TRANSVERSE LOW FREQUENCY BROAD-BAND IMPEDANCE MEASUREMENTS IN THE CERN PS

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Abstract

The base-line scenario for the High-Luminosity LHC upgrade foresees an intensity increase delivered by the injectors. With its 53 years, the CERN PS would have to operate beyond the limit of its performance to match the future requirements. Beam instabilities driven by transverse impedance are an important issue for the operation with high intensity beams as for the high-brightness LHC beams. Measurements of transverse tune dependence with beam intensity were performed at injection kinetic energy 1.4 GeV and at LHC beam extraction momentum 26 GeV/c. This allows deducing the low frequency inductive broad-band impedance of the machine. Then an estimation of the real part of the impedance is made by the rise time measurement of a fast transverse instability at transition energy believed to be a TMCI type. Those are the first step towards a global machine impedance characterization in order to push forward the performances of the accelerator.

INTRODUCTION

The CERN Proton Synchrotron accelerates several types of beams with different intensities per bunch. One could mention the single bunch beam ToF dedicated for the neutron Time-of-Flight facility [1] which had increased its beam intensity in 2010 from $700 \cdot 10^{10}$ protons to $850 \cdot 10^{10}$ in normal operation. With such high intensity, space charges forces and machine impedance constitute the main limitations at injection [2]. Both provoke betatron frequency shifts and therefore could put the the beam onto resonances [2]. Coherent tune shift measurements were performed at two different energies in order to get an order of magnitude of the contribution from the low frequency inductive broad-band impedance. The total tune shift for a given energy and beam intensity is written as $\Delta Q = \Delta Q_{sc} + \Delta Q_{bb}$, where ΔQ_{sc} is the tune shift due to indirect space charge, ΔQ_{bb} the tune shift caused by the imaginary part of the broad-band impedance. An estimation of the ΔQ_{sc} contributions can be made from analytical formulas in order to isolate ΔQ_{bb}. In this paper, we present the impedance measurements done recently in the PS and the results are discussed and compared to previous measurements [3, 4].

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COHERENT TUNE SHIFT MEASUREMENTS

Two different single bunch proton beams were set up with the parameters of Table 1 with a long flat magnetic cycle in each case as shown in Fig. 1. The transverse tunes $Q_{x,y}$ were matched with low energy quadrupoles at injection energy and with the special coils (Pole Face Winding PFW) on the main magnets at extraction energy. For each set of data, the longitudinal emittance was measured and the horizontal and the vertical tunes are acquired for different beam intensities with the ”diode-based-band tune” system [5] so called BBQ. The tune was obtained by applying a Fast Fourier Transform (FFT) on the raw transverse position given by the BBQ.

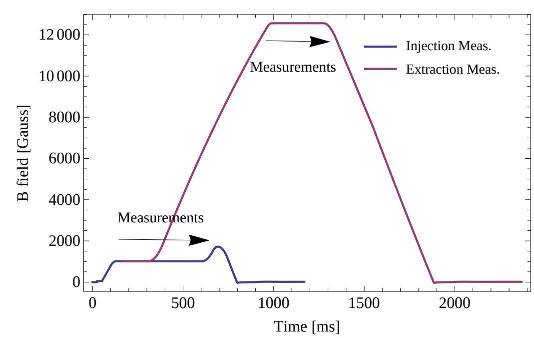

Figure 1: Magnetic field cycle used respectively for 1.4 GeV and 25 GeV measurements.

Table 1: Beam parameters during the measurements for 1.4 and 25 GeV.

Kinetic energy K	1.4 GeV	25 GeV
Relativistic γ	2.47	27.7
Transverse tunes $Q_{x,y}$	6.21,6.245	6.24,6.26
Chromaticities $\xi_{x,y}$	-0.8,-1	0.2,0.2
RF Harmonic h	8	8
Full bunch length 4 σ_t	180 ns	50 ns
Longitudinal emittance ϵ_l (2 σ)	$\simeq$ 2 eVs	$\simeq$ 2.7 eVs

The tune shifts have been plotted as a function of the bunch intensity Fig. 2 for 1.4 GeV and Fig. 3(b) for ΔQ_y at 25 GeV. The tune shift in the vertical plane at 1.4 GeV is more important than the horizontal one due partly to the space charge forces [6] and the elliptical shape of the PS vacuum chamber since the indirect space charge coherent

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ΔQ is [7]

$$\Delta Q_{coh} = -\frac{NRr_0}{\pi Q \gamma \beta^2}\left(\frac{\epsilon_1}{h^2} + \frac{\epsilon_2}{g^2} + \frac{\xi_1}{h^2}\frac{1-\beta^2}{B^2}\right) \quad (1)$$

with N the total number of particles in the bunch, R the machine radius, r_0 the classical proton radius, Q the unperturbed tune (Q_v/Q_h), γ, β the relativistic parameters, B the bunching factor, h half inside height of the vacuum chamber (h=35 mm for the PS), w half inside width of the vacuum chamber (w=70 mm) and $\epsilon_{1,2}, \xi_1$ the Laslett coefficients. A linear fit is applied to the measured tune shift as a function of the intensity. The computed R^2 of Fig. 2 show a very good agreement with the linear tendance. From the slope, the effective impedance is deduced later in this paper.

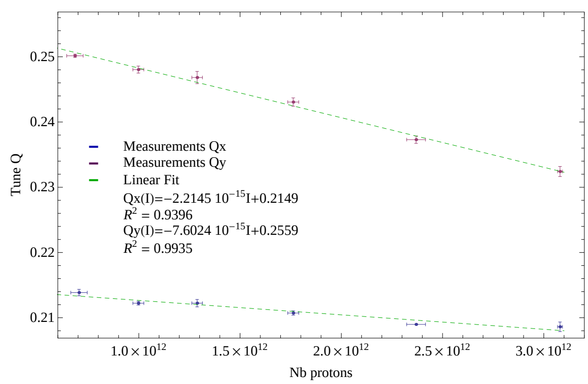
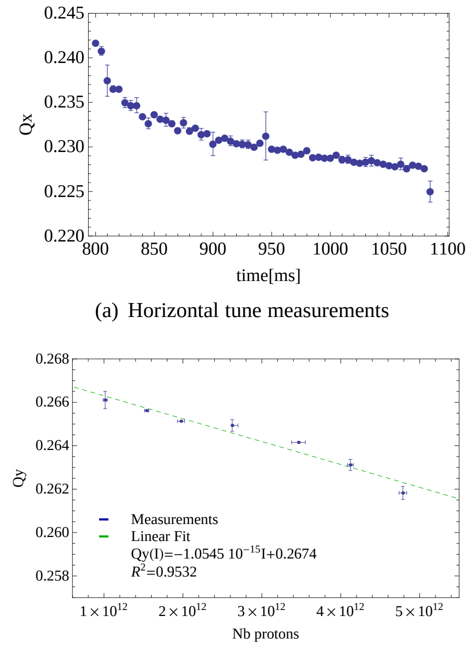


Figure 2: Transverse tune shift measurements as a function of the beam intensity in number of particles at 1.4 GeV.

The analysis of the horizontal tune at 25 GeV revealed almost no ΔQ_x with the beam intensity. In addition Q_x appeared to be drifting with time on the flat top as shown in Fig. 3(a), whereas the optics was not changing. This phenomenon is unfortunately not understood. More detailed tune measurements [8] on the long plateau at different beam energies show that both betatron frequencies $Q_{x,y}$ are affected. In our case the effect seems to be more visible in the horizontal plane. The tune analysis has been done in the y-plane only because the horizontal ΔQ_x does not allow to find a good linear fit.

EFFECTIVE GENERALIZED INDUCTIVE IMPEDANCE

The beam-impedance interaction generates a complex tune shift $\Delta\omega$ of the betatron frequency. The real part of $\Delta\omega$ measured at injection and extraction energy corresponds to the interaction of the beam with the imaginary part of the transverse impedance $Z_\perp$ that we suppose broad-band [9]. $Im(Z_\perp)$ is defined as the effective impedance, i.e. the impedance weighted by the transverse bunch spectrum $h(\omega)$ centered at the chromatic frequency ω_ξ [6],



(a) Horizontal tune measurements

(b) Vertical tune shift measurements at 26 GeV/c.

Figure 3: Transverse tune measurements at extraction.

$$Z_{eff} = \frac{\sum_{p=-\infty}^{\infty} Z(\omega')h(\omega'-\omega_\xi)}{\sum_{p=-\infty}^{\infty} h(\omega'-\omega\xi)} \begin{cases} \omega' & = \omega_0 p + \omega_\beta \\ \omega_\xi & = \xi\omega_\beta/\eta \\ h(\omega) & = e^{-\omega^2\sigma^2/c^2} \end{cases} \quad (2)$$

The real coherent tune shift is related to the effective generalized impedance by the Sacherer formula for bunched beam [9]

$$\Delta Q_m = -\frac{1}{1+m}\frac{j}{2Q_0\omega_0^2}\frac{e\beta I}{\gamma m_0 \tau_b} Im Z_{eff} \quad (3)$$

with m the oscillation mode, Q_0 the transverse tune, ω_0 the revolution frequency, e the electron charge in Coulomb, β and γ the relativistic parameters, m_0 the proton mass in kg, I the intensity and τ_b the full bunch length in meter. The formula gives an effective generalized transverse impedance composed by a dipolar impedance Z^{dip} and a quadrupolar Z^{quad} for any beam energy [10]

$$Z_{x,y} = Z_{x,y}^{dip} + Z_{x,y}^{quad} \quad (4)$$

For ultra relativistic beams ($\gamma \to \infty$), $Z_x^{quad} = -Z_y^{quad}$, however this approximation is not valid for the CERN PS (Maximum $\gamma \approx 26$). Hence the measured coherent tune shift for asymmetrical vacuum chamber is composed by the dipolar contribution of the impedance ΔQ_{dip}^Z and the quadrupolar part ΔQ_{quad}^Z (or incoherent tune shift)

$$\Delta Q_{coh} = \Delta Q_{dip}^Z + \Delta Q_{incoh}^Z \quad (5)$$

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From the equation (3) and the slope of the fitted equations, an effective generalized impedance at injection and extraction energy can be estimated. The results are summarized in the Table 2.

Table 2: Effective generalized impedance

Kinetic energy (GeV)	1.4	25
Hor. $Im(Zeff)$ (MOhm/m)	3.5	< 1
Vert. $Im(Zeff)$ (MOhm/m)	12.5	6.1
Previous measurements [3, 4]		
Kinetic energy (GeV)	25	
Hor./Vert. $Im(Zeff)$ (MOhm/m)	3-13 / 3-7.9	

Impedance due to indirect space charge

The results reveal $\Delta Q_x \approx 0$ at 25 GeV whereas at 1.4 GeV a coherent tune shift is still observable. This means that $\Delta Q^Z_{dip} = \Delta Q^Z_{incoh}$ at 25 GeV while space force are still applied at 1.4 GeV. The measured tune shift in the vertical plane has two mains contributions: the impedance supposed broad-band ΔQ_{bb} and the indirect space charge. ΔQ_{sc} can be estimated by the analytical formulas Eq. (1) and compared to the total vertical measured tune shift in Fig. 4 at 1.4 GeV and 25 GeV. ΔQ_{sc} is about 1/4 of the total ΔQ_v which would correspond to $Z_{sc} \simeq 3$ MOhm/m using the Eq. (3). Z_{bb} at 1.4 GeV would be about 9 MOhm/m which is in the same order of magnitude as the effective generalized impedance deduced at 25 GeV. Space charge becomes negligible at extraction energy Fig. 4. However, to compare these two values, the bunch length has to be the same according to Eq. (3). Hence a complete PS impedance model would be needed. Similar previous measurement were done [3, 4] and the generalized effective impedance was found to be about 3 MOhm/m. However the measurements were done two years consecutives and gave significant different results from one year to another as shown in Table 2. However some are consistant with the results found in this paper.

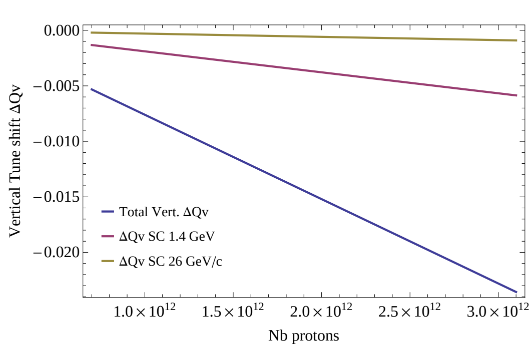

Figure 4: Tune shift due to space charge estimation at different energies compared to the total measured vertical tune shift.

ESTIMATION REAL PART OF THE BROAD-BAND IMPEDANCE

The CERN PS uses a second order $\gamma_{\rm tr}$ jump scheme to cross transition energy. Fast beam losses due to a vertical single bunch instability can be observed near transition [12] on a high intensity beam ($700 \cdot 10^{10}$ protons) if the longitudinal emittance is not sufficiently large. This effect is believed to be a transverse mode coupling instability (TMCI). To caracterize the real part of the effective impedance, the intensity instability threshold for different longitudinal emittances is needed as well as the momentum compaction factor threshold $\eta_{th} = 1/\gamma_{tr}^2 - 1/\gamma^2$. The measurement results without the gamma transition jump were benchmarked with HEADTAIL simulations [13] to deduce the effective impedance presented in Table 3 [14]. The parameters of the transverse broadband impedance used in the code are the quality factor Q=1 and the angular resonator frequency $\omega_r = 1$GHz .

Table 3: Effective impedance at transition energy.

Vertical chromaticity	$\xi_v = 0$	$\xi_v \approx -0.1$
η_{th}	0.0004	0.001
Vert. $Re(Zeff)$ (MOhm/m)	1.6-2.2	1.4

CONCLUSIONS

Instabilities and impedance measurements performed recently show that the limit on intensity accelerated by the CERN PS has been reached. Despite a real effort to optimize the impedance budget, a complete model is needed as done for the SPS [15], to push forward the performance of the accelerator. The measurements presented in this paper constitutes the first step towards a global machine impedance characterization which will be the aim of the PS Upgrade project.

REFERENCES

[1] http://pceet075.cern.ch/

[2] E. Benedetto et al, MOPS014, IPAC2011.

[3] R. Cappi et al, CERN-PS-89-39-PA.

[4] R. Cappi, E. Metral et al, PPC meeting, 2001.

[5] M. Gasior, R. Jones, LHC-Project-Report-853, 2005.

[6] A. W. Chao, Physics of Collective beam instabilities in high energy accelerators, New York, Wiley, 1993.

[7] Y. Baconnier, CERN/PS 87-89 (PSR).

[8] B. Vandorpe, S. Gilardoni, private conversation,2011.

[9] F.J. Sacherer, CERN/PS/BR 76-21.

[10] S. Heifets et al., SLAC-AP-110, 1998.

[11] E. Metral, private conversation,2011.

[12] S. Aumon et al, THO1DO2, HB2010, Morschach.

[13] G. Rumolo et al, SL-Note-2002-036, CERN Note.

[14] S. Aumon et al, Fast Transverse Instability at Transition Energy in the CERN PS, CERN Note.

[15] B. Salvant, CERN-THESIS-2010-087.

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