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BEAM MEASUREMENTS OF THE LHC IMPEDANCE AND VALIDATION OF THE IMPEDANCE MODEL

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Abstract

Different measurements of the longitudinal impedance of the LHC done with single bunches with various intensities and longitudinal emittances during measurement sessions in 2011-2012 are compared with particle simulations based on the existing LHC impedance model. The very low reactive impedance of the LHC, with Im $Z/n = 0.08\ \Omega$, is not easy to measure. The most sensitive observation is the loss of Landau damping, which shows at which energy bunches become unstable depending on their parameters. In addition, the synchrotron frequency shift due to the reactive impedance was estimated following two methods. Firstly, it was obtained from the peak-detected Schottky spectrum. Secondly, a sine modulation in the RF phase was applied to the bunches of different intensities and the modulation frequency was scanned. In both cases, the synchrotron frequency shift was of the order of the measurement precision.

MOTIVATION

During the design phase of the LHC, significant efforts were made to reduce its impedance in order to minimize the impact of collective effects on the accelerator performance. Thanks to that, no longitudinal instabilities have been observed for operational parameters so far. However, as anticipated, controlled longitudinal emittance blow-up during the acceleration is required for stability. Future LHC operation with higher intensity beams relies on an improved impedance model verified by measurements.

According to the LHC Design Report [1] and the current LHC impedance model [2], the LHC reactive impedance Im Z/n is 0.08 Ω. This value is very small compared to other CERN proton accelerators, e.g. 4 Ω in the SPS and 20 Ω in the PS. Therefore, beam measurements of the LHC impedance with usual methods are very challenging.

A first attempt to measure the resistive part of the longitudinal impedance from synchronous phase measurements was presented in [3]. In this paper, beam measurements of the reactive part of the longitudinal impedance are described together with simulations based on the LHC impedance model. An estimate of Im Z/n from the synchrotron frequency shift is given therein. Also, observations of the loss of Landau damping are compared with simulations.

In the LHC, injection and acceleration need more time than in other accelerators. In addition, the time dedicated to Machine Development (MD) is very limited and highly demanded, so only a few sessions devoted to this subject took place during the LHC Run1 and the results are discussed here.

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SYNCHROTRON FREQUENCY SHIFT

The reactive part of the longitudinal impedance Im Z/n can be estimated from the measured incoherent synchrotron frequency shift Δf_s with intensity. The expected frequency shift can be calculated for a Gaussian bunch with intensity N and 4 σ length τ using the following expression (e.g. [4]):

$$\Delta f_s = -f_{s0} \left(\frac{2}{\pi}\right)^{1/2} \frac{16\, N\, e\, \omega_0\, h^2}{V_{RF}\ (2\,\pi\, h\, f_0\, \tau)^3}\, \frac{\mathrm{Im}\, Z}{n}, \qquad (1)$$

where h is the harmonic number, f_0 the revolution frequency, and V_{RF} the RF voltage.

Two methods were used to measure Δf_s: peak-detected Schottky spectrum and RF phase modulation.

Peak-detected Schottky Spectrum

The quadrupole line of the peak-detected Schottky spectrum shows the particle distribution in synchrotron frequency [5], from where the incoherent synchrotron frequency can be obtained for bunches with different intensity and length.

During the MD#4 session in 2012, 8 bunches with similar longitudinal emittance and different intensities (0.6–2.0) $\times 10^{11}$ were injected into each LHC ring. A frequency difference smaller than 1 Hz can be seen in Fig. 1 for two bunches of Beam 1 with τ = 1.4 ns. For a difference in intensity of 1.0 $\times$ 10^{11}, we get a upper limit for the absolute value of the synchrotron frequency shift of 0.5 Hz. $|\Delta f_s|$ = 0.38 Hz is expected from Eq. (1).

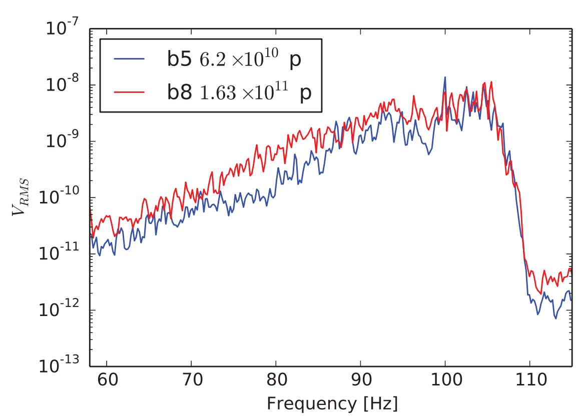

Figure 1: Quadrupole line of the peak-detected Schottky spectrum of two bunches with different intensity and the same length τ = 1.4 ns. The linear synchrotron frequency is f_{s0} = 55.09 Hz for 450 GeV and V_{RF} = 6 MV. During the measurements the Phase Loop was off.

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RF Phase Modulation

During MD#4, the incoherent synchrotron frequency shift was also estimated from measurements with an RF phase modulation at 450 GeV [6]. A sine-wave modulation was applied to the 8 bunches of Beam 2, which had close longitudinal emittance and different intensities. The modulation frequency was reduced in steps of 0.1 Hz starting from 55.3 Hz, above the linear synchrotron frequency $f_{s0} = 55.09$ Hz for an RF voltage $V_{RF} = 6$ MV. A bunch with $N = 0.8 \times 10^{11}$ and $\tau = 1.2$ ns was excited with a frequency 0.1 Hz higher than one with $N = 1.4 \times 10^{11}$ and $\tau = 1.35$ ns. This measurement is in good agreement with the expected 0.11 Hz shift from Eq. (1).

LOSS OF LANDAU DAMPING

The criterion of the loss of Landau damping due to the reactive impedance Im Z/n for the azimuthal mode m can be written in the form [7]:

$$\frac{|\mathrm{Im}\, Z|}{n} < \frac{|\eta|\ E}{e^2\, F_m\, N\, \beta^2} \left(\frac{\Delta E}{E}\right)^2 \frac{\Delta\omega_s}{\omega_s}\, \tau, \tag{2}$$

where η is the slip factor, E the energy of the synchronous particle, F_m a form-factor defined by the particle distribution, $\Delta E/E$ the energy spread, and $\Delta\omega_s/\omega_s$ the synchrotron frequency spread.

Several measurements of loss of Landau damping were done during the LHC Run1. First observations of instability were in 2010 for single bunches accelerated without controlled longitudinal emittance blow-up. Then, in 2011, a few MD sessions were devoted to study the loss of Landau damping during the acceleration ramp [8]. However, due to the presence of the Phase Loop during those tests, it is difficult to reproduce them in simulations.

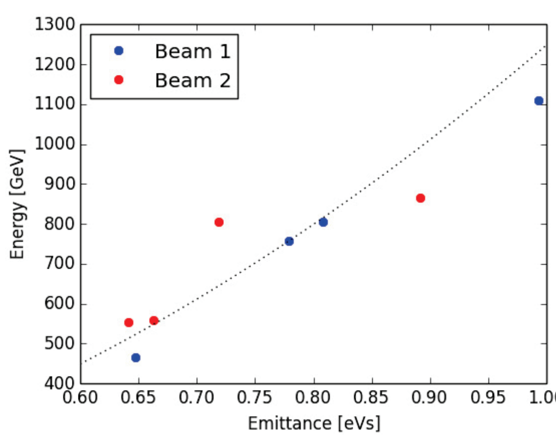

Figure 2: Measured energy threshold E_{th} of loss of Landau damping as a function of longitudinal emittance ε with Phase Loop off. Average bunch intensity of $(2.36 \pm 0.7) \times 10^{11}$ (Beam 1) and $(2.39 \pm 0.4) \times 10^{11}$ (Beam 2). The dashed line is the fit of the measurements according to $E_{th} \propto \varepsilon^2$.

During an MD in 2012, 4 bunches of similar intensity ($\sim 2.4 \times 10^{11}$) and different longitudinal emittances were accelerated to 4 TeV with Phase Loop off. The energy at which the bunches became unstable is shown in Fig. 2, and the dependence on the longitudinal emittance is in accordance with the expected scaling $E_{th} \propto \varepsilon^2$ from Eq. (2). We plan to try to reproduce these measurements in simulations. However, it will be difficult to extract the accurate value of Im Z/n, as the energy at which the instability starts cannot be defined very precisely.

During another MD session in 2012, three bunches with different intensities (5×10^{10}, 1×10^{11} and 1.6×10^{11}) and a longitudinal emittance in the range of 0.6–0.7 eVs were injected into both LHC rings and accelerated to 4 TeV with Phase Loop on, but with a smaller than usual controlled emittance blow-up (final bunch length of 0.8 ns, 4 σ Gaussian fit from FWHM). In this way, the three bunches had at top energy the same longitudinal emittance of 1 eVs. Then the Phase Loop was switched off and dipole oscillations were observed from measurements of the synchronous phase (Fig. 3). In both rings, the bunches with the lowest intensity were stable and the bunches with the highest intensity were unstable. For the bunches with intermediate intensity, the one in Beam 1 was unstable and the one in Beam 2 was marginally stable. As both rings are believed to have the same impedance, for a 1 eVs emittance the intensity threshold is estimated to be 1×10^{11}.

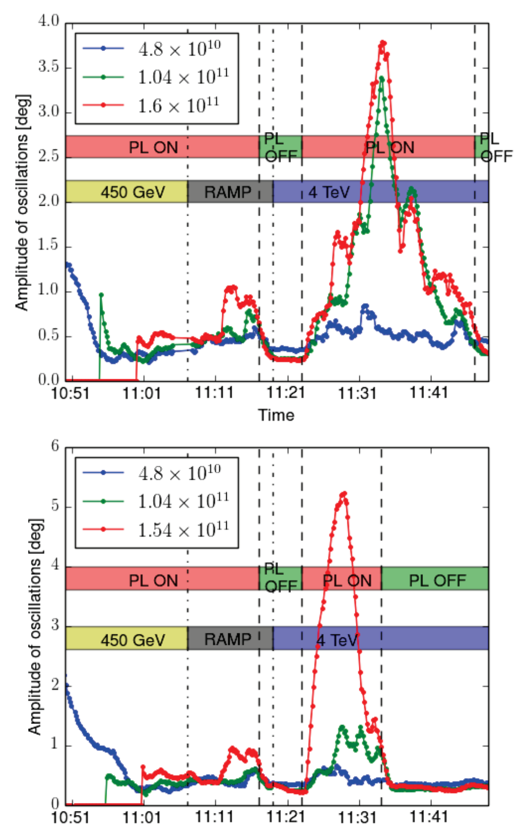

Figure 3: Amplitude of dipole oscillations during a fill with acceleration to 4 TeV for Beam 1 (top) and Beam 2 (bottom). All bunches were stable at 450 GeV. Phase Loop status and energy are indicated in the plots.

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SIMULATIONS

Simulations of loss of Landau damping using the current LHC impedance model [2] were performed with the code ESME [9], with the aim of reproducing the measurements at LHC top energy described above. A line density, $\lambda(t)$, close to the one measured in the LHC was used:

$$\lambda(t) = \lambda_0 \left(1 - \left(\frac{2t}{\tau}\right)^2\right)^{5/2}, \quad |t| \leq \frac{\tau}{2} \tag{3}$$

The corresponding particle distribution in phase space was obtained without intensity effects and then the intensity was ramped up in the simulations. A phase kick of 1 deg was applied to the bunch and then the bunch phase oscillations were observed during 4 s ($\sim$ 100 synchrotron periods).

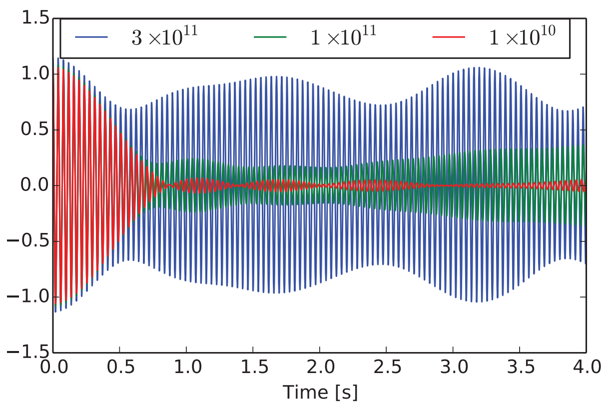

Figure 4: Phase oscillations of bunches with $\varepsilon = 1$ eVs and three different intensities at 4 TeV with $V_{RF} = 12$ MV. According to our stability criteria, the bunch with 1×10^{10} intensity is stable and the oscillations of the other two are not damped. Note that the oscillation damping during the first 0.5 s for the bunch with $N = 1 \times 10^{11}$ is caused by the filamentation after the phase kick.

The threshold of loss of Landau damping was defined in simulations from the envelope of the bunch phase oscillations. Our stability criterion is to consider that a bunch is stable when the average of the envelope over the last 1 s is smaller than 0.2 deg. This value was chosen taking into account that after the phase kick, the bunch filaments and the amplitude of the oscillations can be reduced, as in Fig. 4. In this way, the threshold for a 1 eVs bunch is 0.84×10^{11}, similar to the measured 1×10^{11}. Figure 5 shows the intensity threshold for different longitudinal emittances found in simulations and the dependence of the threshold on the longitudinal emittance is in agreement with the expected scaling $N_{th} \propto \varepsilon^{5/2}$ from Eq. (2).

SUMMARY AND FUTURE PLANS

The reactive part of the LHC longitudinal impedance has been estimated using different methods. The usual techniques are useful for obtaining an upper limit, but they don't provide sufficient resolution to measure the very low LHC impedance accurately. The expectations based on the LHC impedance model were confirmed by measurements of the incoherent synchrotron frequency shift in the peak-detected Schottky spectrum, and then from the RF phase modulation. The latter method could be further improved by reducing the modulation frequency steps. Measurements of the loss of Landau damping during the ramp have shown that bunches with different longitudinal emittances become unstable at energies that scale according to the theory, Eq. (2). Finally, the instability threshold of loss of Landau damping was also measured at 4 TeV and results were reproduced in macro-particle simulations. Measurements with more bunches with a smaller difference in intensity are planned for 2015 at 6.5 TeV to verify these findings with better precision.

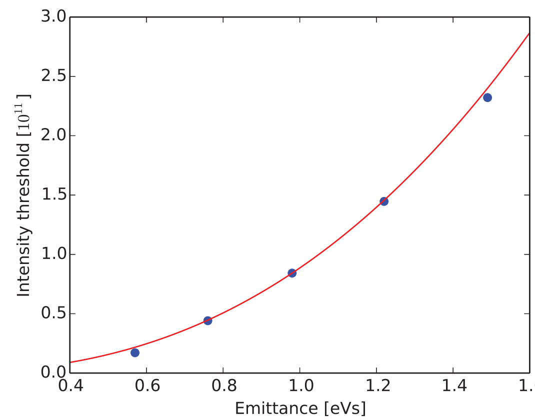

Figure 5: Intensity threshold of loss of Landau damping from simulations (blue circles) together with the scaling expected from Eq. (2) (red line). 4 TeV, $V_{RF} = 12$ MV.

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