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First Beam Transfer Function measurements in the LHC

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Abstract

For the first time in the LHC, Beam Transfer Function (BTF) measurements have been performed. Different machine configurations have been tested to determine the safety of the BTF measurement system that results to be completely transparent on single beam. To evaluate the spread given by different Landau octupole currents, an octupole current scan was performed. The data analysis is still ongoing. The BTF measurements have been tested also for beams in collision, the first attempt at $450\,\mathrm{GeV}$ resulted in the excitation of the beam-beam coherent π-mode, while a second attempt at $6.5\,\mathrm{GeV}$ did not show any signs of instability. This is still under investigation and further tests are needed also with trains of bunches.

Keywords: Accelerator Physics, beam-beam effects, beam instabilities.

Contents

1 Motivation

In the LHC Landau octupoles are the main source of spread for Landau damping [1], but this can be affected by other sources of spread in the machine such as the beam-beam interaction or electron cloud. In the 2012 run, several instabilities have been observed during the betatron squeeze where beam-beam interactions become stronger and change the total tune spread. These instabilities are still not fully understood, indeed studies of the Stability Diagrams [2] computed by evaluating the dispersion integral for different tune spread could not explain the 2012 observations in the squeeze [3]. Other possible explanations involve the deprecation of the stability diagram from noise [3] and/or resonances [4, 5]. However, the Stability Diagrams do not depend only in the tune spread but they are also sensitive to particle distribution changes that can deteriorate the stability area significantly causing a lack of Landau damping [6]. The Beam Transfer Function (BTF) measurements are direct measurements of the Stability Diagrams [7] and they can be used to experimentally validate the Landau damping models helping to understand the 2012 instabilities. The final goal is therefore to perform BTF measurements at the end of the squeeze to characterize the long-range beam-beam interactions and Landau octupoles interplay and measure the Stability Diagram in such complex configuration. BTFs are also powerful tools to monitor the machine tunes and coherent beam-beam modes in colliders as for example in RHIC [8] where they are used during operation. In this note the set-up of the BTF measurements in the LHC will be described and some preliminary results will be shown for different machine configurations.

2 The BTF system

The BTF system is installed in parallel to the tune development system in SX4, where the signals from the BPMs arrive over cables long about 500m. The Tune and the BTF systems share the same BPMs, but use independent digitizers whose inputs are connected in a daisy chain configuration. The BPM used for beam 1 are BPLH.A6R4.B1 and BPLV.B6R4.B1, while for beam 2 we use BPLH.B7L4.B2 and BPLV.B5L4.B2. All those BPMs are equipped with non gated front ends, meaning that the system observes the response of the ensemble of all the bunches in the machine. The signals required for the beam excitation and synchronous detection are also generated in SX4 and are sent to the damper system via long coaxial cables. The excitation signals are conditioned before reaching the damper inputs in such a way that a full scale BTF excitation will use about 0.01 % of the damper power.

3 BTF measurements on non-colliding beams

We performed several tests of the BTF measurements for different machine configurations parasitically to some Machine Developments studies (MD) of block I.

3.1 Set up of the BTF measurements

The first test of the BTF was parasitically performed the 22h of July 2015 at injection energy ($450\,\mathrm{GeV}$) with pilot bunches. The data taking was performed by a basic GUI developed with a python based interface: "btf_guy.py" specifying the beam to excite (1 for Beam 1 and 2 for Beam 2). From the interface the user can set the excitation amplitude, the range of excitation frequencies and the resolution of the steps in frequency. The excitation can be performed on the chosen beam and one plane at a time and the data acquisition time depends on the range of excitation frequencies with the chosen resolution. Since the calibration of the system was not performed we could not translate the excitation amplitudes in units of beam RMS size. We opted for an empirically approach to choose an optimum BTF excitation to be completely transparent to the beam (no emittance growth or losses observed) keeping a good amplitude and phase response signal to noise ratio. We excited Beam 1 in the vertical plane with the amplitudes of 1×10^{-2}, 1.8×10^{-2}, 3.6×10^{-2}, 5.8×10^{-2} (a.u.) until an emittance blow up was observed in the Beam Synchrotron Radiation Telescopers (BSRT). This is shown in Fig. 1, the black dashed lines correspond to each time we changed the excitation amplitude. An emittance blow up of $\approx 10\%$ was observed for the last step, therefore we have set the excitation amplitude at 1×10^{-2} a.u. to be completely transparent to the beam.

Figure. 2 shows the measured BTF amplitude response (Fig. 2a) and phase (Fig. 2b) for Beam 1 horizontal plane. The coherent tune peak is observed in the amplitude response together with the synchrotron

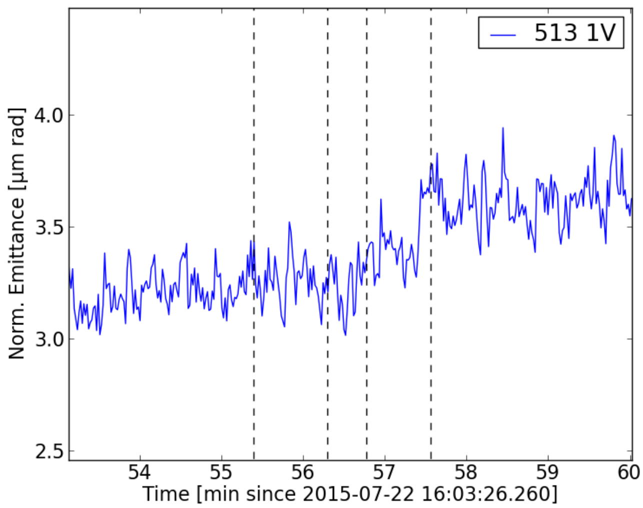
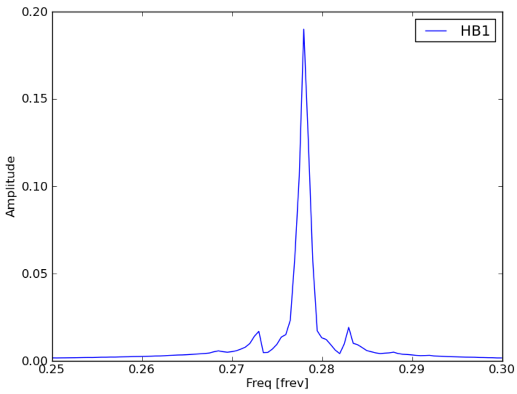
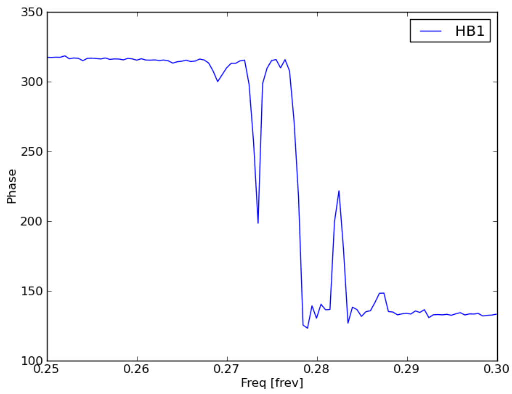


Fig. 1: Normalized emittance for Beam 1 vertical while scanning the excitation amplitude of the BTF. Dashed lines identify the time of change in the amplitudes.



(a) Amplitude response B1 horizontal.



(b) Phase B1 horizontal.

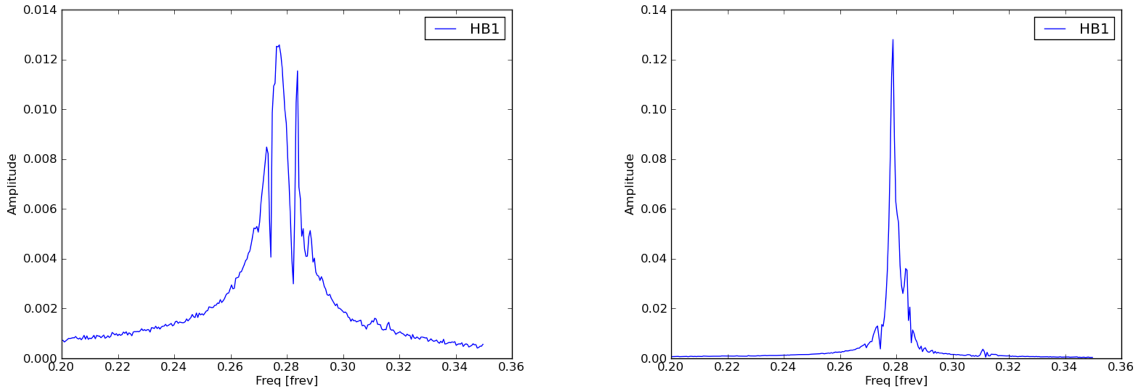
Fig. 2: Measured BTF amplitude response and phase for Beam 1 horizontal plane.

sidebands expected at $\pm 5 \times 10^{-3}$ from the coherent tune at injection. Phase jumps are clearly visible in correspondence of the frequencies of the coherent peaks.

We had also evaluated the effects of the transverse damper (ADT) on the BTF signal. Fig. 3 shows the comparison of the BTF response with the ADT turned on (Fig. 3a) and with the ADT turned off (Fig. 3b). The amplitude response of the BTF results to be strongly affected by the ADT contribution, therefore, BTF measurements have been acquired without ADT acting on the beam.
For the vertical acquisition of Beam 2, the BTF signal resulted to be very noisy and this is still under investigation.

3.2 Octupole current scan

Afterwards testing the setup of the BTF data taking, we performed an octupole current scan on nominal bunches at injection energy with collision tunes (0.31, 0.32). We started with 0 A octupole current and then we moved to: 13 A, 26 A, 6.5 A in sequence. Due to the collision tunes, an octupole current of 26 A was too high since the corresponding spread was bringing 5-6σ particles on the 3rd order horizontal and vertical resonances in the tune diagram (Fig. 4) causing incoherent beam losses. Further analysis would be needed to understand if the losses are mostly due to the horizontal or vertical plane. Figure 5 shows the



(a) ADT turned on.

(b) ADT turned off.

Fig. 3: Measured BTF amplitude response in the horizontal plane for Beam 1 with and without transverse damper acting on the beam.

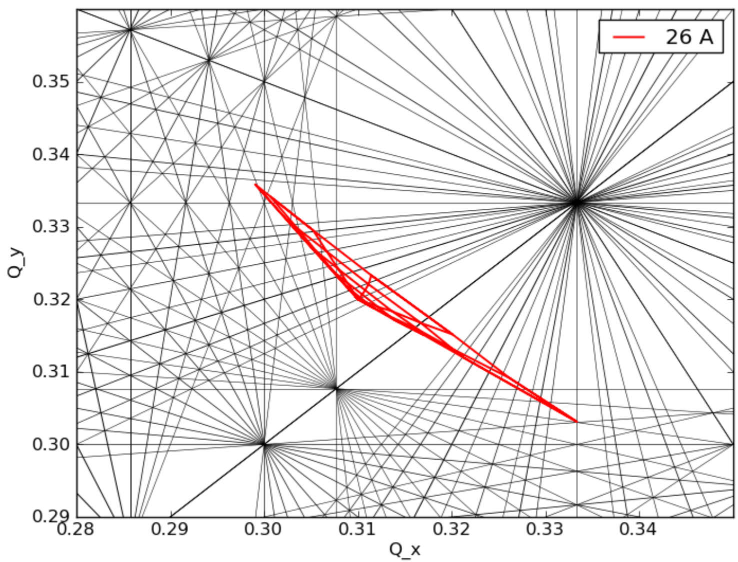


Fig. 4: Tune diagram at injection with collision tunes and octupole current of 26 A.

beam intensity for Beam 1 (red line) and Beam 2 (blue line) together with the octupole current (pink line) and the main frequencies (horizontal and vertical) for both beams. Intensity losses are observed at 18:45 h for Beam 1 and they seem to be related to the tune modulation for chromaticity measurement visible in the main frequencies for Beam 1 in the horizontal and vertical plane (green and brown line respectively). Downstream intensity losses are visible for both beams, in correspondence of 26 A octupole current. We therefore stepped back to 6.5 A to reduce the incoherent losses. For each step in current of the Landau octupoles, we took a BTF measurement for both beams and planes. Figure 6 shows the measured BTF response in function of the octupole current for Beam 1 in vertical and horizontal plane. Each BTF amplitude has been normalized to its maximum amplitude response.

Increasing the octupole current, the width of the amplitude response of the BTF enlarges because the tune spread is increasing. We can also notice that for each current, the highest peak of the BTF response is slightly moving. Figure 7 shows the measured tune shift as a function of the octupole current (blue dots). The variation is calculated with respect to the position of the highest peak of the amplitude response with 0 A octupole current, assumed to be the bare tune. The solid green line represents the corresponding polynomial fit. In case of Beam 1 vertical plane the variation of the tune reaches a maximum value of

$\Delta Q \approx 0.8 \cdot 10^{-3}$ for the highest octupole current of 26 A (Fig. 7b). Further studies are ongoing to explain such effect.

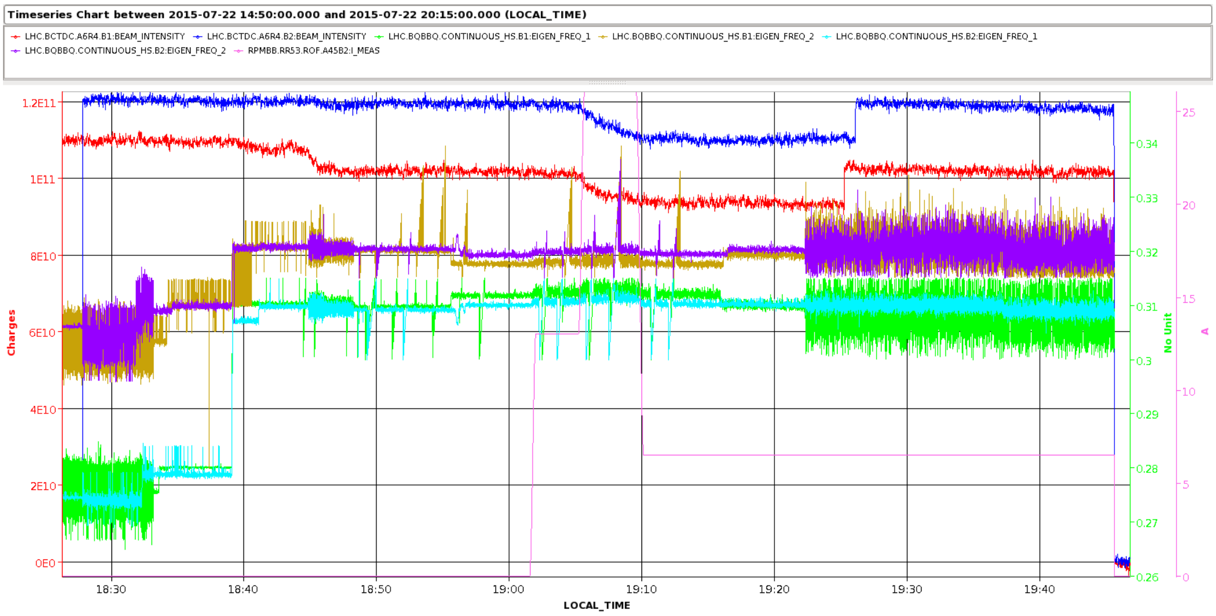
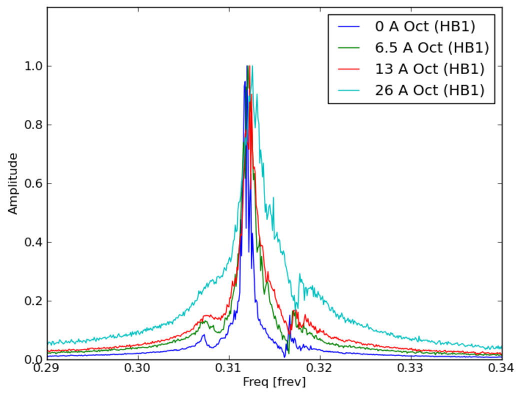
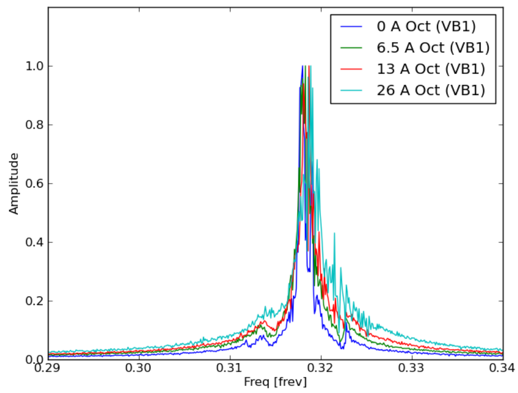


Fig. 5: Summary plot for the test of the 22h July 2015. Total beam intensity for Beam 1 (red line) and Beam 2 (blue line), Landau octupole current (pink line), mean frequency horizontal Beam 1 (green), mean frequency vertical Beam 1 (brown line), mean frequency horizontal Beam 2 (light blue line), mean frequency vertical Beam 2 (purple line).



(a) BTF excitation in the horizontal plane.



(b) BTF excitation in the vertical plane.

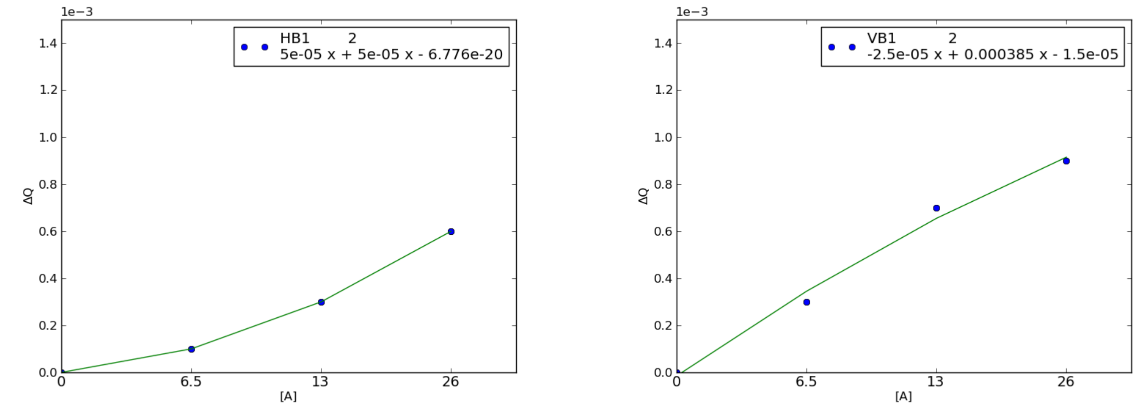
Fig. 6: Measured BTF response for Beam 1 in function of the octupole current.

3.3 BTF measurements at 6.5 TeV

Parasitically to the "Combined ramp & squeeze" MD (23rd of July 2015), the BTF has been tested at 6.5 TeV on pilot bunches. The BTF measurements resulted to be transparent to the beams: no emittance blow up neither losses were observed as well as during a further test on single nominal bunches at flat top during the "Threshold instability" MD (24th of July 2015).

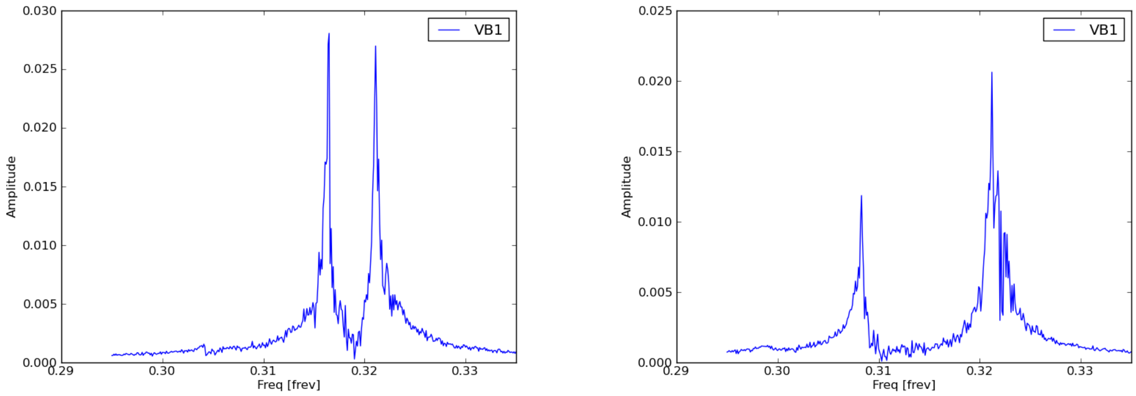
4 BTF measurements on colliding beams

The first BTF measurement with beams in collision was performed during the first fill of the "Head-On" MD of the 24th of July 2015 with nominal bunches at injection energy with collision tunes (single bunch



(a) Tune change in the horizontal plane. (b) Tune change in the vertical plane.

Fig. 7: Tune shift in function of the octupole current for Beam 1. The variation is calculated with respect to the position of the peak given by the BTF measurement with 0 A octupole current. The blue dots correspond to measured data, the solid green line is the corresponding polynomial fit.



(a) BTF amplitude response for colliding beams, before crossing angle plane optimization. (b) BTF amplitude response for colliding beams, after crossing angle plane optimization.

Fig. 8: BTF amplitude response for colliding beams before and after crossing angle plane optimization for Beam 1 vertical plane

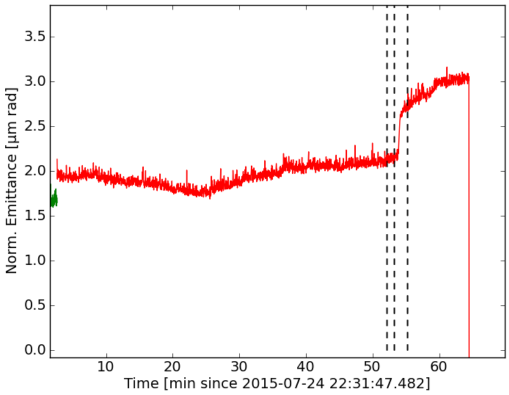
per beam). The beam parameters are summarized in Table 1 together with the corresponding beam-beam parameters for each beam.
We acquired the BTF measurements with beams in collision in IP1 and IP5, and the coherent peak of the beam-beam π-mode appeared in the amplitude response. The amplitude response with colliding beams is shown in Fig. 8 for Beam 1 vertical plane: on the left (Fig. 8a), before the IP optimizations and on the right (Fig. 8b), after the optimization. The expected beam-beam tune shift for Beam 1 was $\Delta Q \approx -0.0133$, and this corresponds to the position of the π-mode in the BTF response after the optimization of the IPs.

Table 1: Beam parameters for the first Fill of the "Head-On" MD of the 24th of July 2015, beam-beam parameter also reported for each beam.

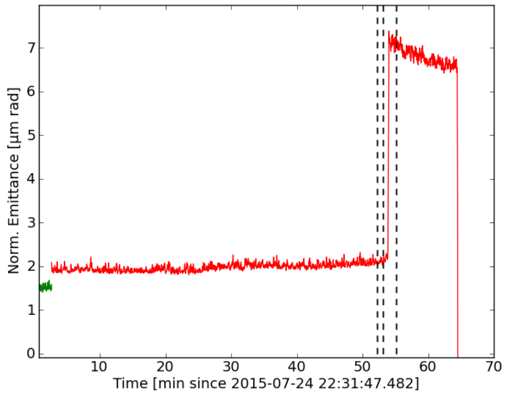
	I [10^{11} p/b]	ϵ_x [μm rad]	ϵ_y [μm rad]	$\Delta Q = 2 \cdot Y \cdot \xi_{bb}$
B1b1	1.09	2.11	2.05	$1.33 \cdot 10^{-2}$
B2b1	0.891	1.92	2.01	$1.56 \cdot 10^{-2}$

After few minutes an instability occurred characterized by a fast emittance blow up as shown in Fig. 9 in case of Beam 1 horizontal plane (Fig. 9a) and vertical plane (Fig. 9b), also Beam 2 was affected in both planes. The dashed lines correspond to the time of the data taking of the BTF. The instability is most probably due to the excitation of the coherent π-mode since excited by the BTF excitation without the ADT acting on the beams. The instability was visible in the BBQ spectrum as shown in Fig. 10 for Beam 1 horizontal plane. Both the π-modes in horizontal and vertical plane are excited but the vertical one is more visible in the BBQ spectrum since it is characterized by an emittance blow-up up to a factor of $\approx$ 3.5.

During the "Collide and squeeze MD" on 29th of August 2015, other BTF measurements have been performed with beam in collisions at 6.5 TeV with nominal single bunch per beam. The ADT was turned off, the Landau octupole current at 0 A and the beams were colliding in IP1 and IP5 with an offset of 1σ. Any evidence of instability was observed in this case during the BTF acquisition.



(a) Emittance measured by the BSRT for Beam 1 horizontal plane



(b) Emittance measured by the BSRT for Beam 1 vertical plane

Fig. 9: Emittance measured by the BSRT for Beam 1. The dashed lines identify the times of the BTF data taking.

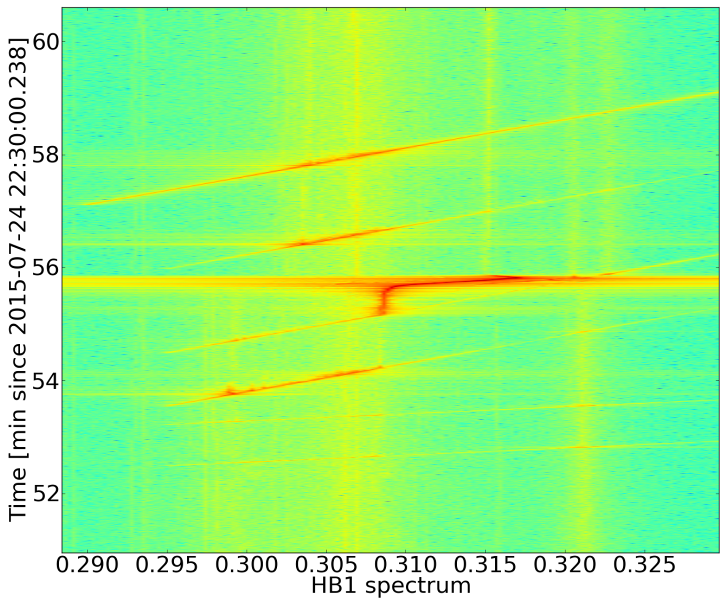


Fig. 10: BBQ spectrum for Beam 1 in the horizontal plane with colliding beams during BTF excitation.

5 Summary

The results of the BTF measurements for the first time in LHC can be summarized as follow:

- BTF measurements have been successfully performed during different machine configurations (with single bunch per beam):
  - At injection energy on pilot and nominal bunches
  - At 6.5 TeV on pilot and nominal bunches
  - With beams in collision at injection and at flat top
- The BTF measurements have been set-up, resulted to be completely transparent for non-colliding beams.
- An octupole current scan has been performed to evaluate the tune spread from the BTF, data analysis is still ongoing. An octupole current scan at flat top would be useful to identify resonances.
- During the first attempt of BTF measurements with beams in collision at injection energy with the ADT off, we observed an instability most probably due the coherent excitation of the beam-beam $\pi-$mode, as shown in Fig. 10, where the strongest excitation in the vertical plane for Beam 1 is visible at ~ 0.308, same as in Fig. 8b.
- However, there was not sign of instability due to BTF excitation during a second test with beams in collision at 6.5 TeV without ADT acting on the beams.
- Some other tests are required to investigate the observed instability with beams in collision and furthermore perform measurements with trains.

6 Acknowledgements

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