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claudia.tambasco@cern.ch

MD 2197: Experimental studies of Landau damping by means of Beam Transfer Function measurements in the presence of beam-beam interactions and diffusive mechanisms

C. Tambasco, J. Barranco*, M. Barros, A. Boccardi, X. Buffat, R. Bruce, M. Gasior, M. Hostettler, T. Lefevre, T. Levens, D. Louro, E. Métral, T. Persson, T. Pieloni*, M. Pojer, B. Salvachua, M. Solfaroli*
CERN, Geneva, Switzerland

Abstract

Beam Transfer Function (BTF) measurements are direct measurements of the stability diagrams that define the stability threshold of coherent beam instabilities driven by the impedance. At the LHC, some coherent instabilities at flat top energy are still not fully understood and the BTF measurements provide a method to experimentally probe the Landau damping of the proton beams. The BTF response is sensitive to the particle distribution changes and contains information about the transverse tune spread in the beams. The BTF system has been installed in the LHC in 2015 in order to investigate the Landau damping at different stages of the operational cycle, machine configurations (different octupole currents, crossing angles, tunes etc...) and in presence of beam-beam excited resonances that may provoke diffusion mechanisms with a subsequent change of Landau damping. Past MDs showed some difficulties for the reconstruction of the stability diagram from BTF measurements and several improvements on the BTF system have been put in place in order to improve the signal to noise ratio. In this note a detailed procedure of the MD is described together with some preliminary results of BTF measurements in the presence of linear coupling.

Keywords: Accelerator physics, beam-beam effects, beam instabilities, Beam Transfer Function, stability diagram

*École polytechnique fédérale de Lausanne (EPFL), Lausanne, CH

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1 Motivation and introduction

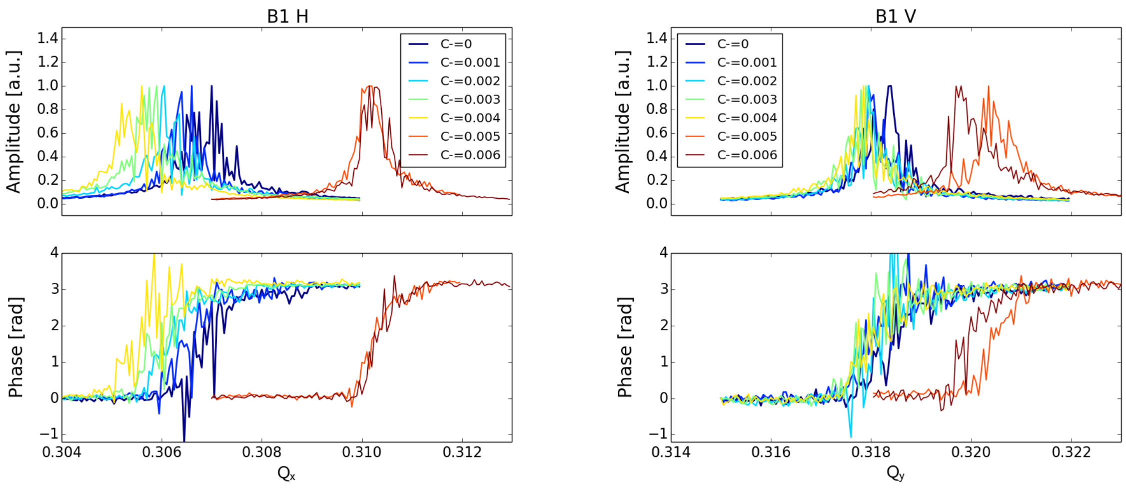
In the past LHC Physics runs several coherent instabilities were observed during the LHC cycle. Possible explanations of the observed instabilities can be found in [1, 2] but the mechanisms are still not fully understood. The Beam Transfer Function (BTF) system was installed in the LHC in 2015 in order to experimentally investigate the Landau damping of the LHC proton beams [3]. The BTF is a direct measurement of the stability diagram that quantifies the stability thresholds due to beam coupling impedance. In the presence of strong beam-beam interactions, particle may diffuse due to beam-beam excited resonances with a consequent change of the particle distribution that may lead to a loss or reduction of Landau damping. The BTF response is sensitive to the particle distribution and can quantify the effects due to the particle distribution changes on the stability diagram [4, 5]. Past MDs have revealed an unexpected Landau damping of the beams at the end of the betatron squeeze [6, 7] when beam-beam long range interactions become important: an important asymmetry between the two planes was observed related to the presence of transverse linear coupling [6]. By including this effect in the models, the observed asymmetry between the two planes can be reproduced [2, 8]. A much smaller tune spread in the vertical plane was found in this configuration, in agreement with BTF measurements. We aim to experimentally evaluate the Landau damping of the beams by means of BTF measurements and understand the limitations of the models due to linear coupling or diffusive mechanisms. Beam Transfer Functions have been acquired as a function of the machine set-up: octupoles linear coupling ($|C^-|$ values) and the results of the measurements are presented in this note.

2 MD procedure

The experiment was carried out the 26$^{\text{th}}$ of July 2017. The first part of the MD was dedicated to test the new GUI developed by the LHC Beam Instrumentation team and test some new BTF features implemented in order to improve the reconstruction of the stability diagram from the measurements. The new features are:

- the possibility to add a delay time between excitation steps in order to let the beam oscillations decay and remove fake tune spread after tune excitation;
- adapting BTF excitation amplitude to improve signal to noise ratio with less impact on beam quality.

By using these new features we tested several settings: number of steps, duration of the BTF excitation and excitation amplitude. Measurements were acquired at injection energy on single nominal bunch



(a) Horizontal plane. (b) Vertical plane.

Fig. 1: Measured BTF on Beam 1 (injection energy) for different values $|C^-|$.

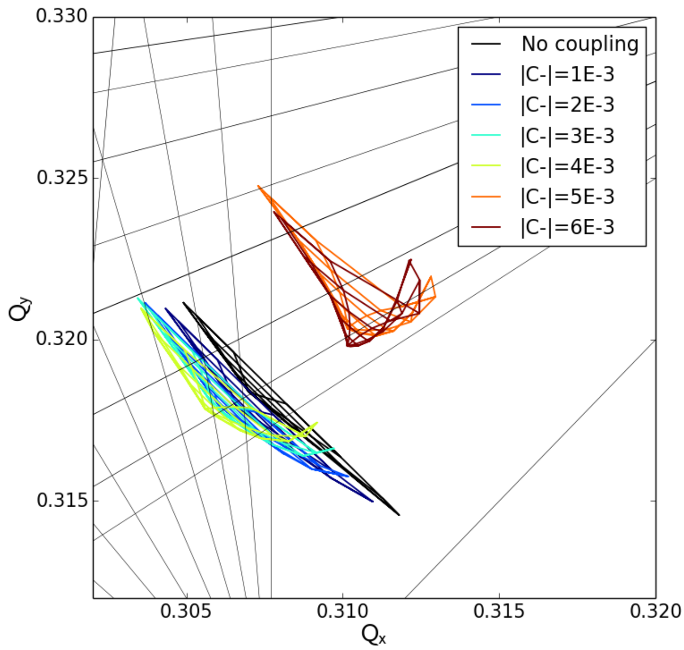


Fig. 2: Tune footprints for without linear coupling (black line) and for different $|C^-|$.

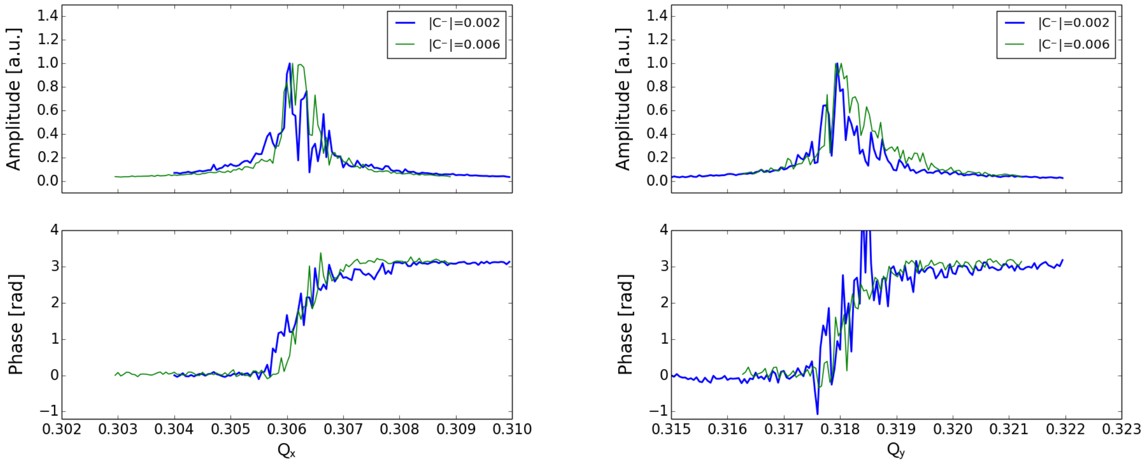
($N_b \approx 1.1 \times 10^{11}$) p/bunch however an optimal set up for stability diagram reconstruction has not been found without impact on beam quality. Due to a cryogenic problem and the limited amount of time, we decided to perform BTF measurements only at injection energy. In this configuration the effect of linear coupling on Landau damping was investigated. The linear coupling was corrected at the beginning of the scan and then introduced in a controlled way. We performed a linear coupling scan from $|C^-| = 1 \times 10^{-3}$ to $|C^-| = 6 \times 10^{-3}$ and acquired BTF measurements for each step. The $|C^-|$ value has been evaluated by the minimum tune approach. At the end of the MD we increased the octupole current from 4 A to 15.6 A and acquired BTF measurements at each octupole current change. Measurements with beam-beam interactions have not been performed due to the limited time available.

3 Preliminary results

Figure 1 shows the BTF responses acquired on single pilot bunch during the linear coupling scan for different $|C^-|$ values. The measurements were acquired with a fixed octupole current $I_{oct} = 4$ A at injection energy with collision tunes (0.31, 0.32). The corresponding expected tune footprints are shown in Fig. 2. The footprints are obtained by the tracking module of MAD-X with tunes, emittances and $|C^-|$ values as during the experiment conditions.

The case without linear coupling (black line in Fig. 2) is compared to the cases with linear coupling for different $|C^-|$. As visible in the presence of linear coupling an overall reduction of the tune spread is expected in both planes as well as a distortion of the footprint with a consequent asymmetry between the horizontal and vertical plane tune spread. This asymmetry becomes more important while increasing the $|C^-|$ value. The BTF measurements in the two transverse planes are shown in Fig. 3 for two different values of $|C^-|$: a smaller one $|C^-| = 2 \times 10^{-3}$ (blue line), and a larger one $|C^-| = 6 \times 10^{-3}$ (green line) .

As expected, an overall reduction of the tune spread is observed by increasing the linear coupling, but it is more important in the horizontal plane (Fig. 3a). A distortion of the BTF is more evident in the vertical plane where the amplitude response is not symmetric anymore: a larger tune spread is observed at betatron frequencies higher than the betatron tune (Fig. 3b). This distorted shape is not an artifact of the BTF signal, since the reversed frequency sweep (from higher to lower frequencies) confirms the same trend (Fig. 4). A similar behavior has been also observed in the vertical plane of Beam 2. This effect has been qualitatively reproduced by using the COMBI code as shown in Fig. 5. The simulated BTF



(a) Horizontal plane.
(b) Vertical plane.

Fig. 3: Measured BTF response in the horizontal (left) and vertical plane (right) of Beam 1 for different values of $|C^{-}|$.

response is plotted in the presence of linear coupling (blue line) and without linear coupling (red line) in both horizontal (Fig. 5a) and vertical (Fig. 5b) plane. As visible in the presence of linear coupling the tune spread is reduced in both cases while the asymmetric response is more pronounced in the vertical plane (Fig. 5b). In this case the BTF response is no longer symmetric around the betatron tune with a long tail appearing on the right side of the vertical betatron tune.

A scan of the octupole current was performed at the last step of the linear coupling scan with $|C^{-}| = 6 \times 10^{-3}$. The octupole current was increased from 4 A to 7.8 A and then to 15 A. The BTF response as a function of the octupole current in the horizontal and vertical plane of Beam 1 is shown in Fig. 6. A larger tune spread is observed in the horizontal plane than in the vertical one. The noise in

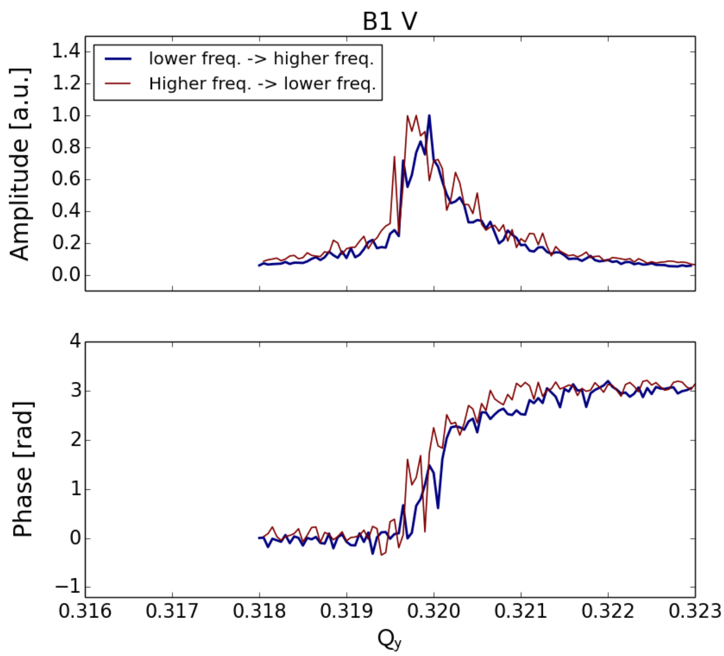
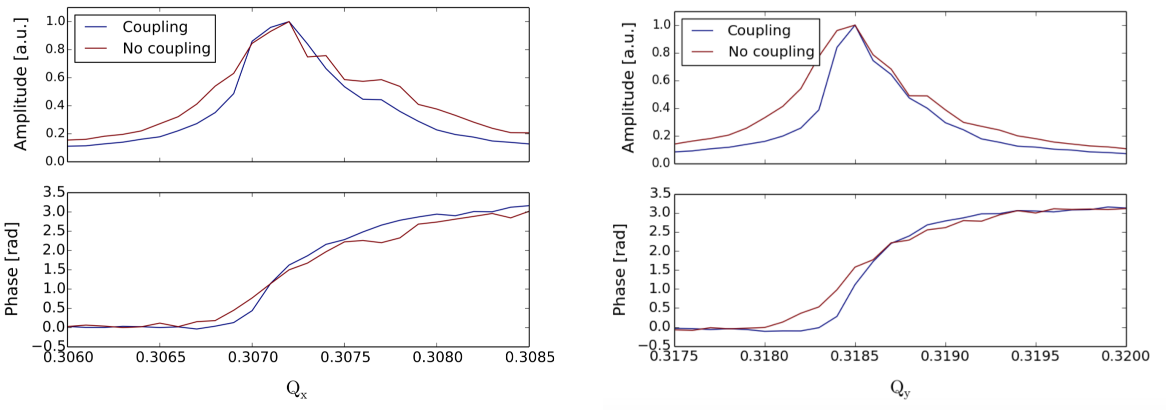


Fig. 4: Comparison of the BTF response in the vertical plane of Beam 1 for a BTF frequency from lower to higher frequencies (blue line) and from higher to lower frequencies (red line).



(a) Simulated BTF response in the horizontal plane.

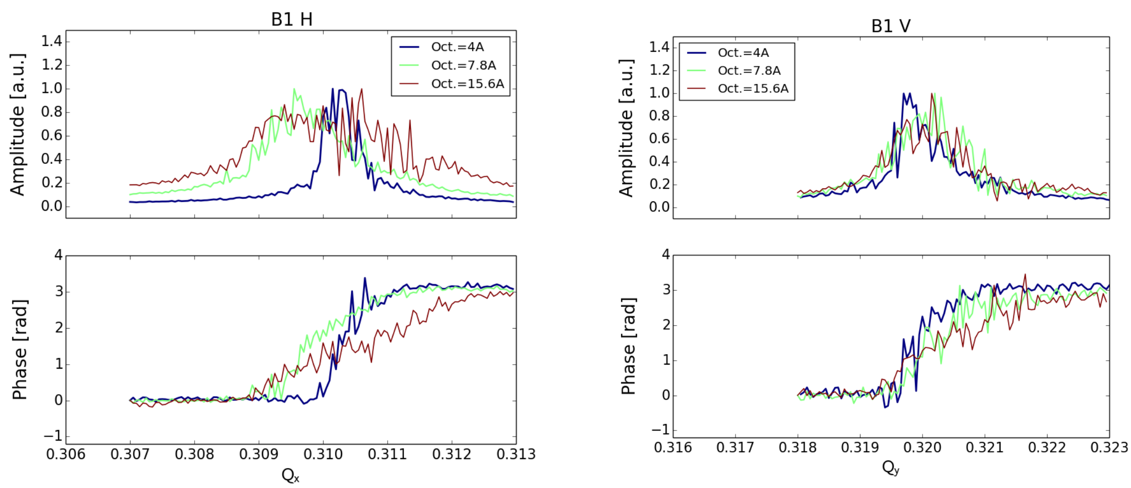
(b) Simulated BTF response in the vertical plane.

Fig. 5: Simulated BTF by using the COMBI code in the presence of linear coupling (blue line) and without linear coupling (red line). Simulations have been carried out for an octupole current of 4 A.

the BTF signal makes the reconstruction of the stability diagram impossible. However by using a fitting function it is possible to evaluate the amount of Landau damping (tune spread) w.r.t. expectations by considering the following parameterization:

$$\begin{cases} \varphi(Q_{meas}) = \varphi\left[p_0 + p_1 \cdot (Q_{model} - Q_0)\right] \\ A(Q_{meas}) = p_2/p_1 \cdot A_{model}(Q_{model}) \end{cases} \tag{1}$$

where the parameter p_0 gives the tune shifts w.r.t. the frequencies of the analytical detuning $(Q_{model} - Q_0)$ with Q_0 the model bare tune, p_1 is a factor related to the measured tune spread w.r.t. the expected one. The factor p_2 is a scaling factor of the amplitude response w.r.t. the reference case (A_{model}). By applying Eq. 1 to the BTF data a quantitative comparison to expectations is carried out. The results of the fit in the horizontal plane are shown in Fig. 7 where the tune spread factor p_1 is plotted as a function of the octupole current. The black line represents the expectations w.r.t. to the initial case of 4 A without linear coupling. The black points are the corresponding measurements. The red line represents the expectations w.r.t. to the initial case of 4 A with linear coupling. An overall tune spread reduction of the 40% is expected for this last case and well reproduced by the measurements (red stars). The colored



(a) Measured BTF response in the horizontal plane.

(b) Measured BTF response in the vertical plane.

Fig. 6: Measured BTF response as a function of the octupole current at injection energy with $|C^-| = 6 \times 10^{-3}$.

shadows represent an uncertainty of ±20% on the transverse emittance for both cases.

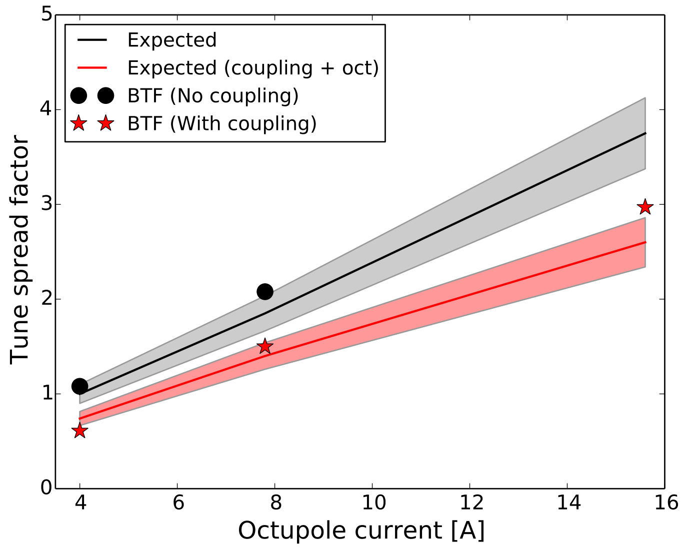


Fig. 7: Measured tune spread factor p_1 as a function of the octupole current. The black line are the expectations w.r.t. to the initial case of 4 A without linear coupling. The black points are the corresponding measurements. The red line represents the expectations (including the linear coupling in the model) w.r.t. to the initial case of 4 A without linear coupling, the corresponding measurements are represented by the red stars.

4 Summary

The procedure of the MD has been presented in this note together with some preliminary results. The first part of the MD was dedicated to test the new features of the BTF system: new GUI, possibility to introduce a delay between excitation steps, adapting BTF excitation amplitude. The delay time between excitations removes the fake spread from measurements observed during past MDs. This was confirmed during the MD by looking at the measured tune spread for both frequency sweep directions when in presence of asymmetric BTF response due to linear coupling.

Despite the adapting excitation amplitude it was not possible to improve the signal to noise ratio, which is critical for stability diagram reconstruction, without causing emittance blow up. Further improvements are needed in order to reconstruct the stability diagrams from BTF measurements with the level of accuracy needed to study more subtle mechanisms, such as the modification of the beam distribution.

Due to a cryogenic problem and limited time we performed BTF measurements at injection to study the effects of linear coupling on Landau damping. Therefore, the planned measurements with beam-beam interactions at the end of the betatron squeeze have not been performed. A linear coupling scan was performed for different $|C^-|$ values at injection energy. An asymmetric tune spread was observed between the horizontal and the vertical plane, that becomes more important while increasing the $|C^-|$ values. The distortion of tune spread in the vertical plane is more visible than the horizontal plane as also expected from BTF simulations with COMBI in presence of linear coupling. An overall reduction of Landau damping (tune spread) by increasing the linear coupling was expected and confirmed by BTF measurements that reproduce well the tune spread expectations in the horizontal plane by using a fitting function method. A reduction of Landau damping of $\approx 40\%$ was measured and it is consistent with expectations. The use of the fitting function for the BTF data in the vertical plane seems to be limited by the shape of BTF response that makes difficult a quantitative comparison with expectations.

5 Acknowledgements

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6 References

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