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claudia.tambasco@cern.ch

MD 1407 - Landau Damping: Beam Transfer Functions and diffusion mechanisms

C. Tambasco, J. Barranco[*], *A. Boccardi, X. Buffat, M. Crouch*[†], *M. Gasior, T. Lefevre, T. Levens, T. Pieloni*[‡], *M. Pojer, B. Salvachua, M. Solfaroli*
CERN, Geneva, Switzerland

Abstract

In the 2012, 2015 and 2016 run several instabilities were developing at flat-top, during and at the end of the betatron squeeze where beam-beam interactions are present. The tune spread in the beams is therefore modified by the beam-beam long-range interactions and by other sources of spread. Studies of the stability area computed by evaluating the dispersion integral for different tune spreads couldn't explain the observed instabilities during the squeeze and stable beams. The size of the stability area given by the computed dispersion integral depends on the transverse tune spread but its shape is defined by the particle distribution in the beams. Therefore any change of the particle distribution can lead to a deterioration of the Landau stability area. The Beam Transfer Functions (BTF) are direct measurements of the Stability Diagrams (SD). They are sensitive to particle distributions and contain information about the transverse tune spread in the beams. In this note are summarized the results of the BTF measurements acquired during the MD devoted to experimentally characterize the stability diagram for different Landau octupole currents, chromaticities, beam-beam long range separations and head-on separations.

Keywords: Accelerator Physics, beam-beam effects, beam instabilities, BTF, stability diagram

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[*] Ècole polytechnique fèdérale de Lausanne (EPFL), Lausanne, CH
[†] University of Manchester, Manchester, U.K / The Cockcroft Institute, Daresbury, U.K.
[‡] Ècole polytechnique fèdérale de Lausanne (EPFL), Lausanne, CH

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1 Motivation and introduction

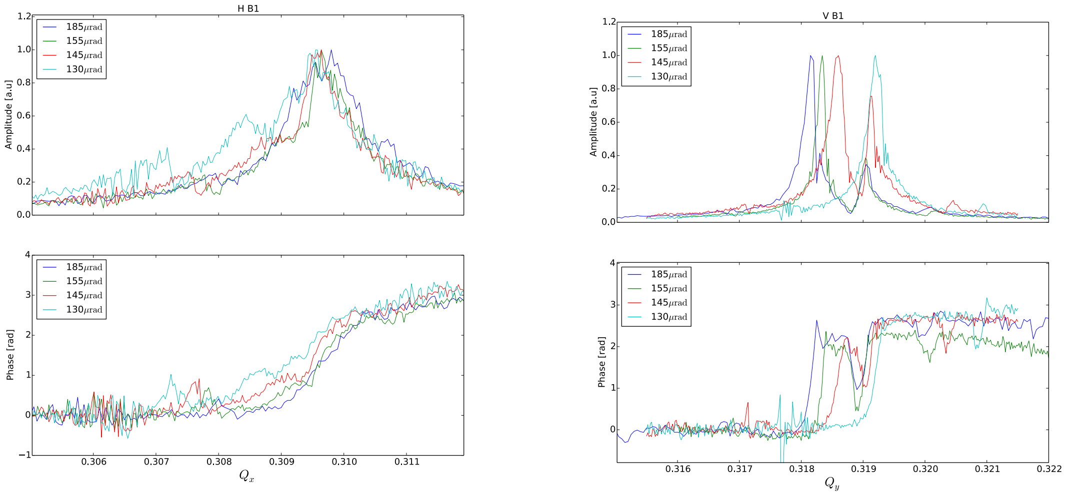
During the 2012, 2015 and 2016 Physics runs several instabilities were observed during the LHC cycle. Possible explanations of the observed instabilities can be found in [1,2] but the mechanisms are still not fully understood. The BTF measurements are a possible method to experimentally explore the Landau damping properties of the beams [3,4] difficult to predict when in the presence of diffusion mechanisms due for instance to strong beam-beam interactions. These modifications may lead to a deterioration of the particle distribution and therefore the Landau stability area could be deprecated. The BTF system has been set up and tested during 2015 for several machine configurations [5,6].

The aim of this Machine Development study, devoted to BTF measurements in the presence of diffusion mechanism, was to characterize the SD in presence of strong beam-beam long range interactions. This will be done by acquiring BTF measurements with Landau octupoles while reducing the long range beam-beam separation. In this note the full experimental procedure will be presented together with some preliminary results.

2 MD Procedure

The MD activity was carried out the 21st of August 2016. At the beginning of the MD no trains were available from the injectors, therefore BTF measurements on a single nominal bunch were acquired at injection energy for several chromaticity values. Then we proceeded with the first fill: we injected a single lower intensity bunch in Beam 1 (B1) of intensity 6.62×10^{10} and a train of 48 bunches in Beam 2 (B2) of nominal intensity. Because of the lack of time, we went directly at the end of the squeeze and no measurements were acquired at flat top. At the end of squeeze we performed a crossing angle scan in IP1 and IP5 with fully separated beams. We reduced simultaneously the crossing angles in IP1 and IP5 from 185 µrad to 125 µrad (half crossing angle) in several steps and acquired BTF measurements in both planes at each step. At the smallest angle an instability occurred in B1 in the vertical plane. Losses and emittance blow up were observed: we therefore decided to dump and re-fill the machine since the blown-up bunch was not representative of the beam-beam effects we wanted to study.

In the second fill we injected a single lower intensity bunch in B2 and a train of 48 nominal bunches in B1. We went at the end of the squeeze and we reduced the chromaticity. We therefore brought the beams into collisions, and after the IPs optimization we acquired some BTF measurements. Then we separated the beams up to 2 σ in steps of $\approx 0.25\sigma$ in IP1 and IP5 and acquired BTF at each step. After the parallel separation scan, we separated the beams by 5 σ and acquired BTF measurements. Lastly, we reduced



(a) B1 horizontal plane.

(b) B1 vertical plane.

Fig. 1: Measured BTF amplitude and phase responses for different crossing angles at the end of squeeze.

also the Landau octupole current to 225A and acquired BTFs in this configuration.

3 Preliminary results

All the BTF measurements were acquired on a single bunch with the ATD switched off in order to avoid its response in the BTF measusurements. The BTF responses acquired during the crossing angle scan at the end of squeeze are shown in Fig. 1 for some of the crossing angles during the scan in the first fill. For this case the measurements were performed on the single bunch of B1. At the end of squeeze the beam-beam long range separation corresponds to $\approx 12\ \sigma$ considering a normalized beam emittance of 2.5 µm rad. The expected tune footprints are shown in Fig. 2 at the end of squeeze for an octupole current $I_{oct} = 470\,\mathrm{A}$ as during the measurements. In this configuration an increase of the tune spread in both planes is expected due to the beam-beam long range and octupole interplay. The beams emittances are summarized in Tab. 1 for both fills during the MD while the angles used during the scan together with the beam-beam long range separation are summarized in Table 2. As shown in Fig. 1, an unexpected asymmetry was observed between the horizontal and the vertical plane: a tune shift is observed in the vertical plane with a small increase of the tune spread while reducing the crossing angle, while in the horizontal plane a big impact on the spread is visible with a smaller impact on the tune shift compared to the vertical plane. This observation is in line with what we observed during MD 1429 [7]. The measurements performed of the tune shift as a function of the crossing angle has been then used in operation to improve beam lifetimes at the end of the squeeze [8] . A secondary peak is observed in the vertical plane due to the tune of the pilot bunch accidentally left in the beams. At the last (half) crossing angle step of 125 µrad in IP1 and IP5 an emittance blow-up was observed only in B1 V as visible in Fig. 3 (green line) while no sign of instability is observed in B2.

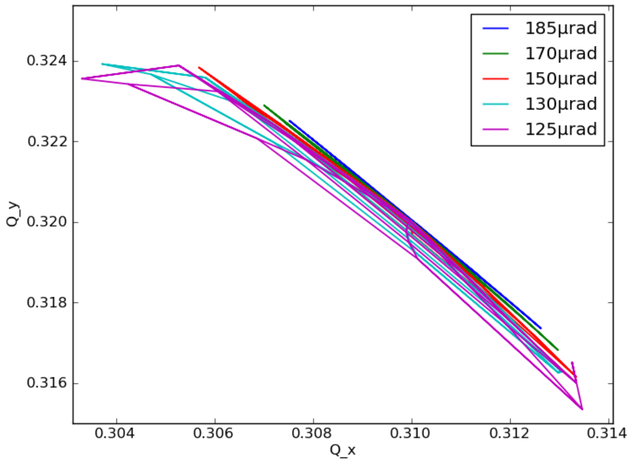


Fig. 2: Tune footprint at the end of squeeze for different crossing angles.

Table 1: Normalized emittance at the end of squeeze for Fill 1 and Fill 2 .

	Beam 1 (H) [µm rad]	Beam 1 (V) [µm rad]	Beam 2 (H) [µm rad]	Beam 2 (V) [µm rad]
Fill 1	2.8	2.2	3.3	2.5
Fill 2	2.8	2.4	3.3	1.9

Due to this instability the beams were safely dumped and a second fill was injected in the LHC. This time the train of 48 bunches was injected in Beam 1 while the BTF measurements were performed on the single bunch of B2 with the transverse feedback turned off. The corresponding emittances were already summarized in Tab. 1. In this configuration we performed a separation scan in IP1 and IP5 with beams in collision. Afterwards, we separated the colliding beams in IP1 and IP5 up to $2\ \sigma$ in steps of

Table 2: Normalized beam-beam long range separation for different crossing angles used during the BTF experiment. The given crossing angle values are half of the total crossing angle in IP1 and IP5.

Angle [μrad]	**BB Long Range separation** [σ]
185	12.32
170	11.32
160	10.66
155	10.32
150	9.99
145	9.66
140	9.32
135	8.99
130	8.66
125	8.32

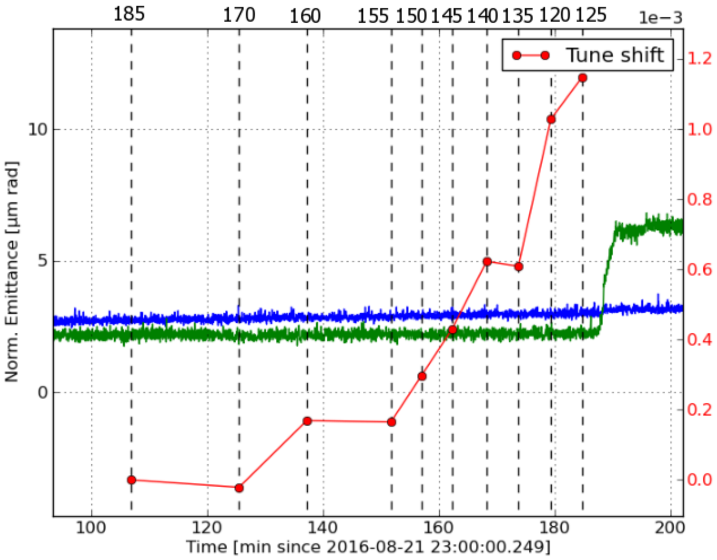


Fig. 3: Normalized emittance of B1 in the horizontal plane (blue line) and vertical plane (green line) as a function of the time during the separation scan. The dashed lines represent all the angle changes (half of the crossing angle at the IPs) made during the MD time since the end of the betatron squeeze. The measured tune shift as a function of the separation is also plotted (red line).

$\approx 0.25\sigma$ and acquired BTFs at each step. The Landau octupoles were turned on during all the scan, with a current of 470 A. The normalized luminosity recorded by ATLAS and CMS is presented in Fig. 4 together with the corresponding parallel separations calculated by using:

$$\mathscr{L}_d = \mathscr{L}_0 \cdot e^{-\frac{d^2}{4\sigma^2}}. \tag{1}$$

where d is the parallel separation at the IPs between the two colliding beams. No instabilitiy was observed in B2 on single bunch while acquiring BTF measurements, however some non-colliding beams in B1 were affected by an emittance blow-up as shown in Fig. 5 where we also summarize the slot numbers of the bunches that were unstable in the vertical plane.

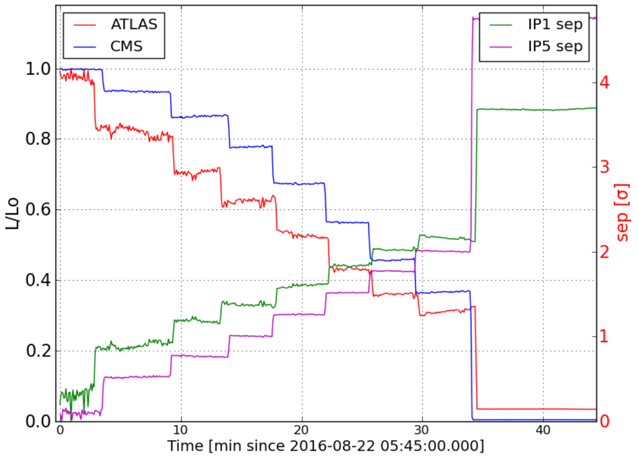


Fig. 4: Relative luminosity changes as a function of the separation at the IPs during the separation scan.

The BTF responses during the parallel separation scan are presented in Fig 6 while increasing the separations in the two IPs. In the BTF response the π-mode and the σ-mode are visible. The π-mode moves towards the σ-mode while increasing the separation between the two colliding beams. From the distance between these two peaks, it is possible to calculate the tune shift ΔQ due to the beam-beam head-on interaction as a function of the parallel separation. A maximum tune shift of $\Delta Q_y = 9.38 \times 10^{-3}$ was observed in the vertical plane and $\Delta Q_x = 6.9 \times 10^{-3}$ in the horizontal plane. In Fig. 7 both the horizontal and vertical tune shifts are shown as a function of the parallel separation at the IPs and normalized to the maximum tune shift in each plane.

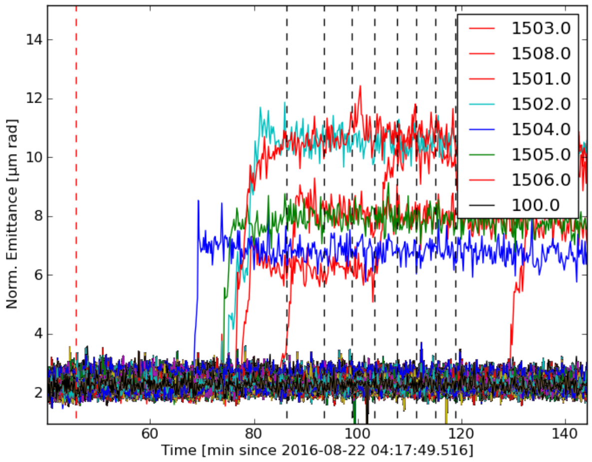
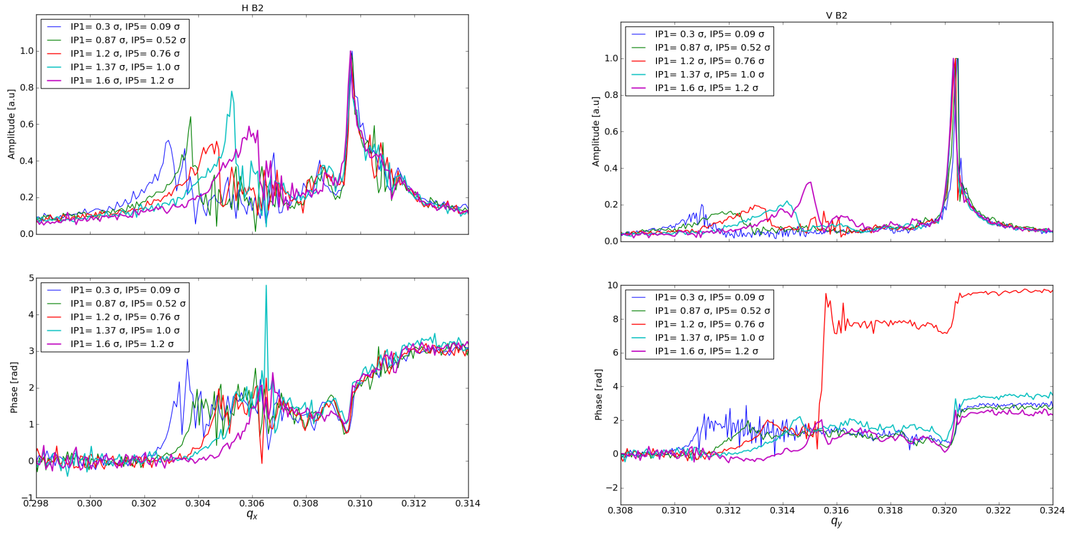


Fig. 5: Bunch by bunch normalized emittance of B1 during Fill 2 of the MD. Bunches undergoing a blow up are highlighted with their bunch slot position.



(a) B2 horizontal plane.

(b) B2 vertical plane.

Fig. 6: Measured BTF amplitude and phase response for different parallel separations in IP1 and IP5.

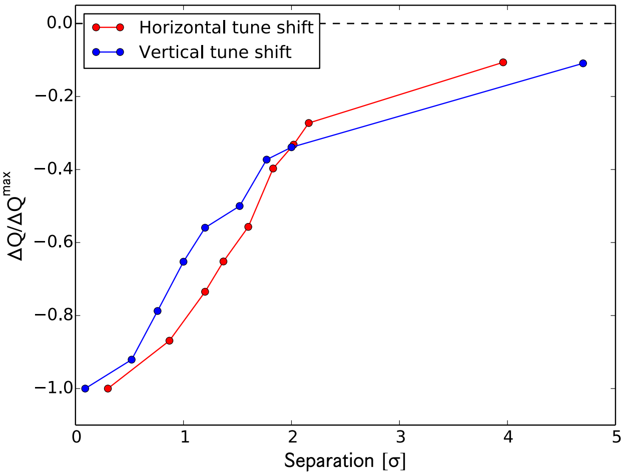


Fig. 7: Horizontal (red) and vertical (blue) normalized beam-beam head-on tune shifts as a function of the separation at the IPs.

4 Summary

The procedure of the MD was described in this note and some preliminary results have been presented. A crossing angle scan has been performed at the end of squeeze in order to investigate by means of BTF measurements the Landau damping properties of the beams in the presence of beam-beam long range interactions with reduced crossing angles in IP1 and IP5. An unexpected behavior was observed between the horizontal plane and the vertical plane during the reduction of the beam-beam long range separations: the horizontal plane showed an evident tune spread increase with the reduction of the crossing angle while the vertical plane was dominated by a larger tune shift and a smaller tune spread. The tune shift as function of the crossing angle was consistent with what was observed in MD 1429 and the measured tune shift has been corrected at the end of the squeeze in operational Physics fills [8]. At the last step of the crossing angle scan, B1 was unstable with an emittance growth in the vertical plane. The second fill of the experiment was characterized by a parallel separation scan in IP1 and IP5 with colliding beams. The tune shifts due to the head-on interaction have been calculated as a function of the parallel separation at the IPs and presented here for both planes. Further MDs would be required to investigate the behavior of Landau damping with beam-beam interactions and linear coupling interplay and in the presence of negative octupole currents at the end of the betatron squeeze.

5 Acknowledgements

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