REFERENCE MEASUREMENTS OF THE LONGITUDINAL IMPEDANCE IN THE CERN SPS

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Abstract

First reference measurements of the longitudinal impedance were made with beam in the SPS machine in 1999 to quantify the results of the impedance reduction programme, completed in 2001. The 2001 data showed that the low-frequency inductive impedance had been reduced by a factor 2.5 and that bunch lengthening due to the microwave instability was absent up to the ultimate LHC bunch intensity. Measurements of the quadrupole frequency shift with intensity in the following years suggest a significant increase in impedance (which nevertheless remains below the 1999 level) due to the installation of eight extraction kickers for beam transfer to the LHC. The experimental results are compared with expectations based on the known longitudinal impedance of the SPS.

QUADRUPOLE FREQUENCY SHIFT

Measurements of the quadrupole synchrotron frequency shift with intensity N using a single bunch at 26 GeV/c were performed in the SPS from 1999 to monitor the evolution of the low-frequency longitudinal impedance [1]. In general this task is not straightforward since the shift of the quadrupole oscillation frequency

$$\omega_{2s}(N) = \Delta\omega_{inc}(N) + \Delta\omega_{coh}(N) + 2\omega_{s0}, \qquad (1)$$

where ω_{s0} is the linear synchrotron frequency, consists of two parts: the incoherent shift $\Delta\omega_{inc}$, a function of the potential well distortion coming from the spectrum of the stationary bunch distribution, and the coherent shift $\Delta\omega_{coh}$ which depends on the spectrum of the oscillation and is defined by the eigenfrequencies of the system. Therefore the measured frequency shift depends on two different effective impedances, determined by convolution of these spectra with the imaginary part of the SPS impedance. Due to the complicated dependence on bunch length the same experimental conditions (bunch length and bunch line density distribution) are essential for comparison of results from different years. In addition, due to the measurement method used (mismatched injection, see below) the longitudinal emittance affects the amplitude of bunch oscillations (or average bunch length) and therefore the oscillation frequency.

The frequency of the quadrupole oscillations measured as a function of intensity in different years is presented in Fig. 1. The linear fit of the form

$$\omega_{2s}(N)/(2\pi) = f_{2s}(N) = a + b \times N/10^{10} \qquad (2)$$

was used to define the slope b (in [Hz]). As one can see in Fig. 1 the slope $|b|$ first reduced from 5.6 to 1.8 due to the

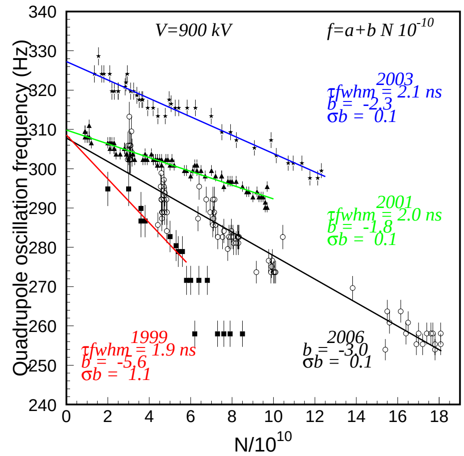

Figure 1: Measurements of the quadrupole synchrotron frequency shift at 26 GeV/c in the SPS since 1999.

SPS impedance reduction programme and then increased again in 2003 and in 2006 after the installation of 4 and 5 extraction kickers (MKE) for LHC beams. While the large changes are easy to see, to observe small variations of impedance (such as shielding or removal of a few kickers) much higher measurement accuracy is required. Indeed, instead of the impedance reduction expected in 2007 due to the removal of one MKE kicker and partial shielding of another, some increase was obtained ($|b| = 4.4$) in the first MD. A lack of reproducibility of the longitudinal parameters (including emittance) of the injected beam for different intensities as well as for different Machine Development (MD) sessions was suspected. In the following MDs this was investigated in more detail [2], [3] and results are reported here.

MEASUREMENTS

The main requirement for experimental conditions is to have a single bunch with a variable intensity and constant longitudinal parameters. This beam is prepared in the SPS injector chain and its production scheme has evolved with time. In 2008 intensity variation was done in the PS Booster by longitudinal shaving, reducing the main RF voltage during acceleration, followed by controlled emittance blow-up using resonant phase excitation with the 4th harmonic RF system. All settings for different intensities were carefully prepared and tested in advance. During MDs bunch length, $\tau = 4\sigma$, was measured (Gaussian fit to bunch profile) for each cycle in the PS before extraction and in the SPS at the first turn. Longitudinal emittance was measured in the PS using phase space reconstruction (tomography) just before bunch rotation prior to extraction.

Three types of measurements of the quadrupole frequency have been performed in the SPS. The first (I) uses longitudinal bunch profiles acquired each turn. The second method (II) is based on a direct observation from the first 12-13 oscillations of the peak detected (PD) signal immediately after injection into the mismatched bucket. The third (III) is the measurement of the maximum frequency in the PD Schottky spectrum [4] using the PD signal as an input to the dynamic signal analyser (DSA) at 1 s after injection, acquisition time 400 ms or 800 ms. Other experimental conditions in the SPS were always the same: mismatched RF capture at 26 GeV/c flat bottom with an RF voltage V_0 of 900 kV at 200 MHz. The frequency of the quadrupole oscillations was recorded as a function of bunch intensity measured by a beam current transformer (BCT) in the SPS (averaged over the first 100 ms).

There were several MD sessions in 2007 and 2008. Measurements done with two sets of injected emittances and bunch lengths in one MD session in 2007 and during two MD sessions in 2008 are summarised in Table 1. Results strongly depend on injected emittance and this is even more clear from measurements done 1 s after injection (III).

ε	τ	$\lvert b \rvert$ [Hz] by method		
eVs	ns	I	II	III
0.1	3.0 ± 0.3	4.0 ± 0.2	4.1 ± 0.1	3.5 ± 0.3
0.1	2.1 ± 0.1	3.4 ± 0.2	3.4 ± 0.2	3.5 ± 0.1
0.19	4.0 ± 0.2	3.4 ± 0.2	3.1 ± 0.1	2.3 ± 0.2
0.19	2.8 ± 0.1	2.8 ± 0.2	2.2 ± 0.3	2.1 ± 0.2
0.14	2.5 ± 0.1	3.8 ± 0.2	3.8 ± 0.3	-
0.17	2.75 ± 0.2	4.2 ± 0.2	3.9 ± 0.3	4.1 ± 0.2

Table 1: Slope $|b|$ measured for different emittances and bunch lengths in 2007 (above line) and in 2008 (below).

One set of measurements of bunch length, emittance and quadrupole frequency (method II) is shown in Fig. 2 for the second MD in 2008. One can see a large scatter at low intensity and a nonlinear dependence of quadrupole frequency on bunch intensity. This also is observed by the other methods and in different measurement sets.

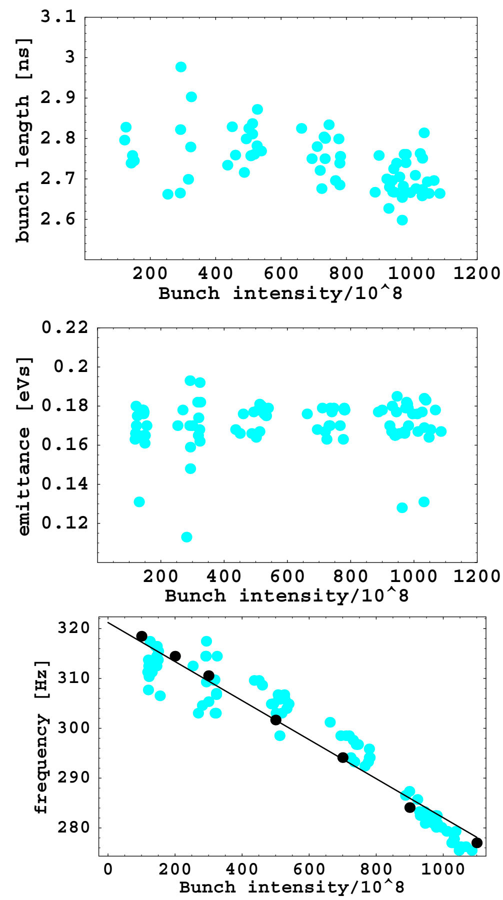

Figure 2: Bunch length (top), emittance (middle) and quadrupole frequency (bottom) together with linear fit and results of ESME simulations (black circles).

SPS IMPEDANCE ESTIMATION

The slope b can be calculated using the following expression (e.g. [5]) for the quadrupole frequency shift as a function of intensity and bunch length:

$$\omega_{2s}(\tau, N) \simeq 2\omega_{s0}\{1 - \frac{(\omega_{rf}\tau)^2}{64} + \frac{Ne\omega_0}{4\pi h V_0} Z_1 +$$

$$+(\frac{2}{\pi})^{1/2}\frac{16 N e\omega_0 h^2}{V_0(\omega_{rf}\tau)^3}[(\frac{\mathrm{Im}Z}{n})_0 - \frac{3}{16\sqrt{2}}(\frac{\mathrm{Im}Z}{n})^{m=2}_{eff}]\}, \quad (3)$$

where $\omega_{rf} = h\omega_0$, h is the harmonic number and ω_0 the revolution frequency. Here $(\mathrm{Im}Z/n)_0$ is a constant term, independent of bunch length, due to space charge and the inductive impedance from high frequency resonant impedances. The effective impedance

$$\mathrm{Im}(Z/\omega)^m_{eff} = \frac{\sum_{p=-\infty}^{\infty} h_m(\omega_p) Z(\omega_p)/\omega_p}{\sum_{p=-\infty}^{\infty} h_m(\omega_p)}, \quad (4)$$

where $\omega_p \simeq p\omega_0$ and for a Gaussian line density spectral density is $h_m(\omega) = (\omega\sigma)^{2m} e^{-\omega^2\sigma^2}$ and

$$Z_1 \simeq \sum_{p=-\infty}^{\infty} p\,\mathrm{Im}Z(\omega_p) e^{-\omega_p^2\sigma^2/2}. \quad (5)$$

The effective impedances are calculated from the known impedance sources: the fundamental mode of the 200 MHz and 800 MHz RF systems, the HOM of the 200 MHz RF system at 629 MHz and all (19) SPS kickers. The total reactive SPS impedance is shown in Fig. 3.

The main changes in the SPS impedance from 2001 to 2008 are due to the number of the MKE kickers in the ring. The reactive part of the longitudinal impedance of all kickers in SPS in 2001 and in 2008 [6] is shown in Fig. 4.

The slope b found from (3) as a function of bunch length $\tau = 4\sigma$ is shown in Fig. 5 for the SPS impedances in 2001

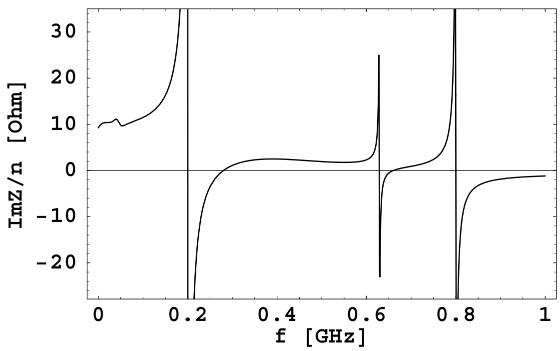

Figure 3: Total reactive SPS impedance in 2008.

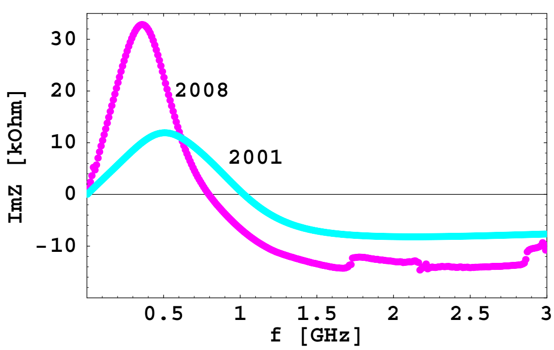

Figure 4: Reactive part of the longitudinal impedance of all kickers in SPS in 2001 and in 2007-2008, data [6].

and 2008 (with space charge term $(\mathrm{Im}Z/n)_0 = 0.1$ Ohm). All measured $|b|$ (method I) [3] during different MDs in 2001 as well as in 2007 and 2008 are also plotted there for the bunch length determined as an average during initial bunch oscillations in the SPS. Like this the variation of injected longitudinal emittance from one MD to another can be taken into account.

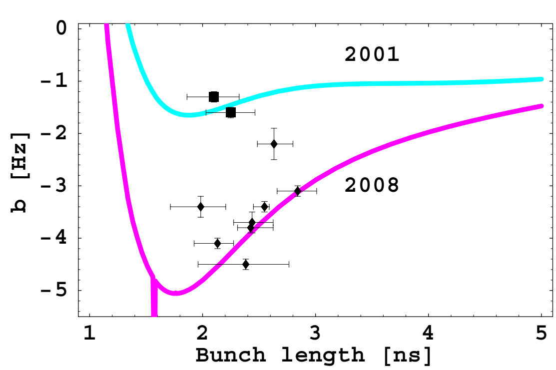

Figure 5: Calculated b for known SPS impedance in 2001 and 2008 and $(\mathrm{Im}Z/n)_0 = 0.1$ Ohm (solid lines). Measured b (method I, data from 2001 and 2007-2008) for average bunch length during oscillations in the SPS.

Finally the measured quadrupole oscillation frequency can be compared with that obtained from numerical simulation with ESME [7]. The purpose of these simulations was to test the SPS longitudinal impedance model as well as to try and explain the nonlinear behaviour of the quadrupole frequency as a function of intensity observed at small intensities in both MDs in 2008. The Gaussian bunch used in ESME simulations had an average measured bunch length and emittance. The impedance model was the one as described above except for the fact that for the kicker impedance only the reactive part was used. The resistive part of this impedance leads to strong dipole oscillations which in the SPS are damped by a phase loop. The comparison of experimental data with simulations is presented for the first MD in 2008 in Fig. 6 and also shown in Fig. 2 (bottom) for the second MD.

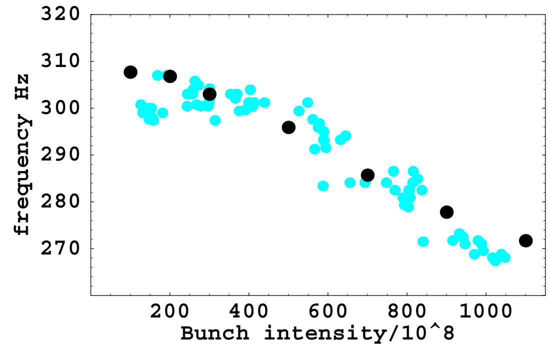

Figure 6: Measured (method II, 1st MD in 2008) quadrupole oscillation frequency (blue circles) together with frequencies from ESME simulations (black circles).

Similar measurements in the transverse plane follow well the expected relative changes of the SPS impedance but at the same time reveal that 30% of the total transverse impedance has not yet been identified [8].

Summary. The measured quadrupole synchrotron frequency shift is in general in good agreement with that expected from the known longitudinal impedance and obtained from both the theoretical model and numerical simulations. The increase in shift measured in 2007 is most probably due to insufficient accuracy of the 2006 data (emittance value) and not due to impedance increase.

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