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ASSESSMENT OF THE REAL PART OF THE IMPEDANCE OF THE LHC COLLIMATORS WITH INSTABILITY GROWTH RATE MEASUREMENTS*

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Abstract

The impedance of the Large Hadron Collider (LHC) is a potential source of instabilities and has to be monitored closely. It is usually assessed by measuring the tune shift vs intensity, in particular at top energy, where it is the most critical as the collimators are closest to the beam. On the other hand, to get information on the real part of the impedance, growth rate measurements are required. These are difficult to perform at flat top because triggering the instability in a sharp and fast manner remains a challenge. Moreover, the length of the full cycle, including an energy ramp, prevents a frequent repetition of such measurements. Instead, measuring growth rates at injection is more natural and allows rapid cycling, with the downside that the impedance at injection is not dominated by collimators but rather by devices with fixed aperture. Here we present measurements at injection energy, placing the collimators in tighter positions than the nominal ones, in an attempt to obtain a similar configuration as the flat-top situation. The measurements are performed at several negative chromaticities to study the corresponding evolution of the growth rate of the rigid bunch mode instability. Results are finally compared to simulations.

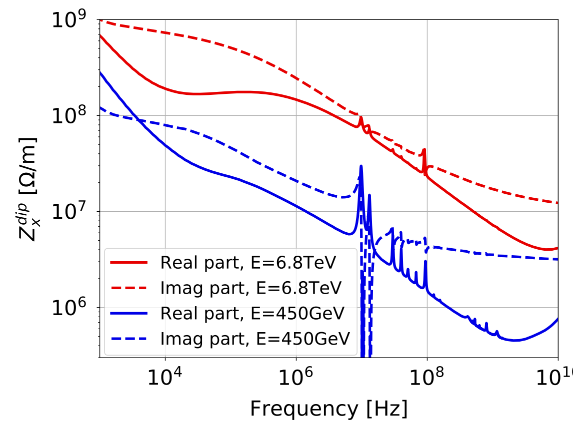

Figure 1: Comparison of the horizontal dipolar impedance of the LHC at injection and at top energy.

INTRODUCTION

Impedance-driven instabilities are one of the factors which may limit the intensity of the proton bunches in the LHC and its high-luminosity upgrade (HL-LHC). It is therefore of paramount importance to estimate and keep under control the machine impedance and its evolution throughout the years. According to the Sacherer formula [1], the growth rate of the transverse instabilities induced on the beam is proportional to the real part of the effective transverse impedance, i.e. a linear combination of the product between the impedance sampled at the betatron lines and the spectrum of the instability mode sampled at the same frequencies, but shifted by the chromatic frequency. Consequently, it is possible to validate the real part of the transverse impedance model by triggering a beam instability and measuring its growth rate.

As shown in Fig. 1, the LHC transverse impedance is an order of magnitude higher at top energy than at injection energy, hence impedance-related instabilities are more problematic at top energy. The main cause for the higher impedance at top energy is that the collimators are gradually moved closer to the beam while ramping the energy, to follow the beam size reduction. As a result, at top energy the collimators dominate the total transverse impedance of the machine, while at injection energy the contributions of other parts of the LHC, such as the beam screens and the warm pipe sections, are quite significant. Therefore, in order to keep the instabilities under control in future configurations of the machine (such as the HL-LHC one, featuring large intensities), it is of primary importance to monitor the machine impedance in the top-energy configuration.

On the other hand, it is difficult to trigger and measure instabilities in a safe and repeatable manner at top energy due to the long time it would take to inject and ramp a new bunch after each instability measurement. This difficulty can be overcome by carrying out the measurements at injection energy, but to get an impedance more similar to the top-energy configuration, the collimators must be set at tighter gaps than in nominal conditions. We tighten the primary collimators to 3σ half-gap[1], at the most, since further tightening could scrape the bunch transverse tails and induce losses, while the secondary collimator half-gaps (TCSGs and TCSPMs) are always 1σ larger than the primaries. Figure 2 shows the various contributions of the different machine elements to the total effective impedance with injection beam and machine parameters and a chromaticity value of -10. With tighter settings than nominal, the collimators dominate the other contributions of the LHC impedance and a situation close to the top-energy one can be created at injection energy.

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[1] All along the paper, 1σ corresponds by convention to the RMS transverse size of a bunch of normalized emittance 3.5 µm (c.f. Table 1); note that the typical emittance of a bunch in the LHC is significantly lower than that (~2 µm).

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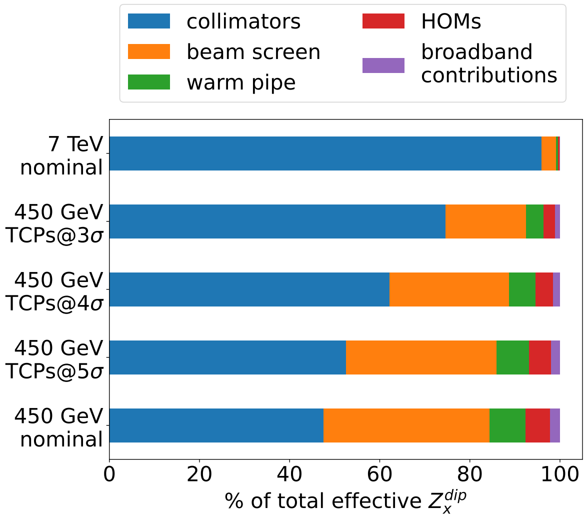

Figure 2: Contribution of the different LHC elements to the total horizontal dipolar effective impedance in different machine configurations.

As shown in [2, Section 2.4.2] the instability growth rate at injection is small for positive chromaticities, while it is higher for negative chromaticities, hence we performed the measurements with negative chromaticities. Moreover, in this paper we will focus on the horizontal plane, but the same measurements can be equally performed in the vertical plane. Similar measurements are reported in [2], but the procedure which was used at the time to excite the instabilities suffered from repeatability issues, which can be avoided by using the procedure reported below.

MEASUREMENT METHOD

To carry out instability growth rate measurements, one needs to be able to trigger instabilities in a controlled and reproducible way, and, in this case, with the additional difficulty of having to change the chromaticity to negative values. In order to do this, we inject a low-intensity bunch with positive chromaticity ($Q' = 10$) and with transverse damper (ADT) activated (with 10 turns gain). Then we trim the chromaticity to the desired negative value and, once the sextupole current has settled, we deactivate the damper and kick the bunch transversely. The choice of using pilot bunches (intensity of $8 \cdot 10^9$ p/b) was imposed by machine protection considerations. This method differs from the one used in [2], where the chromaticity was set to the negative value before injection, and the instabilities were triggered by the injection oscillations. The amplitude of such oscillations can vary from one injection to another, leading to a lack of reproducibility.

Applying single-turn kicks to the bunch using the fast electrostatic kickers of the ADT helps triggering the instabilities in a reproducible manner. The procedure was repeated for several chromaticity values in the range $[-20, 0]$ and different collimator configurations. In Table 1, we report a summary of the used collimator settings.

Table 1: IR7 Collimator Settings in σ's, as Used During the Measurements

Scenario	Primaries	Secondaries	Tertiaries
nominal	5.7	6.7	10
tight 5σ	5	6	10
tight 4σ	4	5	10
tight 3σ	3	4	10

When moving the secondaries to tighter setting, the old graphite secondary collimators (TSCGs), next to the new molybdenum ones (TCSPMs), were also unwillingly tightened. These TCSGs are normally kept in parking position during standard operation; hence this spurious tightening gives a significant impedance increase which would not occur in physics operation at top energy. Since their impedance dominates the one of the new TCSPMs, in future measurements these collimators should be left in retracted position.

In order to calculate the instability growth rate from the recorded turn-by-turn data, we extract the exponentially growing amplitude of the oscillations using a Hilbert transform and we fit an exponential function to its amplitude, the rate of which being the instability growth rate. Figure 3 shows an example of turn-by-turn data retrieved from the circular buffer of the ADT, together with its exponential fit. Throughout the measurement session, tune, orbit, coupling and chromaticity corrections were regularly performed during the phase with positive chromaticity

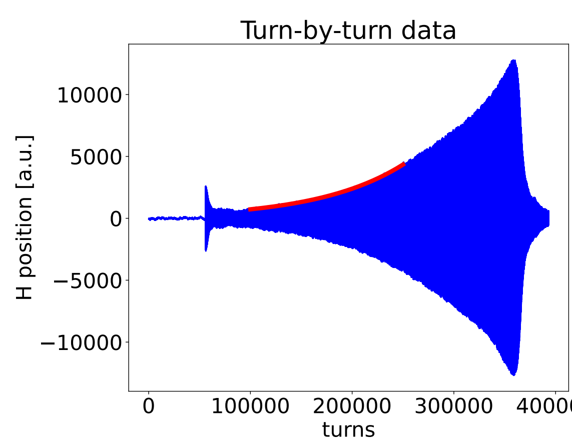

Figure 3: Blue curve: turn-by-turn horizontal position data during an instability. The initial jump in the position is caused by the ADT kick, after which the bunch oscillates and becomes unstable. Red curve: exponential fit to the amplitude of the oscillations.

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Table 2: Main Machine and Beam Parameters During the Instability Growth Rate Measurements

Transverse feedback (ADT)	OFF
β^* (IP1 & 5) [m]	11
Tune H/V (fractional part)	0.275/0.293
Octupole current [A]	0
Bunch intensity [10^9p/b]	8
Bunch length ($4\sigma_{\rm RMS}$) [ns]	0.9

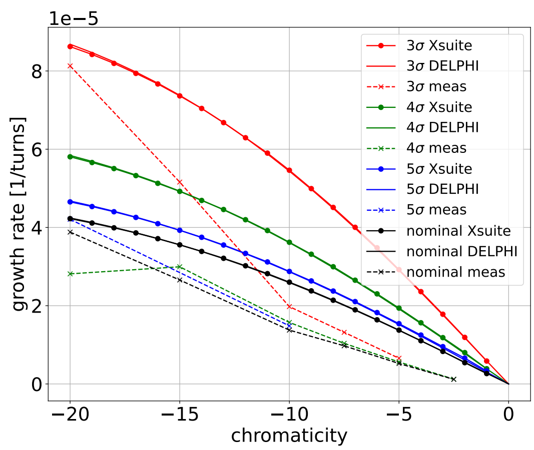

Figure 4: Comparison between the measured growth rates and the ones simulated with DELPHI and Xsuite.

MEASUREMENT RESULTS

We repeated the measurements for a set of negative chromaticities for each of the collimator scenarios in Table 1. In Table 2 we show some of the relevant machine and beam parameters.

In Fig. 4 we report the measured growth rates. As expected, at any given chromaticity the instability growth rate is higher when reducing the half-gaps of the collimators. At the same time, in each scenario the growth rate increases when lowering the chromaticity, which is also expected.

SIMULATIONS

In order to validate the LHC transverse impedance model, we compare the measurements results with simulations carried out with the Vlasov solver DELPHI [3, 4] and the tracking code Xsuite [5, 6]. The impedances used for the DELPHI simulations are obtained using the LHC impedance model code [7] and are shown in Fig. 5.

The tracking simulations use as inputs the wake functions, which are obtained by applying an inverse Fourier transform to the impedance. Because of the various time scales at stake (bunch length, bunch spacing and revolution time), the frequencies are sampled unevenly, and we use the method explained in [8, Section 1.6.3],implemented in the Neffint package [9], to obtain the wake functions, shown in Fig. 5. Note that in Xsuite we use the transfer matrix approach, applying wake kicks at each turn.

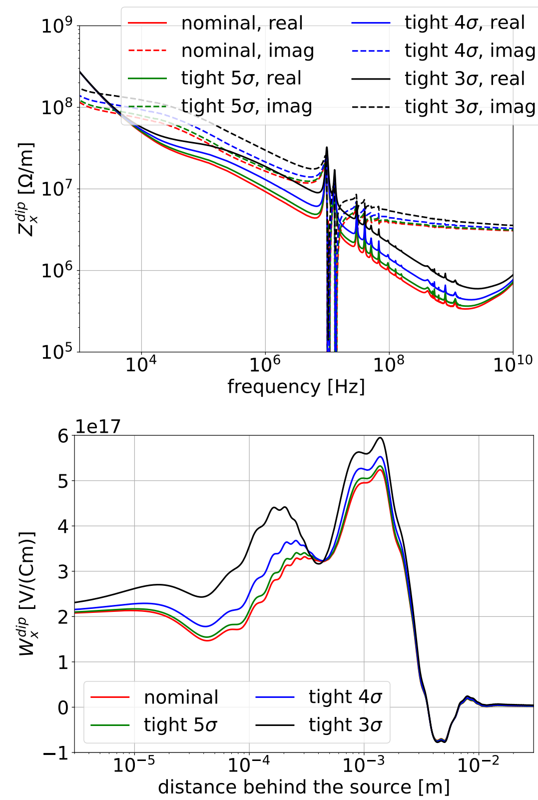

Figure 5: LHC horizontal dipolar impedance (top) and wake function (bottom) at injection with different collimator settings (see Table 1).

In Fig. 4, we show a comparison of the measured growth rates with the simulated ones with the two codes. While the DELPHI and the Xsuite results are in excellent agreement, the measured growth rates are lower than the simulated ones for all chromaticities. Unknown sources of Landau damping are a likely cause of the observed discrepancy—several effects such as uncorrected amplitude detuning and non-linear chromaticity, are not considered in the simulations. In the future, similar measurements should be performed with such optics non-linearities corrected.

CONCLUSIONS

The real part of the transverse impedance model can be validated through growth rate measurements. These measurements can be efficiently performed at injection energy by adjusting the collimator gaps to represent the impedance seen by the beam at top energy. These measurements are performed with negative chromaticity, where the instabilities are the strongest. A new measurement procedure, which relies on kicking the bunches with the ADT, was successfully tested. The measured growth rates are compared with the ones simulated with the DELPHI Vlasov solver and Xsuite tracking simulations, showing similar trends but significant discrepancies. The reasons for the discrepancy is under investigation.

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