FIRST BTF MEASUREMENTS AT THE LARGE HADRON COLLIDER

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Abstract

During the Run I in 2012, several instabilities have been observed at the Large Hadron Collider (LHC) during the betatron squeeze. The predictions of instability thresholds are based on the computation of the beam Landau damping by calculating the Stability Diagrams (SD). These instabilities could be explained by a deterioration of the SD due to beam-beam resonance excitation which could change the particle distributions. Beam Transfer Functions (BTF) provide a measurement of the SD. The BTFs are sensitive to the particle detuning with amplitude as well as to the particle distributions therefore they represent a powerful tool to experimentally understand the stability of beams during the LHC operational cycle. First BTF measurements at the LHC are presented for different machine configurations and settings and compared to predictions.

INTRODUCTION

In the LHC, the Landau octupole magnets are powered to provide the necessary tune spread to stabilize the beams by the Landau damping mechanisms [1]. In order to predict the Landau damping and quantify the stability threshold, the SDs are analytically evaluated by solving the dispersion integral for a given detuning $\omega_{x,y}(J_x, J_y)$ and particle distribution $\psi(J_x, J_y)$ as a function of the transverse actions J_x and J_y in each plane [2]:

$$SD^{-1} = \frac{-1}{\Delta Q_{x,y}} = \int_0^{\infty} \frac{J_{x,y}}{\Omega - \omega_{x,y}(J_x, J_y)} \frac{d\psi}{dJ_{x,y}} dJ_x dJ_y \quad (1)$$

where $\Delta Q_{x,y}$ are the complex tune shifts at the stability limits for each frequency Ω. The term $\omega_{x,y}(J_x, J_y)$ contains the information about the spread that can be affected by other sources of non-linearities in the accelerator machine such as the beam-beam interaction, space charge and electron cloud. In presence of strong excited resonances the beam particle distribution could also be modified leading to a change of the SD provoking a lack of Landau damping. During the Run I of the LHC in 2012, several instabilities have been observed at the LHC during the betatron squeeze that could be explained by deterioration of the SD due to beam-beam resonance excitation. BTF measurements are direct measurements of the SD [3] and they can be used to experimentally validate the Landau damping models in presence of beam-beam interactions and Landau octupoles interplay. The BTFs are also powerful beam diagnostic tools, for example they can be applied to monitor tunes and to recover the tune spread in presence of coherent beam-beam modes in collider [4] . A transverse BTF system was installed in the LHC in 2015 and tested for the first time. First measurements performed for different machine settings are presented and compared to predictions.

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THE TRANSVERSE BTF SYSTEM

The transverse BTF system of LHC was developed and installed in the LHC during the first part of 2015. During a BTF acquisition the chosen beam is safely excited, i. e. without causing losses or emittance blow up, within a betatron frequency range of interest in both planes. The beam is excited by the kickers of the transverse damper (ADT), while the beam response is recorded by the Beam Position Monitors of the BBQ (Base Band Q measurements) system. The measured SD is reconstructed through the relation: $SD = 1/R(\Omega)$, where $R(\Omega)$ is the complex BTF response at each excitation frequency Ω and it is defined as the dispersion integral in Eq.(1).

Set-up of the BTF System

The BTF system was set-up in order to be completely transparent to the beams at injection on low intensity bunches. Since the calibration of the system was not yet performed the excitation amplitudes can not be expressed in units of beam transverse RMS size. To find an optimum BTF excitation with neither emittance growth nor losses, an empirical approach was chosen keeping a sufficient amplitude and phase response signal to noise ratio. During the set-up, Beam 1 (B1) was excited in the vertical plane with different amplitudes: 1.0, 1.8, 3.6, 5.8 (a.u.) until an emittance blow up was observed in the Beam Synchrotron Radiation Telescopes (BSRT) as shown in Fig. 1 where the black dashed lines correspond to excitation amplitude changes. An emittance blow up of $\approx$ 10% was observed for the last step, therefore we have set the excitation amplitude at 1.0 a.u.

TRANSVERSE BTF MEASUREMENTS AT THE LHC

Transverse BTF measurements are presented for different machine settings. They have been performed on a single bunch with the ADT turned off to avoid the transfer function contribution of

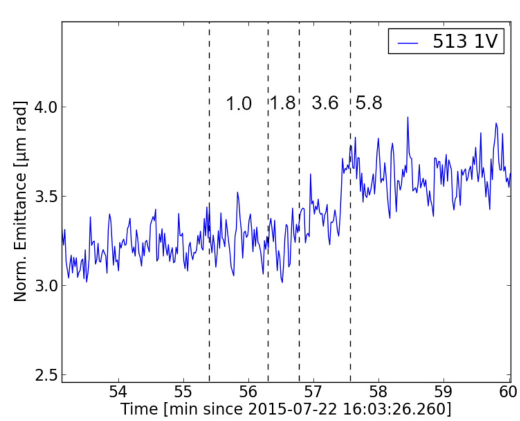

Figure 1: Normalized emittance for Beam 1 vertical while scanning the excitation amplitude of the BTF.

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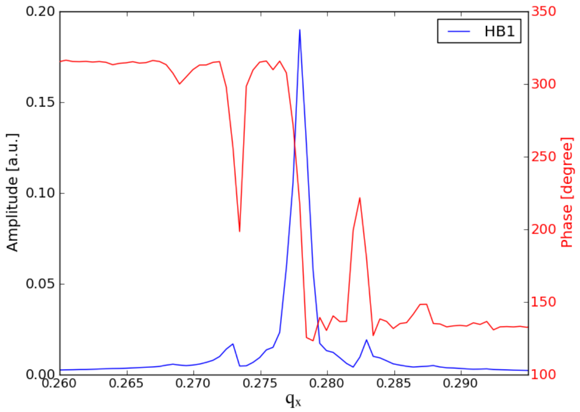

Figure 2: The BTF amplitude response and phase for B1 horizontal plane.

the ADT in the BTF signal. A typical BTF measurement is shown in Fig. 2 where the beam amplitude response for B1 is plotted with the corresponding phase response. Phase jumps are visible in correspondence of the horizontal betatron tune, ~ 0.28 at injection, and in correspondence of the synchrotron sidebands expected to be at $\pm 5 \times 10^{-3}$ from the bare betatron tune at injection energy.

Octupole Scan at Injection

An octupole current scan was performed at injection energy on nominal bunches with collision tunes (0.31, 0.32). Figure 3 shows the measured BTF amplitude responses for B1 in the horizontal plane as a function of the octupole current from 0 A to 13 A, 26 A, 6.5 A in sequence. Each amplitude response is normalized to its maximum amplitude value at the betatron frequency. The width of the amplitude response increases with the octupole current due to the largest tune spread in the beam. The BTF amplitude response for an octupole current of 0 A (blue line) is shown in Fig. 4 for B1 horizontal plane and compared to predictions. Simulations are carried out by using the COMBI code (Coherent Multibunch Beam-beam Interaction) [5, 6] in presence of a linear detuning due to an octupole current of 5 A and for a chromaticity $Q' = 7$ units (green line). The red line represents simulations by the PySSD code [7] that computes the SD from the calculation of the dispersion integral in Eq.(1) for a Gaussian distribution. The amplitude detuning is

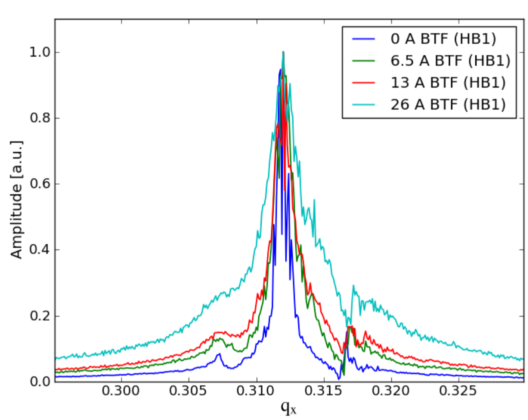

Figure 3: Measured BTF amplitude response in the horizontal plane for B1 as a function of the octupole current.

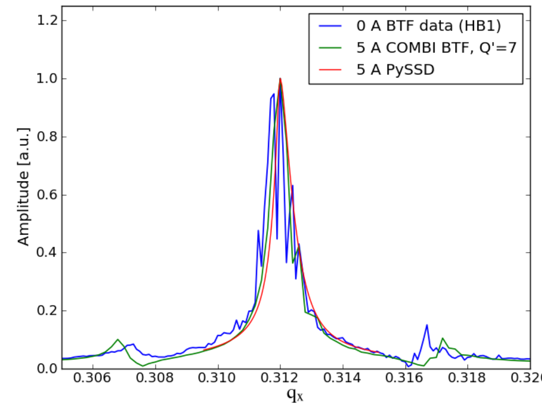

Figure 4: Measured BTF amplitude response for an octupole current of 0 A at injection energy compared to simulations.

computed by the MAD-X tracking module [8, 9] for an octupole current of 5 A. As shown, the measured BTF amplitude width is reproduced for an octupole current of 5 A. The discrepancy between the measured spread with 0 A octupole current and the one recovered by simulations is still not fully understood. A larger tune spread could be due to machine non-linearities at injection and other sources of tune spread such as space charge. Further studies are needed, including other measurements in this configuration. The reconstruction of the SD from BTF amplitude and phase response of the beam is shown in Fig. 5 for an octupole current of 6.5 A (blue dots). Measurements are compared to the semi-analytical SD calculation computed by the PySSD code for an octupole current of 11.5 A (red line), for which we have added the 5 A octupole current needed to well reproduce the spread for 0 A as previously presented in Fig.4. For the reconstruction of the SD, the measured BTF amplitude response has been normalized to the predicted amplitude response at the betatron tune, since the calibration of the BTF system was not yet performed.

Colliding Beams

Beam Transfer Function measurements on colliding beams were taken in the LHC both at injection and at top energy. Figure 6 shows the BTF amplitude response for colliding nominal bunches (single bunch per beam) at injection energy with collision tunes in

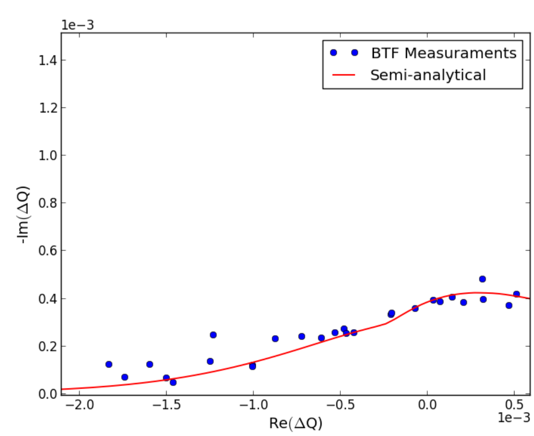

Figure 5: Measured SD at injection with 6.5 A octupole current.

two of the interaction points (IPs) of the LHC: IP1 and IP5. The beam parameters at the moment of the BTF measurements are presented in Table 1 together with the corresponding beam-beam tune shift of the coherent π-mode calculated by the beam-beam parameter, ξ_{bb} as: $\Delta Q = 2 \cdot Y \cdot \xi_{bb}$ where Y is the Yokoya factor $Y = 1.21$ [10]. The expected beam-beam tune shift for B1 was $\Delta Q \approx -0.0133$, and this is consistent with the distance between the π-mode and σ-mode, both visible in the BTF response (Fig. 6).

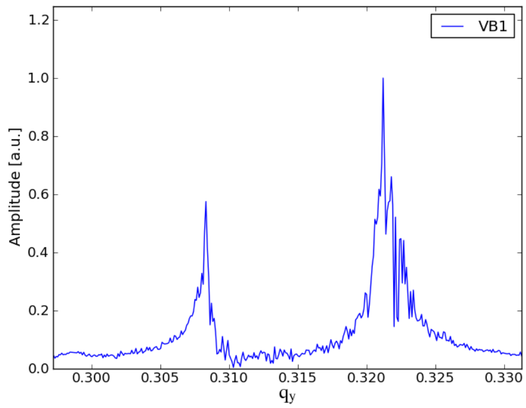

Figure 6: BTF amplitude response for colliding beams, B1 vertical plane.

Table 1: Beam Parameters During BTF Measurements on Colliding Beams at Injection Energy

Beam	**Intensity** 10^{11}[p/b]	**H. Emit.** [μm rad]	**V. Emit.** [μm rad]	ΔQ $(= 2 \cdot Y \cdot \xi_{bb})$
B1	1.09	2.11	2.05	-1.33 $\cdot 10^{-2}$
B2	0.891	1.92	2.01	-1.56 $\cdot 10^{-2}$

Chromaticity Scan at Flat Top Energy

A chromaticity scan at 6.5 TeV has been performed to investigate the impact of chromaticity on the sideband amplitudes in the BTF response. We started from a chromaticity of $Q' \sim 15$ units and reduced to $Q' \sim 5$ units. Measurements have been performed on a single bunch of nominal intensity and are shown in Fig. 7. The BTF amplitude response is normalized to the height of the coherent tune peak. The sideband amplitudes reduce while decreasing the chromaticity value. The ratio between the amplitude of the tune peak and the amplitude of the lower (black dots) and upper (blue dots) sidebands is plotted in Fig. 8. The fit of the data shows a quadratic dependence of the ratio as a function of the chromaticity. This behavior needs to be confirmed by further measurements as a function of the chromaticity.

CONCLUSION

For the first time BTF measurements have been performed in the LHC for several machine configurations. The BTF response as a function of the Landau octupole at injection has been presented. The measured tune spread for the case of 0 A octupole current is found to be reproducible by simulations with an equivalent octupole current of 5 A. This is still not fully understood but could be due to machine non-linearities at injection and/or space charge. As a confirmation, further measurements in this configuration would be

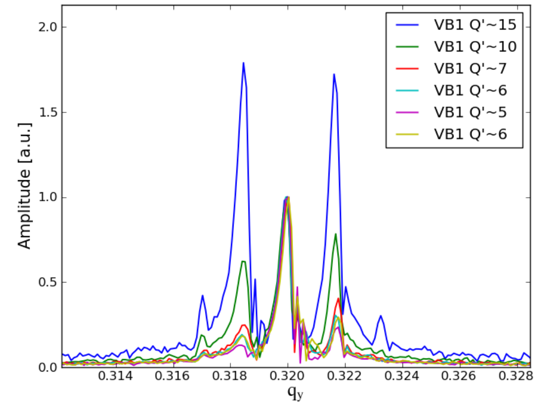

Figure 7: Beam Transfer Function amplitude response as a function of the chromaticity, B1 vertical plane.

required. The first measured SD for the LHC from the BTF complex response has been presented for an octupole current of 6.5 A and compared to predictions. The SD is reproduced by an octupole current of 11.5 A (6.5+5A) in simulations. In order to investigate the effect of long range beam-beam interaction interplay with Landau octupoles on the SD, further measurements are needed in such a complex configuration. Transverse BTF measurements have been acquired also on colliding beams: the π-mode and the σ-mode are clearly visible at the expected frequencies. A chromaticity scan was performed at flat top to investigate the effect of chromaticity on the BTF response and a quadratic dependency has been found. Further studies are needed in order to explore possible scaling laws to predict chromaticity from BTF measurements. Finally, the BTF system could also be applied in the future to study the electron cloud effects.

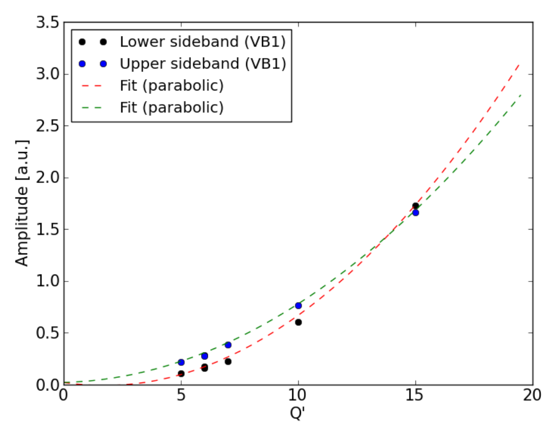

Figure 8: Amplitude ratio between synchrotron sidebands and coherent betatron peak for B1 vertical.

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