MEASUREMENTS OF THE CERN PS LONGITUDINAL RESISTIVE COUPLING IMPEDANCE

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Abstract

The longitudinal coupling impedance of the CERN PS has been studied in the past years in order to better understand collective effects which could produce beam intensity limitations for the LHC Injectors Upgrade project. By measuring the incoherent quadrupole synchrotron frequency vs beam intensity, the inductive impedance was evaluated and compared with the impedance model obtained by taking into account the contribution of the most important machine devices. In this paper, we present the results of the measurements performed during a dedicated campaign, of the real part of the longitudinal coupling impedance by means of the synchronous phase shift vs beam intensity. The phase shift has been measured by using two different techniques: in one case, we injected in the machine two bunches, one used as a reference with constant intensity, and the second one changing its intensity; in the second case, more conventional, we measured the bunch position with respect to the RF signal of the 40 MHz cavities. The obtained dependence of the synchrotron phase with intensity is then related to the loss factor and the resistive coupling impedance, which is compared to the real part of the PS impedance model.

INTRODUCTION

First estimations of the coupling impedance in the CERN Proton Synchrotron (PS) date back to the late 1970s [1]. Further measurement campaigns were performed over the years, and, in 2012 [2], the more recent results of the inductive component of the longitudinal broadband coupling impedance ($Z(p)$) were obtained by measuring the quadrupolar beam transfer function and deducing the zero amplitude synchrotron frequency as a function of bunch intensity. The results of the measurements gave $\mathrm{Im}\left[Z(p)\right]/p = 18.2 \pm 1.2\,\Omega$, with $p = \omega/\omega_0$. In addition to the measurements, longitudinal and transverse impedance models have been developed by taking into account important contributions of the relevant components of the PS [3,4]. The calculated total broad band longitudinal impedance at the frequency of the bunch spectrum cutoff was in good agreement with the measured effective impedance of the PS. The imaginary part of the longitudinal impedance has been measured again in 2015 after the first long shutdown, during which a whole series of renovation work has been carried out in the framework of the LHC Injectors Upgrade project [5]. In Fig. 1 the results of the measurements are shown, confirming the results of 2012.

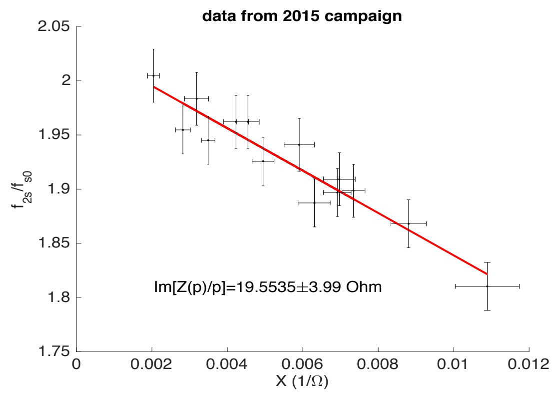

Figure 1: Quadrupole frequency shift vs bunch intensity obtained in the 2015 campaign of measurements. Here $X = \frac{12 e N_p}{V_{RF} h \cos\phi_{s0} \omega_0^2 \tau_b^3}$, where e is the electron charge, N_p the bunch population, V_{RF} the RF peak voltage, h the harmonic number, ϕ_{s0} the unperturbed synchronous phase, ω_0 the angular revolution frequency, τ_b the total bunch length.

In addition to the imaginary part of the coupling impedance, a dedicated campaign of measurements has been performed to determine its real part. We have measured the synchronous phase shift as a function of bunch intensity [6] by using two different techniques. The results, discussed in this paper, are compared with respect to the impedance model, and some considerations on observed discrepancies between the model and the measurements are also presented.

MEASUREMENT SETUP

The measurements of the synchronous phase shift as a function of bunch intensity were performed at a fixed momentum of 26 GeV/c, corresponding to the extraction energy of LHC-type beam in the PS, and with a single-harmonic RF system at 40 MHz (h=84). Two bunches, one with fixed intensity with a population of about $N_p = 2 \times 10^{11}$, and the other one with varying intensity up to $N_p = 3.5 \times 10^{11}$ protons were injected from the PS Booster in the PS with an almost constant longitudinal emittance into two diametric opposite buckets, and accelerated on the 16th harmonic of the revolution frequency up to a momentum of 26 GeV/c. On the flat top, the bunches were first synchronized to a fixed revolution frequency of $f_0 = 476.82$ kHz, allowing to pulse a higher-harmonic RF cavity at 40 MHz. At round 150 ms before extraction, the bunches were handed over from $h = 16$ to $h = 84$. This rebucketing to the 40 MHz RF system was completed 140 ms before extraction. Aside

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from a 5 ms time window for longitudinal emittance and current measurements, about 130 ms were left under stationary conditions to perform the beam measurements. During that time, the bunches were held with a constant 40 MHz RF voltage. The beam signal from a wall current monitor pick-up was used to measure the synchronous phase shift with two methods and with two different devices. In one case we sent the signal directly into one channel of a 14 bit 400 MS/s digitizer. In this way we could record the signal of the two bunches and measure directly the time distance between the two. In addition to this measurement, we also used a second channel to get the signal from the 40 MHz cavity as a reference, so that the distance between the reference and one bunch could also be used to measure the phase shift vs beam current. The digitizer has a relatively poor sampling rate with a maximum value of 400 MS/s, but a long acquisition time with about 64 MS, allowing about 160 ms of total acquisition. We also used an oscilloscope with a maximum sampling rate of 2.5 GS/s over a 4 ms. Also with the oscilloscope we measured the distance between the two bunches and with respect to the 40 MHz cavity. A sketch of the measurement setup is shown in Fig. 2

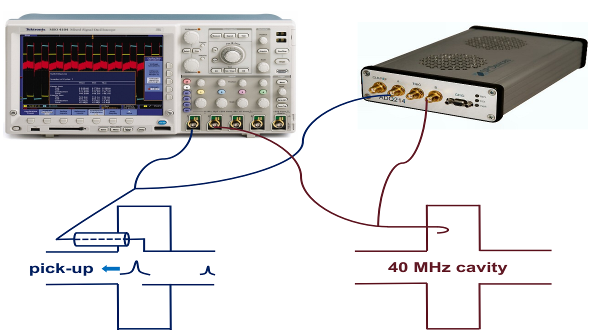

Figure 2: Sketch of the phase shift measurement setup.

DATA ANALYSIS

An example of the pick up signal measured with the oscilloscope over a few turns is shown in Fig. 3, with two different intensity bunches circulating. Figure 4 shows a zoom of a single bunch.

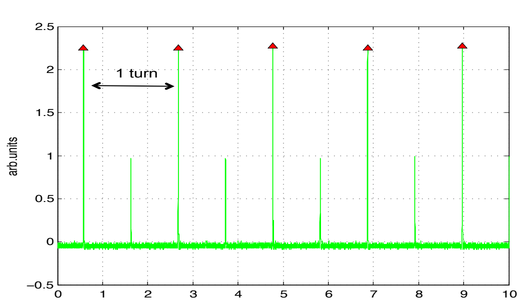

Figure 3: Pick up signal measured over 10 μs.

The same information can be obtained with the Digitizer with a longer time interval. In order to obtain the distance

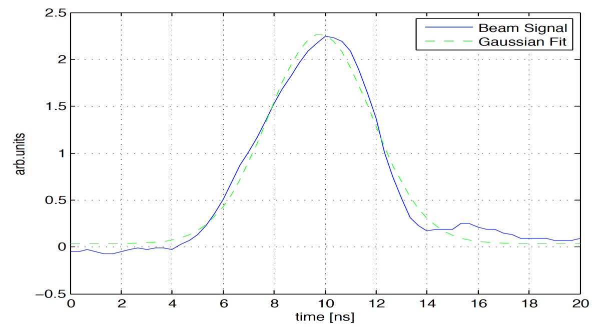

Figure 4: Oscilloscope output showing the bunch distribution and the Gaussian fit.

between two bunches, we fitted any distribution with a Gaussian curve. Even if the shape is asymmetric, the difference in the centres of mass between the two curves is negligible. We then averaged all the centres of mass for the entire time range, obtaining a time distance between two bunches or between one bunch and the 40 MHz signal. As a final result of the analysis we obtained a time as a function of bunch intensity. We made measurements with two different RF peak voltages, 50 and 100 kV. In Fig. 5, we summarize the results for 100 kV. The slope of the linear fit, $\Delta t/\Delta N_p$, can be related to the loss factor. Indeed, in order to compensate the energy loss per turn due to the interaction of the bunch with the real part of the impedance, the RF system has to provide some extra energy that, in the linear approximation of the synchrotron oscillations, is given by [7]

$$\Delta E = h\omega_0 \Delta t e V_{RF} \cos\phi_{s0} = \frac{e^2 N_p}{T_0} \sum_{p=-\infty}^{\infty} Re\left[Z\left(p\omega_0\right)\right] \lambda^2\left(p\omega_0\right) \quad (1)$$

where Δt is the time shift for a given bunch intensity, T_0 the revolution time, $Re\left[Z\left(\omega\right)\right]$ the real part of the longitudinal impedance, $\lambda(\omega)$ the single bunch spectrum.

Since the loss factor is related to the real part of the impedance by

$$k_l = \frac{1}{T_0} \sum_{p=-\infty}^{\infty} Re\left[Z\left(p\omega_0\right)\right] \lambda^2\left(p\omega_0\right) \quad (2)$$

we get

$$k_l = h\omega_0 V_{RF} \cos\phi_{s0} \frac{\Delta t}{e N_p} \quad (3)$$

By taking into account both the measurements performed with the Digitizer and the oscilloscope, we obtained a time shift of about (0.088 ±0.012) ns/10^{11} particles at 100 kV, which gives a loss factor of (0.138 ± 0.019) V/pC. With the measurements at 50 kV, from the previous equation, one should expect a time shift twice higher, since the loss factor should not depend on the total voltage if the longitudinal distribution remains constant. Our measurements gave instead a factor of about 3 higher.

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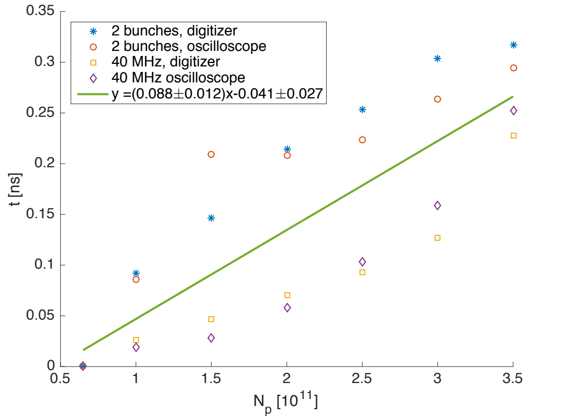

Figure 5: Time shift versus bunch population obtained with a peak voltage of 100 kV.

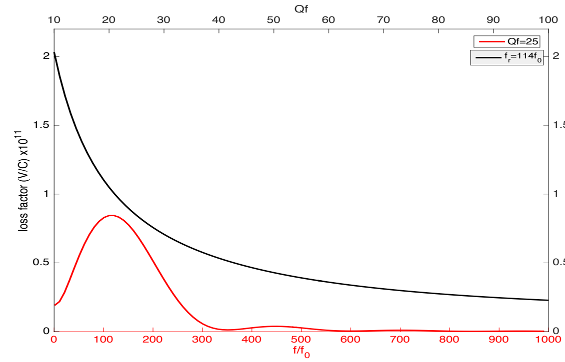

Figure 6: Loss factor vs frequency (Q_f=25, red), and vs quality factor ($f_r = 114 f_0$, black) for the PS parameters.

IMPEDANCE MODEL

The real part of the impedance model was obtained in 2012 by taking into account the contribution of kickers and RF cavities. From the definition of loss factor given by Eq. 2, the model gives $k_l = 0.044$ V/pC, a factor of about 3 lower than the measured one. The loss factor is very sensitive to the bunch length, and, during the measurements, we could not avoid some bunch length variations cycle by cycle. In any case, a factor 3 is quite high, and it is hard to imagine one or more unidentified devices in the machine giving a loss factor higher than that of all the kickers, in particular for long bunches as those used for these measurements. A possible reason of the discrepancy could be due to the presence of one or more HOMs which do not affect the inductive coupling impedance at low frequency, but produce energy losses interacting with the beam spectrum. These HOMs, depending on their resonant frequencies, may not necessarily excite coupled bunch instabilities. In order to check this hypothesis, we investigated some characteristics of HOMs that could produce a high energy loss. In Fig. 6 we show the energy loss as a function of resonant frequency at a fixed quality factor ($Q_f = 25$, red line) and as a function of the quality factor at a fixed resonant frequency ($f_r = 114 f_0$, black line) for constant shunt resistance $R_s = 50$ kΩ. The shape of the loss factor as a function of frequency remains approximately constant for different quality factors. From the figure we see that a singe HOM with $Q_f = 25$ and $f_r = 114 f_0$ has a loss factor of about 0.085 V/pC, which, added to that given by the kickers and RF cavities, could explain the results of the measurements. It is also worth mentioning that the 80 MHz cavities have a resonant frequency of about $168 f_0$.

Of course there could be more than one single HOM producing energy losses. In Fig. 7 we show a possible scenario adding, to the broadband impedance model, two HOMs, one with $Q_f = 30$, $f_r = 146 f_0$, $R_s = 15$ kΩ, and the other with $Q_f = 20$, $f_r = 50 f_0$, $R_s = 15$ kΩ. These two modes do not affect the measurements of the imaginary broadband impedance, producing a small perturbation, as shown in the figure, but, added to the kickers and RF cavity impedances, give a total energy loss of about 0.135 V/pC, this last results being also confirmed by the simulation code MuSiC [8] and very close to the measurements. The choice of the parameters is quite arbitrary: other parameters and other HOMs can be suited to give the same results.

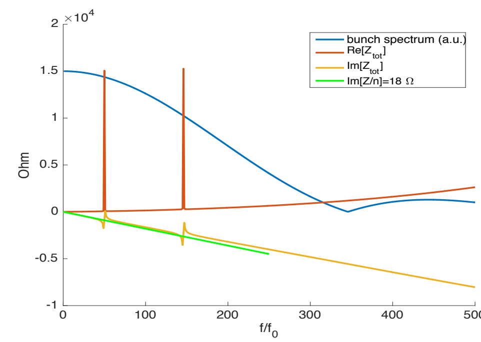

Figure 7: Bunch spectrum (blue), impedance real (red) and imaginary (yellow) part with two HOMs, imaginary measured impedance (green).

CONCLUSIONS

In this paper we have described the measurements of the synchronous phase shift vs bunch intensity of the PS accelerator. The results give us the value of the loss factor, which, together with measurements of the incoherent quadrupole synchrotron frequency, allows to obtain information on the longitudinal coupling impedance. Its imaginary part results to be about 18-19 Ohm, confirming previous measurements and the impedance model described in [2]. The loss factor at 100 kV is about 0.138 V/pC. In this case the impedance model gives only 0.044 V/pC, a factor three lower. A possible explanation of the discrepancy in the real part of the impedance could be the presence of HOMs which do not affect the measurements of the imaginary part of the impedance, whilst they contribute to the total loss factor.

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REFERENCES

[1] D. Boussard *et al.*, in *Proc. of PAC'79*, San Francisco, California, 1979, p. 3568.

[2] M. Migliorati, S. Persichelli, H. Damerau, S. Gilardoni, S. Hancock, and L. Palumbo, Phys. Rev. ST Accel. and Beams, vol. 16, p. 031001, 2013.

[3] S. Persichelli, M. Migliorati, N. Biancacci, S. Gilardoni, E. Metral, and B. Salvant, Phys. Rev. Accel. and Beams, vol. 19, p. 040101, 2016.

[4] S. Persichelli, M. Migliorati, N. Biancacci, S. Gilardoni, E. Metral, B. Salvant, in *Proc IPAC'14*, pp. 4096-4098.

[5] S. Gilardoni *et al.*, in *Proc. of IPAC'11*, p. 2520.

[6] J. F. Esteban Muller *et al.*, in *Proc. of HB'12*, pp. 183-6.

[7] R. Boni *et al.*, *Nucl. Instr. Meth. in Phys. Res. A*, vol. 418, pp. 241-8, 1998.

[8] M. Migliorati and L. Palumbo, "Multibunch and multiparticle simulation code with an alternative approach to wakefield effects", *Phys. Rev. ST Accel. and Beams*, vol. 18, p. 031001, 2015.

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