IMPEDANCE LOCALIZATION MEASUREMENTS USING AC DIPOLES IN THE LHC

N. Biancacci. L. Carver, G. Papotti, T. Persson, B. Salvant, R. Tomàs, CERN, Geneva, Switzerland

Abstract

The knowledge of the LHC impedance is of primary importance to predict the machine performance and allow for the HL-LHC upgrade. The developed impedance model can be benchmarked with beam measurements in order to assess its validity and limit. This is routinely done, for example, moving the LHC collimator jaws and measuring the induced tune shift. In order to localize possible unknown impedance sources, the variation of phase advance with intensity between beam position monitors can be measured. In this work[1] we will present the impedance localization measurements performed at injection in the LHC using AC dipoles as exciter as well as the underlying theory.

INTRODUCTION

Elements like the resistive wall of the beam pipe, RF cavities, kickers and collimators are often large impedance sources. Measuring the betatron coherent frequency shift with intensity gives information on the total reactive transverse impedance according to Sacherer's theory [1]. An extension of this method for measuring the reactive part of transverse localized impedances was proposed the first time in 1995 at CERN [2] by measuring the impedance-induced betatron phase advance shift with intensity, and continued in 2004 in the SPS [3,4] and in the BNL RHIC [5]. In this work we briefly review the impedance localization method based on the impedance-induced phase advance shift with intensity proposing the application of the AC dipole excitation to improve the method capabilities [6].

A circulating beam performs betatron oscillations that may be enhanced by means of a kick. The natural transverse coherent modes of oscillation described in Sacherer's theory are subject to an intensity dependent shift. The contribution of an impedance source to the, e.g. vertical, tune shift increases proportionally to the machine unperturbed betatron function $\beta_y^0(s)$ function and the total effective imaginary part of the impedance $Z_y^{eff}(s)$ (i.e. the impedance weighted by the bunch spectrum). It can be proved [7], that a source of impedance localized at $s = s_k$ along the accelerator will appear as an intensity dependent quadrupole of strength $\mathrm{d}K_{y_k}/\mathrm{d}N_b$ defined as

$$\frac{\mathrm{d}K_{y_k}}{\mathrm{d}N_b} = -\frac{q^2}{2\sqrt{\pi}\beta^2 E_o \sigma_\tau} Im\left(Z_{y_k}^{eff}\right), \tag{1}$$

where N_b refers to the number of particles with rest energy E_o and charge q travelling at relativistic β within a bunch of rms-length σ_τ in s.

Associated with a quadrupolar kick there are also a β-beating and a phase advance beating wave along the machine. Given a reference Beam Position Monitor (BPM) placed for convention at $s = 0$ in the machine, we can define $\mu_y(s)$ as the phase advance from the reference BPM position to the s position in units of 2π.

Defining the unperturbed phase advance as $\mu_y^0(s)$, the phase advance slope versus intensity $\mathrm{d}\mu_y(s)/\mathrm{d}N_b$ due to an intensity dependent quadrupole error located at $s = s_k$ can be calculated as

$$\frac{\mathrm{d}\mu_y(s)}{\mathrm{d}N_b} = \frac{\mathrm{d}Q_{y_k}}{\mathrm{d}N_b}\begin{cases} 1 + \dfrac{c(s)^+ s(s)^+}{\sin(2\pi Q_y^0)}, \text{for } s \geq s_k, \\ \dfrac{s(s)^- c(s)^-}{\sin(2\pi Q_y^0)}, \text{for } s < s_k, \end{cases} \tag{2}$$

with

$$\begin{aligned} s(s)^- &= \sin(2\pi\mu_y^0(s)), \\ c(s)^+ &= \cos(4\pi\mu_y^0(s_k) - 2\pi\mu_y^0(s)), \\ s(s)^+ &= \sin(2\pi\mu_y^0(s) - 2\pi Q_y^0), \\ c(s)^- &= \cos(2\pi\mu_y^0(s) - 4\pi\mu_y^0(s_k) + 2\pi Q_y^0). \end{aligned}$$

We notice that $\mathrm{d}\mu_y(s)/\mathrm{d}N_b$ exhibits a step of $\mathrm{d}Q_{y_k}/\mathrm{d}N_b$ at $s = s_k$. Since the tune shifts associated to impedance are usually negative, the step will be also negative. We conclude noticing that a resistive wall impedance could be treated (on average) as a smoothly distributed quadrupole error provoking a smooth negative slope in the $\mathrm{d}\mu_y(s)/\mathrm{d}N_b$ curve [7].

AC DIPOLE DRIVEN OSCILLATIONS

An AC dipole produces an oscillating field able to excite driven oscillations in the beam [8]. While a normal kick would naturally excite the coherent tune oscillation and sidebands, with an AC dipole it is possible to drive the beam oscillation at different frequencies and maintain coherent oscillations for many turns improving the quality and reproducibility of the optics measurements [9–12].

Figure 1 shows the typical excitation pattern of a driven oscillation at frequency Q_d simulated in HEADTAIL [13, 14]: the ramps before and after the excitation plateau allow for negligible emittance growth [15]. Figure 1 shows the driven Q_d and the natural Q_{nat} frequencies in the spectrum of the transverse beam oscillation during the AC dipole plateau. As we can see the signal corresponding to the driven frequency is much stronger than the natural tune.

The parameter $\delta = Q_d - Q_{nat}$ is the distance between natural and driven frequencies. The phase advance from the

[1] Research supported by the High Luminosity LHC project

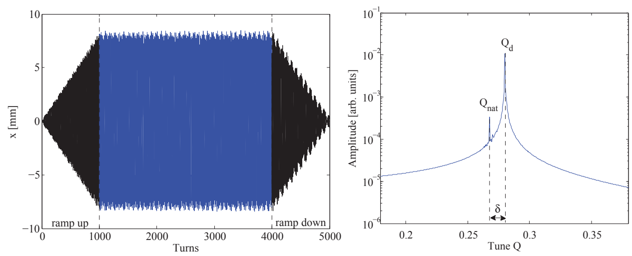

Figure 1: Simulated AC dipole signal (left) and spectrum (right) at the plateau with driven Q_d and natural Q_{nat} tunes.

forced AC dipole oscillation deviates from the natural phase advance according to the relation [16]

$$\tan(2\pi\mu_d - \pi Q_d) = \frac{1+\lambda_d}{1-\lambda_d}\tan(2\pi\mu_{nat} - \pi Q_{nat}), \quad (3)$$

where μ_d is the measured phase advance from the AC dipole location at the driven frequency, μ_{nat} is the phase advance at the natural frequency, and λ_d is given by $\lambda_d = \sin(\pi(Q_d - Q_{nat}))/\sin(\pi(Q_d + Q_{nat}))$. Analogously, the optics at the driven frequency, can be modeled as the natural optics including a quadrupole error of strength K_{AC} at the AC dipole location. The strength K_{AC} is given by [16]

$$K_{AC} = 2\frac{\cos(2\pi Q_{nat}) - \cos(2\pi Q_d)}{\beta_{AC}\sin(2\pi Q_{nat})}, \quad (4)$$

with β_{AC} being the beta function at the AC dipole location.

IMPEDANCE LOCALIZATION MEASUREMENTS WITH AC DIPOLE

We define Q^0_{nat} as the natural tune corresponding to an impedance-free machine (i.e. for virtually $N_b = 0$ ppb). From Eq. (4) the AC dipole driven optics is given by the natural optics perturbed with the quadrupole error

$$K^0_{AC} = 2\frac{\cos(2\pi Q^0_{nat}) - \cos(2\pi Q_d)}{\beta_{AC}\sin(2\pi Q^0_{nat})}. \quad (5)$$

Increasing the intensity by $\mathrm{d}N_b$ a linear tune shift with intensity would modify the coherent natural tune as $Q_{nat} = Q^0_{nat} + \mathrm{d}Q_{nat}$. Inserting this information in Eq. (4) to obtain the equivalent AC dipole quadrupole error, we have

$$K_{AC} = 2\frac{\cos\left(2\pi(Q^0_{nat} + \mathrm{d}Q_{nat})\right) - \cos(2\pi Q_d)}{\beta_{AC}\sin\left(2\pi(Q^0_{nat} + \mathrm{d}Q_{nat})\right)}. \quad (6)$$

Developing at first order considering small tune shifts $\mathrm{d}Q_{nat}$ we get

$$K_{AC} \simeq K^0_{AC} - \frac{4\pi}{\beta_{AC}}\mathrm{d}Q_{nat}\left(1 + \frac{\beta_{AC}}{2}\frac{K^0_{AC}}{\tan(2\pi Q^0_{nat})}\right). \quad (7)$$

For working points sufficiently far from integer and half-integer resonances, we have

$$\frac{\beta_{AC}}{2}\frac{K^0_{AC}}{\tan(2\pi Q^0_{nat})} \ll 1, \quad (8)$$

and, considering the tune derivative versus intensity, we get

$$\frac{\mathrm{d}K_{AC}}{\mathrm{d}N_b} = -\frac{4\pi}{\beta_{AC}}\frac{\mathrm{d}Q_{nat}}{\mathrm{d}N_b}. \quad (9)$$

A step in the slope of phase advance given by Eq. (2) could be distinguished at the location of the AC dipole $s = s_{AC}$

$$\frac{\mathrm{d}\mu_d(s_{AC}+\varepsilon)}{\mathrm{d}N_b} - \frac{\mathrm{d}\mu_d(s_{AC}-\varepsilon)}{\mathrm{d}N_b} = -\frac{\mathrm{d}Q_{nat}}{\mathrm{d}N_b}. \quad (10)$$

with $\varepsilon \to 0$. Therefore, at the AC dipole location, a step corresponding to the opposite sum of all the impedance-induced tune shifts would be observable.

This result is benchmarked with HEADTAIL including a broadband resonator in the LHC beam 1 (B1). The tune shift is expected to be $\mathrm{d}Q_{nat}/\mathrm{d}N_b \simeq -5 \cdot 10^{-14}$. Simulations are performed with a kick and with an AC dipole excitation. Figure 2 shows the phase advance measured at the natural tune and at the driven tune. In both cases the amplitude of the beating oscillation which is roughly the tune shift matches the expected value. Using an AC dipole as exciter, the step in the phase advance at the impedance location is compensated by another step at the AC dipole location as expected from Eq. (10).

This effect can also be intuitively explained since the driven AC dipole frequency does not change with intensity, and eventual steps in the phase advance slope versus intensity must be compensated at the AC dipole location.

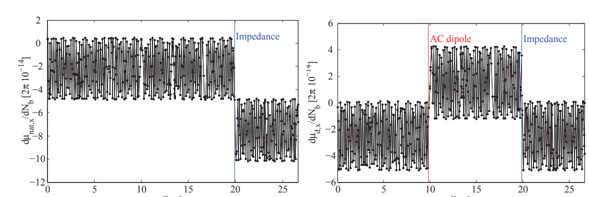

Figure 2: Phase advance beating for an impedance placed in the LHC with kick (left) and AC dipole (right) excitation.

Following these observations, a negative step in the phase advance variation with intensity is correlated with localized impedance sources, while a positive step at the AC dipole location is correlated with the opposite sum of all the machine impedances.

The accuracy of the method is mainly determined by the accuracy of the phase advance measurements. Considering a set of M phase advance measurements at different intensities $Y \in \{Y_1, Y_2, \ldots, Y_M\}$ with negligible uncertainty in the intensity measurement, assuming a BPM system capable of recording N number of turns, the uncertainty in the phase advance slope with intensity $\sigma_{\Delta\mu/\Delta N_b}$ can be found as [7]

$$\sigma_{\Delta\mu/\Delta N_b} = F^{tot}_{\Delta\mu}\frac{\mathrm{NSR}}{\sigma_Y\sqrt{M}\sqrt{N}}, \quad (11)$$

where σ_Y is the standard deviation of the intensity scan Y, NSR $= \sigma_n/\mathrm{A}$ the *Noise to Signal Ratio* with σ_n the standard deviation of the Gaussian noise supposed additive , A

ISBN 978-3-95450-147-2

the signal amplitude at the BPM, and F^{tot} a parameter depending on the Fourier Transform algorithm. For example, with SUSSIX [17] we estimate $F^{tot}_{\Delta\mu} \simeq 0.73$, for NAFF [18] $F^{tot}_{\Delta\mu} \simeq 1.16$, and for a standard FFT $F^{tot}_{\Delta\mu} \simeq 0.37$. This uncertainty should be compared with the impedance-induced phase advance amplitude of Eq. (2).

MEASUREMENTS IN THE LHC

The considerations done in the previous section suggest a method for measuring the total and localized impedance in circular accelerators with an AC dipole: the machine can be filled with a few well separated number of bunches with different intensities, the coherent oscillation excited with the AC dipole and the oscillations acquired for all the bunches at the same time. Alternatively, a single high intensity bunch could be scraped progressively in order to scan different intensities. From the BPM signal the driven optics can be inferred at each intensity. Taking the driven phase advance variation over the intensity scan we can access the information about the impedance distribution along the machine.

In this frame, a first exploratory measurement was done on 28/11/2012 in the LHC for the determination of the measurement accuracy from multi-turn data acquisition. A single high intensity bunch of $N_b \simeq 3 \cdot 10^{11}$ ppb was progressively scraped to $N_b \simeq 10^{11}$ ppb acquiring $M = 14$ phase advance measurements at different intensities. The measurement was done at the injection energy $E = 450\,\text{GeV}$ over 20 minutes. The machine natural tunes were $Q^0_{nat,y} = 0.3085$ and $Q^0_{nat,x} = 0.2743$ and the AC dipole oscillations were driven at $Q_{d,y} = 0.32$ and $Q_{d,x} = 0.27$. A number of $N = 2200$ of coherent driven oscillations were recorded by the BPM system.

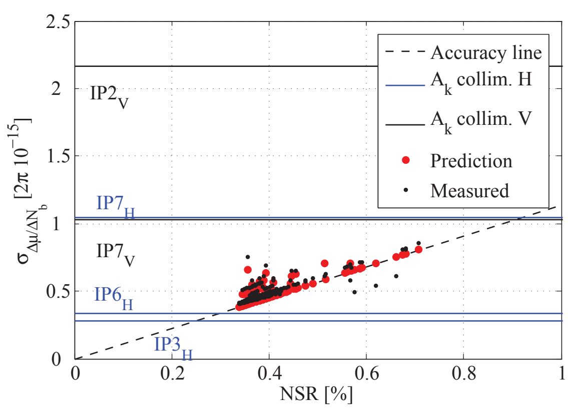

Figure 3: Phase advance slope uncertainty in the LHC machine. Black and red dots represent respectively the measured and predicted uncertainty. Horizontal lines are the signal amplitudes expected from the impedance of horizontal (in blue) and vertical (in black) collimators.

Figure 3 shows the uncertainty predicted with Eq. (11) and measured from the measured phase advances, compared with the amplitudes expected for the most relevant collimator families at the interaction points (IPs) (cfr. Eq. (2)). As we can see a good measurement accuracy is achievable for $NSR < 1\%$.

A second measurement was done on 29/08/2015 on the LHC B1 [19]. The machine was setup at injection with Q'≃ 5 for both beams both planes with 4 bunches with intensities from $6 \cdot 10^{10}$ ppb to $1.2 \cdot 10^{11}$ ppb. Figure 4 shows the phase advance beating as a function of the machine longitudinal position: the step at the AC dipole location is clearly visible for both planes and corresponds to a tune shift of $\simeq 10^{-3}$, a factor $\simeq 2$ higher if compared with the impedance model predictions [20]. Shaded area represents the measurement error. Due to the NSR level, ($\simeq 5-10\%$), the contribution from the collimators at each IP cannot be measured, but the negative slope that gathers the contribution of all the distributed impedance elements (resistive wall, holes, etc.) can be disentangled.

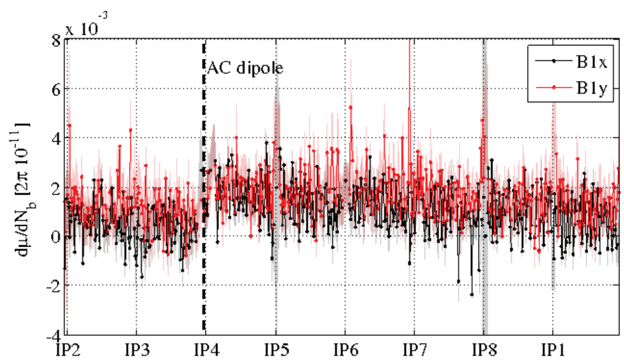

Figure 4: Phase advance beating in the LHC measured with AC dipole.

CONCLUSIONS

In this work we present the application of the AC dipole excitation to the impedance localization method, both from a theoretical and experimental point of view.

The method is based on the acquisition of AC dipole induced betatron oscillations at the BPMs for different beam intensities. The observation of steps in the phase advance variation with intensity is associated with existing impedance sources: a negative step is correlated with localized impedance sources while a positive step at the AC dipole location is correlated with the opposite sum of all the machine impedances. An appropriate pseudo-inversion can therefore be implemented associating defocusing quadrupoles to the machine impedances and a single focusing quadrupole at the AC dipole location lumping the whole machine impedance.

The first exploratory measurements in the LHC have been promising (accuracy achievable and AC dipole step visible) and a new campaign of impedance measurements is currently taking place.

This work is of particular interest for future projects like HL-LHC and the FCC, in which the machine impedance may represent a problem [21] and accurate tools for impedance localization are required.

REFERENCES

[1] F. J. Sacherer. Transverse bunched beam instabilities: Theory. (CERN-MPS-INT-BR-74-8), Apr 1974.

[2] D Brandt, P Castro, Karel Cornelis, A Hofmann, G Morpurgo, G L Sabbi, J Wenninger, and Bruno W Zotter. Measurements of impedance distributions and instability thresholds in LEP. (CERN-SL-95-34 AP):4 p, Jun 1995.

[3] G. Arduini, C. Carli, and F. Zimmermann. Localizing Impedance Sources from Betatron-phase Beating in the CERN SPS. (CERN-AB-2004-083), Aug 2004.

[4] R. Calaga, G. Arduini, E. Métral, G. Papotti, D. Quatraro, G. Rumolo, B. Salvant, and R. Tomás. Transverse impedance localization using intensity dependent optics. *Proc. of PAC 2009, Vancouver, Canada*, 2009.

[5] R. Calaga. RHIC impedance measurements. *APEX Workshop, Stony Brook University, NY, USA*, 2010.

[6] N. Biancacci and R. Tomás. Using ac dipoles to localize sources of beam coupling impedance. *Phys. Rev. Accel. Beams*, 19:054001, May 2016.

[7] N. Biancacci. *Improved techniques of impedance calculation and localization in particle accelerators*. PhD thesis, 2014.

[8] M. Bai et al. Overcoming intrinsic spin resonances with an rf dipole. *Phys. Rev. Lett.*, 1998.

[9] R. Miyamoto. *Diagnostics of the Fermilab Tevatron Using an AC dipole*. VDM Publishing, 2009.

[10] R. Tomás, T. Bach, R. Calaga, A. Langner, Y. Levinsen, E. Maclean, T. Persson, P. Skowronski, M. Strzelczyk, G. Vanbavinckhove, and R. Miyamoto. Record low β beating in the LHC. *Phys. Rev. ST Accel. Beams*, 15:091001, Sep 2012.

[11] S. White, E. Maclean, and R. Tomás. Direct amplitude detuning measurement with AC dipole. *Phys. Rev. Spec. Top. Accel. Beams*, 16(7):071002. 12 p, 2013.

[12] T. H. B. Persson, Y. Inntjore Levinsen, R. Tomás, and E. H. Maclean. Chromatic coupling correction in the large hadron collider. *Phys. Rev. ST Accel. Beams*, 16:081003, Aug 2013.

[13] G. Rumolo and F. Zimmermann. Practical user guide for HEADTAIL. Technical Report SL-Note-2002-036-AP, CERN, Geneva, Nov 2002.

[14] N. Biancacci. HTWG meeting: HEADTAIL and MAD-X, CERN, Geneva, Switzerland, 23 Mar 2012.

[15] R. Tomás. Adiabaticity of the ramping process of an AC dipole. *Phys. Rev. ST Accel. Beams*, 8:024401, Feb 2005.

[16] R. Miyamoto, S. E. Kopp, A. Jansson, and M. J. Syphers. Parametrization of the driven betatron oscillation. *Phys. Rev. ST Accel. Beams*, 11:084002, Aug 2008.

[17] R. Bartolini and F. Schmidt. in Proceedings of Nonlinear and stochastic beam dynamics in accelerators: A challenge to theoretical and computational physics, edited by Bazzani, A. and others (Hamburg, DESY 1998), p.390.

[18] J. Laskar, C. Froeschlé, and A. Celletti. The measure of chaos by the numerical analysis of the fundamental frequencies. Application to the standard mapping. *Physica D Nonlinear Phenomena*, 1992.

[19] N. Biancacci et al. MD 349: Impedance Localization with AC-dipole. Jan 2016.

[20] N. Biancacci et al. Stability margins. LBOC meeting, CERN, 22 March 2016.

[21] X. Buffat and B. Salvant. Impedance meeting: Introduction to FCC-hh impedance, CERN, Geneva, Switzerland, 16 Mar 2015.

ISBN 978-3-95450-147-2