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TRANSVERSE IMPEDANCE OF LHC COLLIMATORS

E. Métral, G. Arduini, R. Assmann, A. Boccardi, C. Bracco1), T. Bohl, F. Caspers, M. Gasior,
O. R. Jones, K. K. Kasinski, T. Kroyer, S. Redaelli, G. Robert-Demolaize, F. Roncarolo2),
G. Rumolo, B. Salvant1), R. Steinhagen, T. Weiler, F. Zimmermann

CERN, Geneva, Switzerland

Abstract

The transverse impedance in the LHC is expected to be dominated by the numerous collimators, most of which are made of Fibre-Reinforced-Carbon to withstand the impacts of high intensity proton beams in case of failures, and which will be moved very close to the beam, with full gaps of few millimetres, in order to protect surrounding super-conducting equipments. We present an estimate of the transverse resistive-wall impedance of the LHC collimators, the total impedance in the LHC at injection and top energy, the induced coupled-bunch growth rates and tune shifts, and finally the result of the comparison of the theoretical predictions with measurements performed in 2004 and 2006 on a prototype collimator installed in the SPS.

1) EPFL, Lausanne, Switzerland
2) UMAN, Manchester, United Kingdom

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CERN,
CH-1211 Geneva 23
Switzerland

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Abstract

The transverse impedance in the LHC is expected to be dominated by the numerous collimators, most of which are made of Fibre-Reinforced-Carbon to withstand the impacts of high intensity proton beams in case of failures, and which will be moved very close to the beam, with full gaps of few millimetres, in order to protect surrounding super-conducting equipments. We present an estimate of the transverse resistive-wall impedance of the LHC collimators, the total impedance in the LHC at injection and top energy, the induced coupled-bunch growth rates and tune shifts, and finally the result of the comparison of the theoretical predictions with measurements performed in 2004 and 2006 on a prototype collimator installed in the SPS.

INTRODUCTION

The storage and collision in the LHC of 7 TeV beams with each 360 MJ of stored energy requires a very powerful collimation system. For this purpose the first phase of LHC collimation will include 44 collimators per ring. The major LHC collimators consist of primary (TCP) and secondary (TCSG) collimators with robust CFC jaws for the interception of the primary and secondary beam halo respectively, tungsten based absorbers (TCLA) at the end of the cleaning insertions to protect the superconducting arcs, and tungsten based absorbers (TCT) for the protection and cleaning at the triplets in the experimental insertions [1].

Some of these devices will be moved into positions very close to the beam, with a full gap between the two jaws of 2b ≈ 2 mm. Remembering that the first unstable betatron line in the LHC is at 8 kHz, where the skin depth for graphite is 1.8 cm, which is smaller than the collimator thickness of 2.5 cm, one could think that the classical thick-wall formula (stating that the transverse impedance goes with b^{-3}) would apply. Fortunately this is not the case, and the resistive impedance is about two orders of magnitude lower at this frequency [2].

In the first section of this paper the estimated transverse impedances for the LHC at both injection and top energy (after the squeeze) are reviewed. The induced coupled-bunch instabilities and their stabilization are then discussed in Section 2. Finally the measurements performed in the SPS at 270 GeV/c to assess the validity of the theoretical predictions are reported in Section 3.

ESTIMATED LHC TRANSVERSE IMPEDANCE

Considering the most significant (known) contributors to the LHC impedance [3], it is found that the total LHC transverse impedance is strongly dominated by the collimators at both injection and top energy. The vertical impedances of the LHC at both injection and top energy are depicted in Fig. 1, using the resistive-wall impedance formula described in Ref. [2].

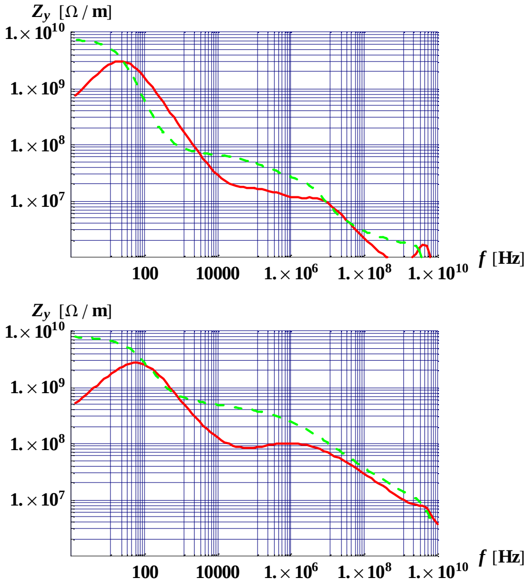

Figure 1: Vertical impedance at injection (top) and top energy after the squeeze (bottom). The full (red) line denotes the real part of the impedance, while the dashed (green) line is for the imaginary part.

STABILITY DIAGRAMS

The coherent tune shifts from the most unstable coupled-bunch mode and head-tail mode 0 for the nominal beam parameters (25 ns bunch spacing) at both injection and top energy are plotted with their corresponding stability diagram in Fig. 2. The stability diagram arising from the combined effect of the external nonlinearities and space charge at injection is plotted in Fig. 2(a) [4], whereas the stability diagram at top energy is assumed to come only from the Landau octupoles (see Fig. 2(b)) [5]. At injection the coupled-bunch instability has a rise-time of ~ 50 ms (= 564 turns) and cannot be damped by Landau damping, as can be seen from Fig. 2(a) where the coherent tune is far outside the stability diagram. The coupled-bunch instability at injection will be damped by a transverse feedback. At top energy with squeezed optics, the coupled-bunch instability has a rise-time of 185 ms (=2083 turns) and it is planned to be damped using only the Landau octupoles. As can be seen from Fig. 2(b), only about half of the nominal intensity can be stabilized by Landau damping.

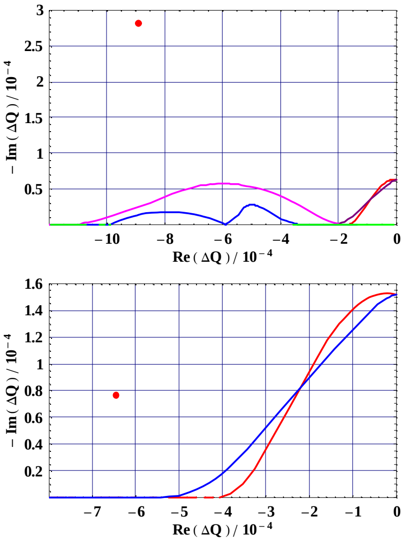

Figure 2: Stability limits [4,5] and (vertical) coherent tune shift for the LHC at (top) injection and (bottom) top energy after the squeeze. The horizontal and vertical axes give the real part and minus the imaginary part, respectively, of the coherent tune shift.

Possible ways to circumvent this stability issue is to increase the gap of the collimators and/or reduce the resistivity of the collimators, as shown in Figs. 3 and 4. In conclusion of the first analysis, the collimator gap shall be increased by ~ 50% to stabilise the nominal beam. The second analysis reveals that beam stability can be reached, but just at the limit and for a very small resistivity of the secondary collimators (10^{-10} Ωm).

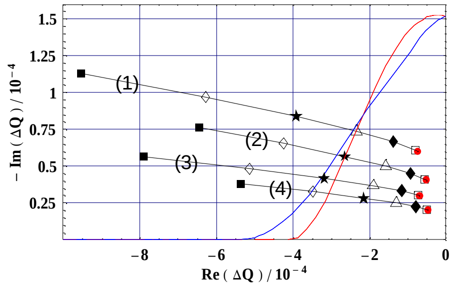

Figure 3: Stability limits: 25 ns spacing with ultimate bunch charge (1) and nominal bunch charge (2), 50 ns spacing with ultimate bunch charge (3), and nominal bunch charge (4). Nominal collimator gap (black squares), no collimators (red square), and intermediate situations where the collimator gap is increased by 20%, 50%, a factor 2, 3 and 10.

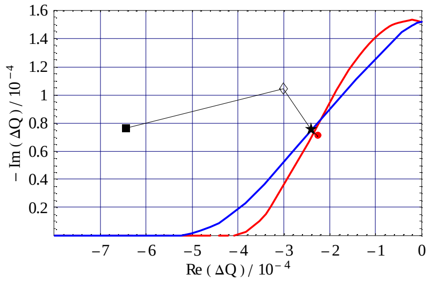

Figure 4: Stability limits: (Filled square) nominal secondary collimator resistivity (10^{-5} Ωm), (unfilled diamond) secondary collimator resistivity of 1.7 10^{-8} Ωm (copper), (filled star) secondary collimator resistivity of 10^{-10} Ωm, (red dot) without secondary collimators.

MEASUREMENTS

An LHC prototype collimator has been installed in the SPS in 2004 and was used to perform benchmarking experiments at 270 GeV/c. The first consisted in measuring the coherent tune shift vs. the gap of the collimator for two symmetric jaws and for only one jaw. With this measurement the imaginary part of the impedance can be assessed. The second consisted in measuring the coupled-bunch instability rise-time induced by the real part of the impedance.

Coherent tune shift vs. collimator gap

The first measurement has been performed in 2004 by moving the two jaws symmetrically. The results, compared to several theories, are shown in Fig. 5. It is shown first that the difference between the classical thick-wall formula and the low-frequency formula from Burov-Lebedev [6] is negligible and not measurable. Furthermore, the SPS measurements can be fully explained but by another mechanism, which is the nonlinearity of the wake field [7]. However, this effect is predicted to be small in the LHC where the primary collimators will be set at ~ 6 σ, as can be seen in Fig. 6. The measurements of the coherent tune shifts have been redone in 2006, confirming the previous results as can be seen in Fig. 7. Furthermore, the case of a single moving jaw has been studied and the results are reported in Fig. 8.

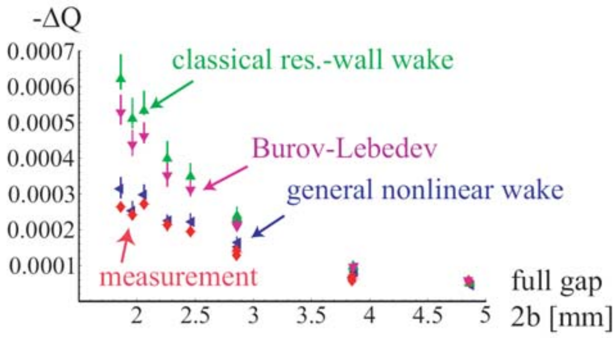

Figure 5: Measured coherent tune shift in the SPS in 2004 vs. collimator full gap, with two symmetrical jaws.

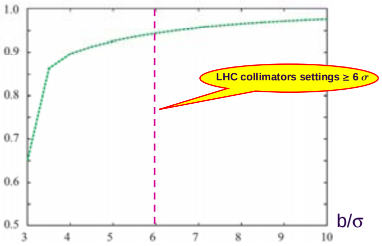

Figure 6: Correction factor to be applied to the coherent tune vs. ratio between the half gap of the collimator b and the transverse rms beam size σ.

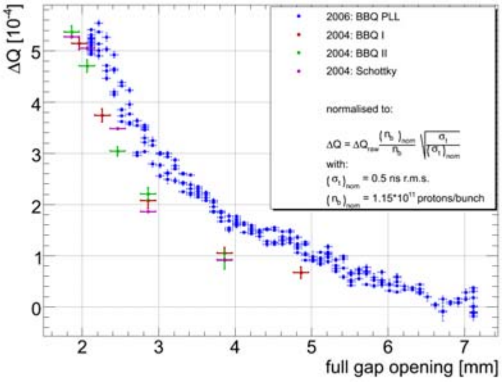

Figure 7: Measured coherent tune shift in the SPS in 2006 compared to 2004 vs. collimator full gap.

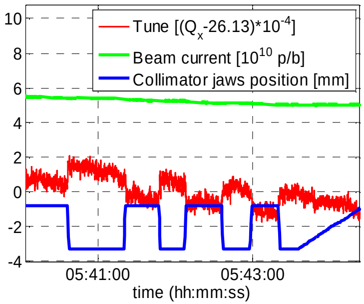

Figure 8: Measured coherent tune shift in the SPS in 2006 with only one jaw.

Instability rise-time vs. collimator gap

The second measurement campaign has been performed in 2006 with a batch of 72 bunches with nominal characteristics for LHC. The predicted coupled-bunch instability rise-times are summarised in Fig. 9, for the case of the resistive-wall impedance of the SPS alone (due to the resistive beam pipe) and for the case where the collimator impedance is added. It is seen that, with the collimator IN with a half gap of less than ~ 2 mm, a smaller rise-time (by few tens of % depending on the formula used) than without collimator should be measured. However, it would be difficult to disentangle between the classical Thick-Wall (TW) formula and the low-frequency (also called in the past inductive by-pass) formula. The measurements shown in Fig. 10 reveal a rise-time of ~ 35 ms (i.e. ~ 1500 SPS turns) for the collimator OUT and for a bunch intensity of ~ 10^{10} p/b, whereas a rise-time between ~ 12 and 32 ms was measured for the collimator IN and with halved bunch intensity. This is consistent with the predictions but not conclusive.

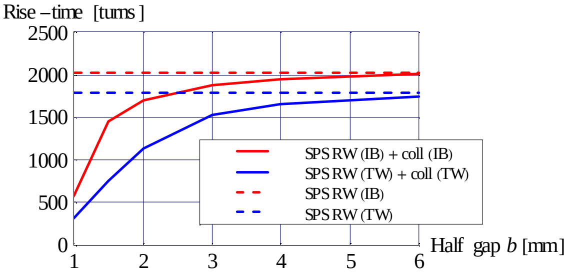

Figure 9: Predicted rise-times (in SPS turns) for 1 batch of 72 bunches (1.15×10^{11} p/b). IB stands for Inductive-Bypass (i.e. low-frequency regime), while TW stands for Thick-Wall formula.

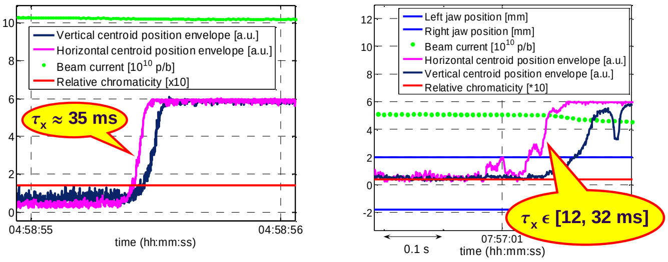

Figure 10: Measured coupled-bunch instability rise-times with collimators OUT (± 30 mm, left) and IN (± 2 mm, right).

CONCLUSION

A new physical regime for the resistive-wall impedance has been revealed by the LHC collimators [2]. However, even with this beneficial effect, the 44 ring collimators required for the phase 1 of LHC collimation dominate the total transverse impedance at both injection and top energy after the squeeze. Measurements performed so far on a LHC prototype in the SPS are in agreement with our theoretical predictions but are not a proof of the low-frequency regime (≤ ~ 1 MHz), which to our knowledge has neither been measured nor simulated. The induced coupled-bunch instability at injection will be damped by a transverse feedback, while at top energy, it is planned to be damped by Landau octupoles.

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