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claudia.tambasco@cern.ch

MD 2722: Investigation of Landau damping by means of BTF measurements

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. Pieloni*, M. Pojer, B. Salvachua, M. Solfaroli*
CERN, Geneva, Switzerland

Abstract

Stability diagrams quantify the LHC stability thresholds due to the beam coupling impedance. Beam Transfer Function (BTF) measurements are direct measurements of the stability diagram and therefore of the Landau damping of proton beams. Some coherent instabilities at the LHC are still not fully understood, especially in the presence of beam-beam long range interactions at the end of the betatron squeeze. The beam-beam excited resonances can cause diffusive mechanisms and particle distribution changes that can lead to a different stability w.r.t. expectations for a Gaussian particle distribution. To investigate limitations of the models, a BTF system has been installed in the LHC in 2015 in order to measure the Landau damping. During past MDs several configurations have been investigated: tune shifts and tune spreads of the beams have been measured as a function of the octupole currents, tunes and beam-beam long range interactions. Some measurements artifacts were observed and mitigated, however the signal quality remains too low to allow for an accurate reconstruction of the stability diagram. Improvements on the reconstruction of the stability diagram from BTF measurements will be shown in this note together with results of BTF measurements for different octupole currents at injection energy.

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

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

Contents

1 Motivation and introduction

At the LHC some coherent beam instabilities are still not fully understood especially in the presence of beam-beam interactions at the end of the betatron squeeze [1]. Due to beam-beam excited resonances, the particles may undergo diffusive mechanisms that can lead to a loss or a reduction of Landau damping. This mechanisms could represent a possible explanation of model failure in predicting Landau damping for Gaussian distributions of the beams [2–4]. The BTF system was installed in 2015 in order to measure the stability of the beams and compare measurements with expectations and investigate the limitations of the models. Successful measurements of Landau damping were achieved by means of BTF measurements during past MDs for different machine configurations (injection and flat top energy, linear coupling, beam-beam interactions, octupole currents, tunes) [5–7] . Several effects were unexpected but have given the possibility to identify the impact of linear coupling [8] and of the particle tunes with major impact to the beam tune spread and therefore stability. However despite the efforts, a good reconstruction of the stability diagrams was not achieved due to the noise present in the BTF signal. Due to this, the first part of the MD was devoted to find an optimal setup of the BTF system to reconstruct stability diagrams with high precision and explore the impact of particle distribution changes on the Landau damping of the beams. The detailed procedure will be presented in the note together with some preliminary results. Unfortunately BTF measurements with beam-beam interactions could not be performed due to an instability, which occurred at flat top energy.

2 MD procedure

The experiment was carried out the 27th of November 2017. The first part of the MD was dedicated to find an optimal setup of the BTF system to reconstruct stability diagrams with high accuracy. During the first fill several scans were performed at injection energy on both beams as function of different excitation lengths, excitation amplitudes and delays on subsequent excitations. For each BTF setup, measurements were acquired 5-6 times in order to allow an averaging of the BTF signal used for the stability diagram reconstruction as well as an estimation of the signal to noise ratio. A good part of the MD was spent for the first fill due to the large amount of BTF acquisitions. For each configuration, BTF measurements were performed with an octupole current of 10 A and low chromaticity ($Q' \approx 0$), on single nominal bunch (both beams) with the ADT switched-off to avoid the ADT response in the BTF signal. During the second part of the MD we wanted to investigate the beam stability at flat top and at the end of the betatron squeeze where beam-beam interactions become important. A train of 48 nominal bunches was injected in Beam 1 and a single lower intensity bunch in Beam 2 ($\mathrm{N_b} \approx 9 \times 10^{10}$ p/bunch). At flat top energy, we acquired BTF measurements on Beam 2 without transverse feedback acting on the single bunch. Whereas measurements could be performed in similar configuration in the past, this time an unexpected instability was observed after the BTF excitation. The impedance was slightly increased w.r.t. those past measurements, due to a reduction of the gap of the secondary collimators. Nevertheless, the octupole current of 510 A used during this experiment is sufficient to stabilise the beams without an external excitation. The mechanism with which the BTF triggered the instability is not clear. Due to the limited amount of time available we decided to not re-inject the beams and rather take advantage of the larger tune spread coming from the beam-beam long range interactions at the end of the betatron squeeze where, unfortunately, the instability was still present. Not even the reduction of the crossing angle, with the consequent increase of the tune spread due to beam-beam long range interactions, was sufficient to stabilise the beams. The crossing angle was reduced in two steps: 290 and 280 µrad. However each time we turned off the transverse feedback to perform BTF measurements, Beam 2 was unstable (chromaticity was set to 10 units). Therefore it was impossible to acquire BTF measurements in this configuration. The correction of the linear coupling from $|C^-| = 5 \times 10^{-3}$ to $|C^-| = 2 \times 10^{-3}$ could not help to increase stability. We therefore decided to dump the beams and acquire some BTF measurements at injection with different octupole currents to conclude the MD.

3 Preliminary results

The first part of the MD was dedicated to the stability diagram reconstruction from BTF measurements. Different settings have been tested in order to improve the signal to noise ratio. For each set-up several

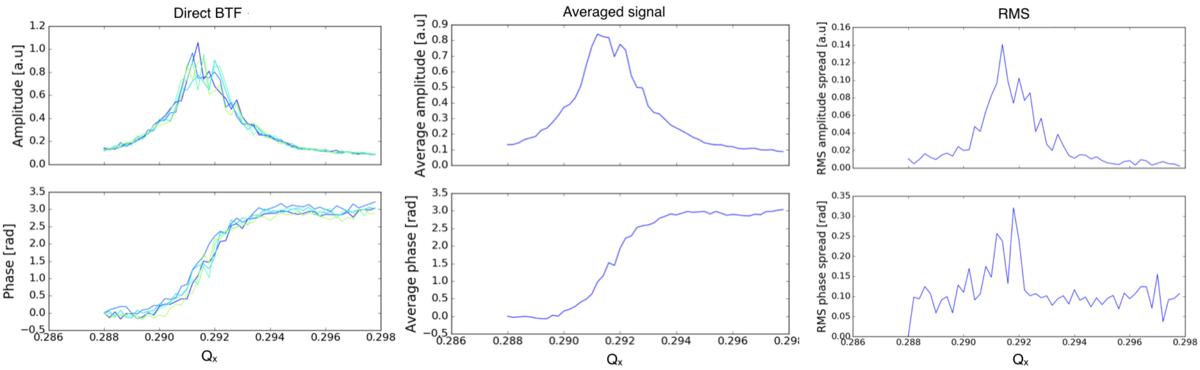
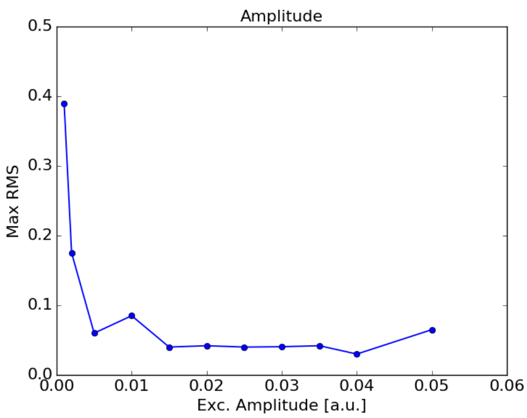
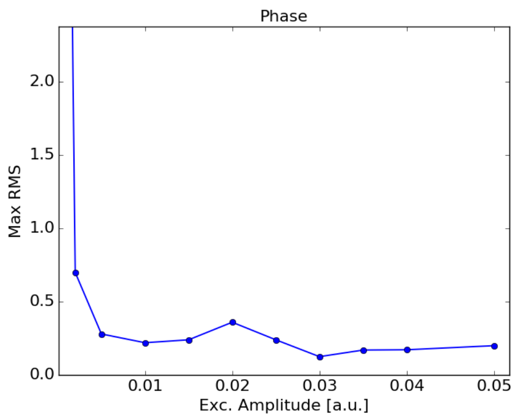


Fig. 1: BTF measurements with averaged signal and rms at injection energy for Beam 1 in the horizontal plane.



(a) Maximum RMS of the amplitude signal.



(b) Maximum RMS of the phase signal.

Fig. 2: Maximum rms calculated over consecutive BTF acquisitions in the same machine and beam conditions as a function of the excitation amplitude (Beam 1 horizontal plane).

measurements have been acquired, then the averaged BTF response has been computed together with the RMS over the different acquisitions. An example of this procedure is shown in Fig. 1.

Several scans have been performed to find an optimal BTF set-up at injection energy (single nominal bunch per beam). The octupole current was fixed to 10 A. Figure 2 shows the maximum rms calculated over different BTF acquisitions as a function of the excitation amplitude, expressed in arbitrary units since the BTF system is not yet calibrated. As expected, the rms is higher for small excitation amplitudes and decreases while increasing the excitation amplitude. In the range of 0.015 - 0.035 [a.u] a plateau is reached, meaning that the signal quality is maximized. An emittance growth was observed in the plane of the scan (horizontal plane of Beam 1) for a amplitudes of 0.04 a.u. and 0.05 a.u. as shown in Fig. 3. For an excitation amplitude of 0.05 a.u. an increase of the rms is observed in the BTF response, probably due to the emittance increase.

A scan of the acquisition length for each BTF frequency step was also performed. Acquiring for a longer period should help to improve the signal to noise ratio. However, contrary to expectations, the noise increases for longer acquisition. This is shown in Fig. 4 where the maximum rms calculated over different BTF acquisitions is plotted as a function of the acquisition length. The red dashed lines represent the case with a small delay between BTF excitations. The signal of the amplitude slightly improves but further data for a longer delay are needed to confirm this trend. No emittance blow-up was observed while increasing the acquisition length per frequency step.

Since the system is not yet calibrated and the excitation amplitude is unknown, the reconstruction of the stability diagram is performed by using the fitting function parameterized as follow:

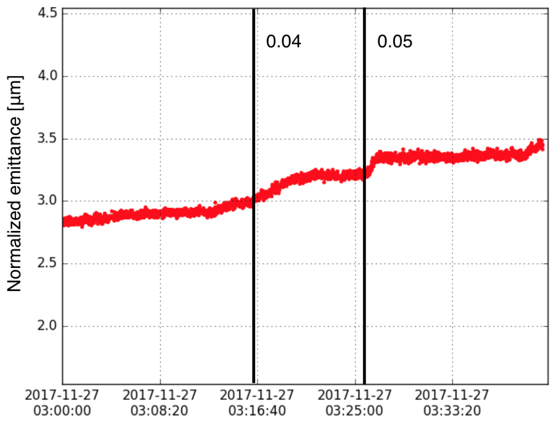
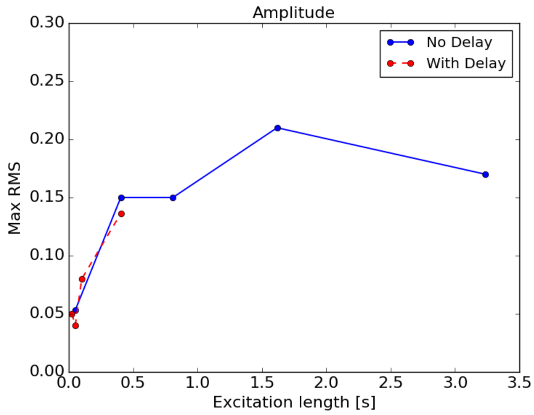
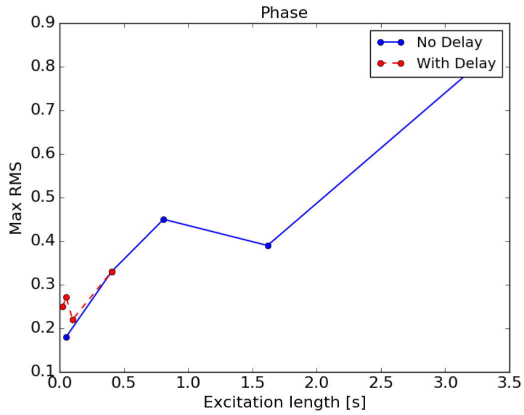


Fig. 3: Normalized emittance during the amplitude scan of the BTF excitation (Beam 1 horizontal plane).



(a) Maximum RMS of the amplitude signal.



(b) Maximum RMS of the phase signal.

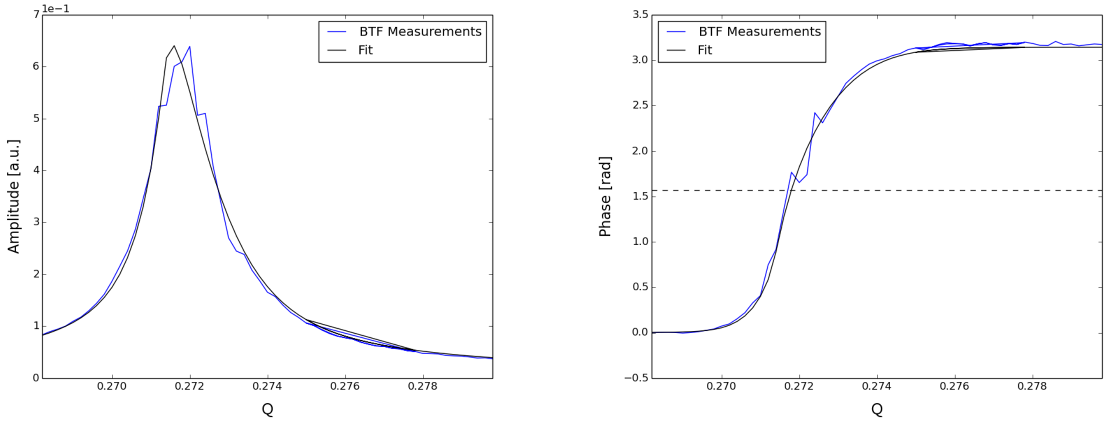
Fig. 4: Maximum rms calculated over different BTF acquisitions as a function of the acquisition length (Beam 1 horizontal plane).

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

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 model is obtained by the computation of the dispersion integral by using the PySSD code [9] including an amplitude detuning evaluated from the tracking module of MAD-X. The factor p_2 is a scaling factor of the amplitude response w.r.t. the reference case (A_{model}). The fitting function is applied to the averaged BTF response. The results of the fit are shown in Fig. 5. The corresponding measured stability diagram (blue crosses) is shown in Fig. 6a, the red line represent the expected reference case according to experimental conditions with an octupole current of 10 A at injection energy. The black line corresponds to the stability diagram resulted from the fitting function. An improvement in the reconstruction of the SD averaging the amplitude and phase signal is observed compared to a case where the averaging of the BTF response is not applied (Fig. 6b). By applying the fitting function, the measured tune spread is 1.71 times larger than the expected one, a similar result is obtained without the averaging method, it differs by 5% w.r.t. the averaged case.

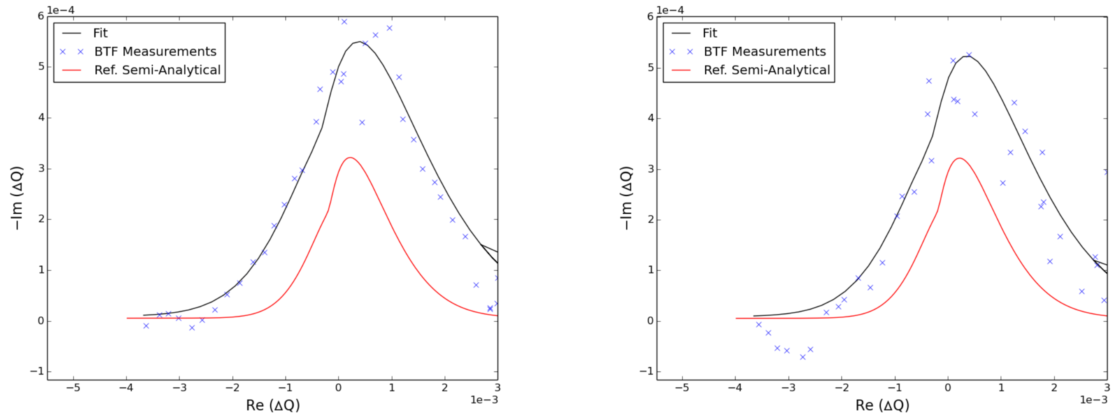
An instability was observed at injection energy on Beam 1 horizontal plane during the BTF acquisition. The BBQ signal and the emittance blow-up are shown in Fig. 7. The instability was due to the drift of the chromaticity, that was measured to be -6 units on Beam 1 and -4 units on Beam 2.

For the second part of the MD we injected one single bunch of 0.9E10 p/bunch in Beam 2 (emit-



(a) BTF amplitude. (b) BTF phase.

Fig. 5: Measured BTF (averaged signal) and applied fitting function. The blue lines are the measurements while the black lines are the computed fits.



(a) Averaged. (b) Raw.

Fig. 6: Reconstructed stability diagram from BTF measurements by applying the fitting function (horizontal plane of Beam 1). The blue crosses are the measurements, the red line represent the expected reference case with an octupole current of 10 A at injection energy. The black line is the stability diagram resulted from the fitting function.

tance: 1.8 μm) and a train of 48 nominal bunches in Beam 1 to study the effect of the long range beam-beam interactions on beam stability and therefore on Landau damping. The asymmetry of the beam intensity was chosen to avoid coherent mode excitation with beams in collisions. After the first BTF acquisition at flat top, an instability occurred in the horizontal plane of Beam 2, as shown in Fig. 8, where the spectrogram of Beam 2 is plotted for the horizontal and the vertical plane. We saved the beam by turning on the transverse feedback that was off for BTF measurements. The octupole current was set to 510 A but each time the ADT was turned off, signs of instabilities were seen in the spectrogram (red spots in Fig. 8). Due to the limited amount of time available we decided to keep the beams and take advantage of the larger tune spread coming from beam-beam long range interactions at the end of the betatron squeeze. However the instability was still present, even for a reduced crossing angle of 290 and 280 μrad. The octupoles were powered with maximum strength and chromaticity that was set to 10 units. Despite this, it was not possible to turn off the transverse feedback to acquire BTF measurements. Figure 9 shows the spectrogram of Beam 2 at the end of the betatron squeeze (nominal 280 μrad crossing angle) and for the two sequentially reduced crossing angle of 290 and 280 μrad (black dashed lines).

We decided to dump the beams and profit of some spare time left to perform an octupole scan at injection energy. Figure 10 shows the BTF measurements acquired at injection energy on Beam 2 horizontal plane for octupole currents of 3 A and 20 A. As visible, increasing the octupole current the tune spread increases. By using the fitting function (Eq. 1), the measured tune spread was found to be 2 times larger than the expected one for an octupole current of 3 A and 1.2 times larger than the expected one for 20 A. The larger tune spread seems to be consisted with previous BTF measurements possibly due to multipolar errors at injection [5] .

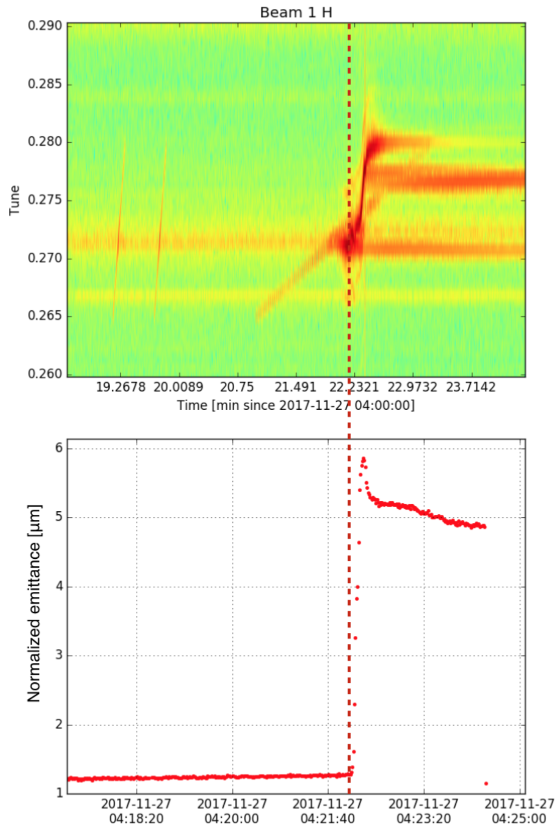
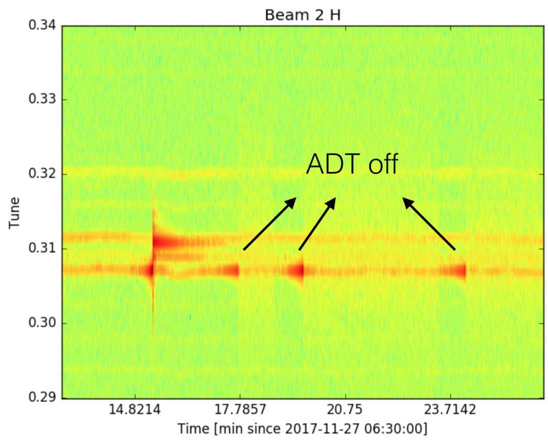
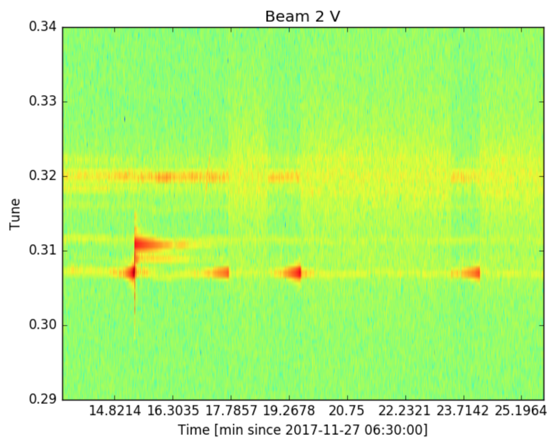


Fig. 7: BBQ signal and normalized emittance of Beam 1 (horizontal plane) at injection energy with 10 A octupole current. Chromaticity was -6 units.

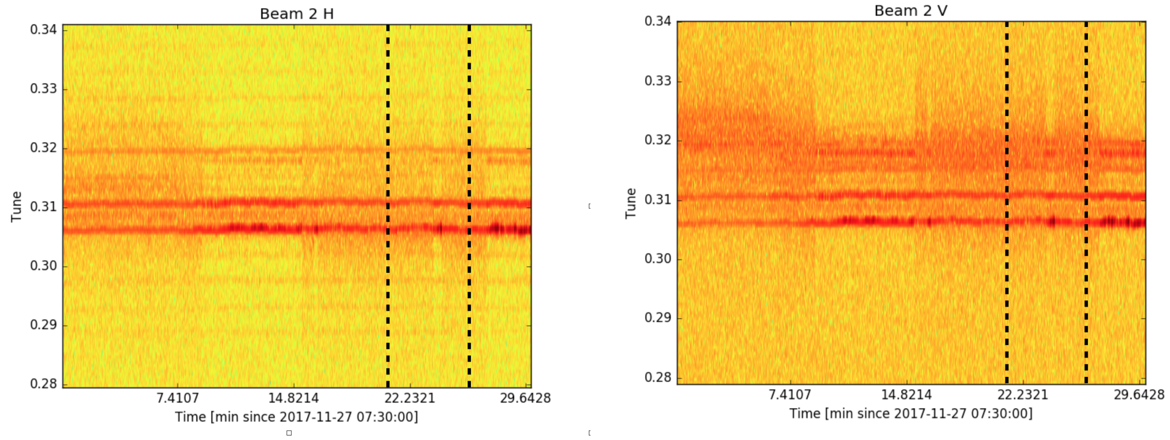


(a) Beam 2 horizontal plane



(b) Beam 2 vertical plane.

Fig. 8: Spectrogram of Beam 2 (BBQ signal) in the horizontal and vertical plane at flat top energy after BTF excitation.



(a) Beam 2 horizontal plane (b) Beam 2 vertical plane.

Fig. 9: Spectrogram of Beam 2 (BBQ signal) in the horizontal and vertical plane at the end of the betatron squeeze after BTF excitation. The black dashed lines represent the time of the crossing angle reduction, from 300 μrad to 290 μrad and then 280 μrad.

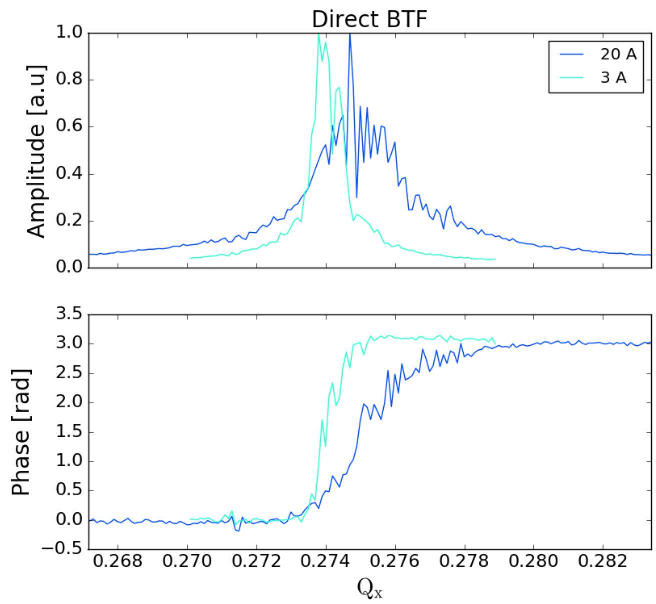


Fig. 10: BTF in the horizontal plane of Beam 2 for an octupole current of 3 A and 20 A.

4 Summary

During the first part of the MD, BTF measurements were acquired at injection energy for both Beam 1 and Beam 2 on single bunch. Several scans have been performed to set-up the BTF measurements and improve the signal to noise ratio for a good reconstruction of the stability diagram. As expected, by increasing the excitation amplitude the noise in the measurements decreases. On the contrary increasing the acquisition length per BTF excitation the noise increases. This was not expected and further investigation are required to better understand this behavior. For each BTF set-up, several measurements were acquired in order to average the BTF signal: a big improvement was observed by using this method to reconstruct the stability diagram by using the fitting function. This method allows a better comparison with the expectations. Instabilities were observed at injection energy due to the BTF excitation: the first one in the horizontal plane of Beam 1 and the second one on horizontal and vertical plane of Beam 2 most probably due to negative chromaticity due to the decay at injection energy (it was measured to be at -6 units). During the second part of the MD at flat top energy we injected a train of 48 bunches in

Beam 1 and lower intensity bunch in Beam 2. At flat top after the BTF excitation an instability was observed. Despite the maximum octupole strength (510 A) and a value of the chromaticity of 10 units, the instability was still present without transverse damper acting on the beam. Further studies are ongoing to understand the reason of this instability. The BTF excitation was small (5×10^{-3} a.u.) and other causes have to be taken into account. At the end of the betatron squeeze the instability was still present without transverse feedback. The crossing angle was reduced from 300 μrad to 290 μrad and then to 280 μrad, however the larger tune spread provided by long range interactions due to the reduced crossing angle could not help to mitigate the instability. Based on this experience, the stability margins have to be increased for the bunches that will experience the excitation for the BTF measurement, either by reducing the machine impedance or reducing the bunch brightness. During the third part at injection energy we recovered earlier settings and an octupole current scan at injection was performed: the measured tune spread for a current of 3.5 A was 2 times larger than expectations, and a 1.2 times larger for a current of 20 A. These results are consistent with past BTF measurements at injection energy. The discrepancy, larger for lower octupole current, can be due to multipolar errors at injection energy as also observed in the past.

5 Acknowledgements

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6 References

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