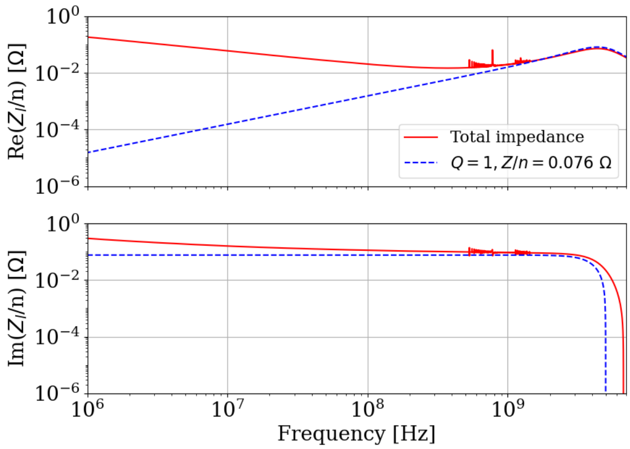

Figure 1: Comparison of the real (top) and imaginary (bottom) parts of the LHC longitudinal impedance at flat-bottom, in the BB resonator (blue) and present (red) models.

RF cavities are following with approximately 22 % and 18 % of the total impedance, respectively. Efforts are ongoing to refine the model of these three contributions, as discussed below.

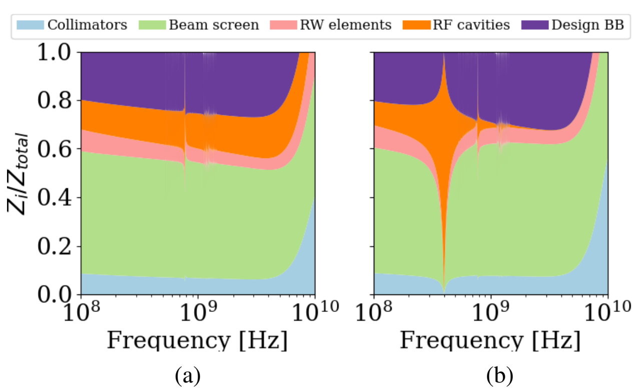

Figure 2: Normalized fraction of the main impedance contributions, as found in the present model (a) and the model with updated RF cavities (b).

RF Cavities

Contrary to the transverse planes, the impedance of the RF cavities is expected to play a significant role in the longitudinal plane, since it consists of narrow-band resonators in a frequency range of the beam spectrum. The dominant mode is the fundamental mode at the main RF frequency, which for proton operation is in the range of 400.8 MHz. In total, the impedance of the eight cavities per beam reaches the value of 7.2 MΩ, which is largely damped by the RF feedback (RFFB). The fundamental mode of the cavities with and without the RFFB is indicated in blue and red, respectively, in Fig. 3.

The impedance model of the LHC includes the HOMs of the cavities, but the fundamental mode with the RFFB is approximated by a BB impedance with $Q = 1$, $R_{\text{shunt}} = 6\,\text{k}\Omega$ and a cut-off frequency of $f_c = 5\,\text{GHz}$. This has been revised and replaced by the real contribution of the fundamental mode under the influence of the RFFB with the corresponding transfer functions. Figure 4 compares the previous model with the updated version, while Fig. 2b shows how the relative contributions over the total impedance are then modified.

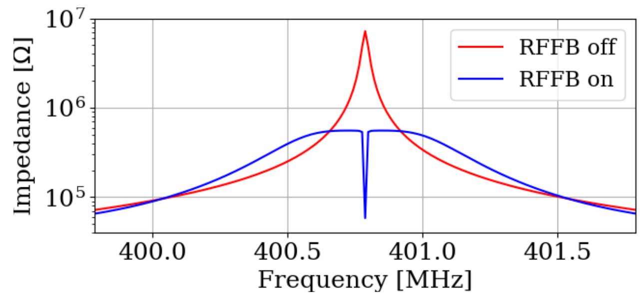

Figure 3: Fundamental mode of the eight RF cavities of the LHC with (blue) and without (red) RF feedback.

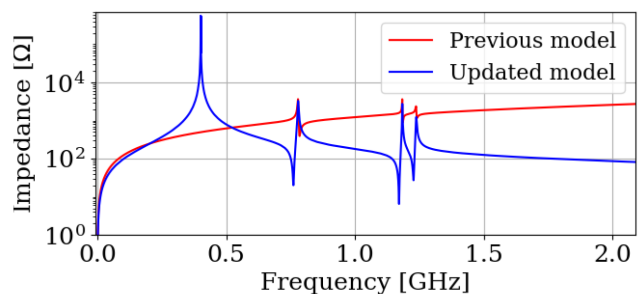

Figure 4: Comparison of the previous (red) and updated (blue) impedance models of the RF cavities.

Beam Screen

The beam screen impedance model is a combination of different contributions. It covers the resistive-wall impedance computed based on the beam screen geometry with the *IW2D* code and from the transverse electromagnetic modes [14]. It also includes the effects of the welding [15] and the pumping holes [16] on the impedance. The latter is known to overestimate the BB contribution, which in reality might be smaller. Wire measurements are in progress to verify the validity of the present model and characterize the behavior near the cut-off frequency.

LOSS OF LANDAU DAMPING

The mechanism of longitudinal LLD can be used to determine the BB component of the impedance. The intensity or emittance threshold gives information on the effective cut-off frequency, while the amplitude of the undamped phase oscillations determines the effective $\text{Im}(Z/n)$ [13].

Using the Beam Longitudinal Dynamics (BLonD) simulation suite [17], two intensity scans were performed at LHC flat-bottom, to estimate the LLD threshold for a BB impedance of $\text{Im}(Z/n) = 0.07\,\Omega$ and the cut-off frequencies of 4 GHz and 8 GHz. Single bunches with a binomial

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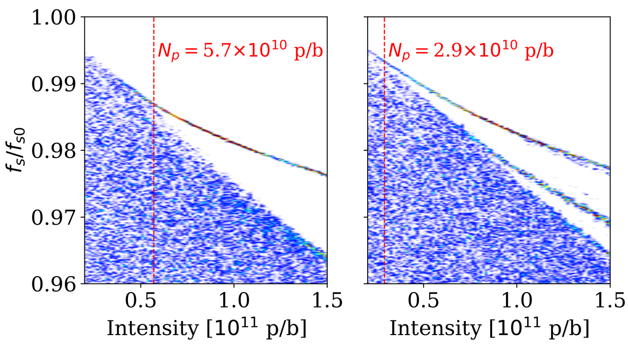
macro-particle distribution of exponent $\mu = 2$ and bunch length $\tau_{4\sigma} = 0.82$ ns[1] were used, while the voltage of the RF cavities was $V_0 = 6$ MV. The results are presented in Fig. 5, where the spectrum of the synchrotron frequency is shown as a function of the bunch intensity. The LLD takes place when the frequency of the coherent bunch oscillations moves outside of the incoherent frequency band, indicated by the red dashed lines in the plots. As observed, a higher cut-off frequency leads to a lower LLD threshold.



(a) (b)

Figure 5: Normalized mode frequency as a function of the beam intensity for BB impedance with $f_c = 4$ GHz (a) and $f_c = 8$ GHz (b). The LLD threshold in terms of beam intensity is indicated by the red dashed lines.

Furthermore, LLD has been probed in simulations by applying a 1° phase kick to a steady-state bunch, and observing the evolution of the resulting oscillation amplitudes to determine emittance as well as intensity thresholds. These simulations were performed with the same BB impedance as in Fig. 5 and with the full impedance model of the LHC using the updated contribution from the RF cavities. The cut-off was $f_c = 4$ GHz in all cases. In Fig. 6, the maximum amplitude of the bunch oscillations after 10^4 turns is shown for the BB impedance (blue) and the full impedance model (orange), as a function of intensity. Results are almost identical meaning that the BB impedance contributes most to the LLD. Thus, for the case of LLD studies, using a BB impedance model is a very good approximation.

MEASUREMENTS

A campaign of beam measurements at LHC flat-bottom is planned to study the LLD mechanism. Single bunches from the upstream SPS will be injected into the LHC, with intensities in the range of $(0.5 - 2.4) \times 10^{11}$ p/b and a bunch length in the range of $(0.8 - 1.5)$ ns. After the bunch reaches its steady state, the beam phase loop shall be opened and a phase kick applied to observe the resulting bunch oscillations and estimate the effective cut-off frequency as well as the imaginary part of the impedance.

In the PS and SPS, phase kicks were successfully applied with beam [18,19]. However, it was never done before for the LHC and a lot of machine time was invested to test and find

[1] In practice the FWHM bunch length is scaled to 4σ

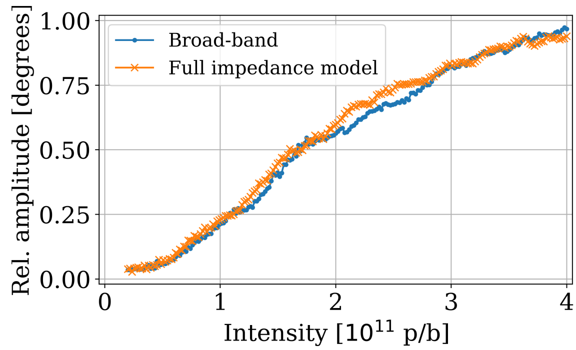


Figure 6: Maximum bunch oscillation amplitude after 10^4 turns for a BB impedance (blue) and the full LHC impedance model (orange).

the right technique. Applying a phase error at injection, with the beam phase loop open, was studied in the past. However, the drawback of this technique is that due to mismatch at injection, both dipole and quadrupole oscillations are present. The proposed technique that acts in just a few turns, is to add a phase offset in the synchronization loop, which offsets the phase reference for the entire beam. During this procedure, the beam phase loop of the RF cavities has to be momentarily opened. The blue line in Fig. 7 represents the impact that a 10° offset has on the phase of a single bunch.

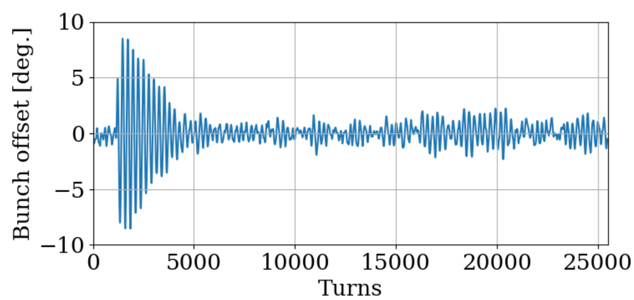


Figure 7: Mean phase offset of a bunch, under the effect of a 10° phase kick via the synchronization loop.

CONCLUSIONS

In this contribution, the importance of refining the longitudinal impedance model for the LHC era was addressed. The beam screen, the design BB impedance and the RF cavities were identified to be the main contributors in the longitudinal plane. A refined model of the fundamental mode of the RF cavities, including the transfer function of the RFFB is now included in the model. Simulations confirm that using a BB impedance model is a good approximation to describe the longitudinal LLD of a single-bunch. This mechanism can be employed in beam measurements to estimate the effective cut-off frequency and Im(Z/n). A measurement technique has been successfully demonstrated with beam in the LHC to study the LLD via phase kick.

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