

## MD 3292: MEASUREMENTS OF LANDAU DAMPING BY MEANS OF BTF MEASUREMENTS

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### Abstract

The methodology applied in previous MDs has shown the possibility of using BTFs measurements to estimate the transverse Landau Damping of the beams for different machine configurations. However, measurements with beam-beam interactions could not be performed during the past MDs. This note summarises the procedure and preliminary results of the MD 3292, carried out in two different MD Blocks (Block 3 and 4), during which BTF measurements in the presence of white noise and beam-beam interactions were acquired.

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

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## Contents

1	Motivation and introduction . . . . .	1
2	MD procedure and preliminary results . . . . .	1
2.1	MD carried out in Block 3 . . . . .	1
2.2	MD carried out in Block 4 . . . . .	5
3	Summary . . . . .	6
4	Acknowledgements . . . . .	7
5	References . . . . .	7

## 1 Motivation and introduction

Beam Transfer Functions (BTFs) can provide measurements of the Stability Diagrams and estimations of the tune spread in the beams for comparisons with the models used to predict the instability thresholds in the LHC. The higher octupole strength required during operations is still not fully understood showing that a complete understanding of the mechanisms is still needed [1–3]. During past MDs, the reconstruction of the Stability Diagram was achieved at injection energy by applying an averaging of the BTF signal [4]. The gated BTF system was shown to be able to measure several bunches at flat top energy (one bunch at a time). The BTF settings found in the previous MD (3290) have been used in order to avoid instabilities during BTF measurements at flat top energy. These studies aim to measure the Stability Diagrams at flat top energy and at the end of the betatron squeeze for different octupole strengths and beam-beam interactions and characterize the impact of particle distribution changes on the measured Stability Diagrams in the presence of an external source of noise (white noise) and diffusive mechanisms due to beam-beam excited resonances, in order to show the limitations of the Landau damping models in these configurations [5]. However due to some technical problems during the MD and some limitations in the data analysis described below the Landau damping of the beams in the presence of beam-beam interactions could not be fully characterized.

## 2 MD procedure and preliminary results

In this section the detailed procedure during the MD is summarised together with a preliminary analysis of the measurements.

### 2.1 MD carried out in Block 3

The first part of the MD was carried out during MD Block 3 on September 13<sup>th</sup> 2018. At the beginning of the MD we injected 2 nominal bunches in Beam 1 to set-up the gated BTF system. Then we injected 13 INDIVs in Beam 1 and 8 trains of 48 nominal bunches in Beam 2. This filling scheme was chosen in order to measure the individual bunches of Beam 1 by using the gated BTF system, while the trains in Beam 2 are needed to have beam-beam long range interactions at the end of the betatron squeeze (but no measurements are acquired on Beam 2). The ADT feedback is switched-on except for the measured bunch on Beam 1. The bunch-by-bunch intensities during the experiment are shown in Fig. 1 for Beam 1 (blue line) and Beam 2 (green line). The average bunch intensity for Beam 1 was  $\approx 0.8 \times 10^{11}$  p/bunch. During the measurements, the gated BTF system was successfully used together with the BTF amplitude

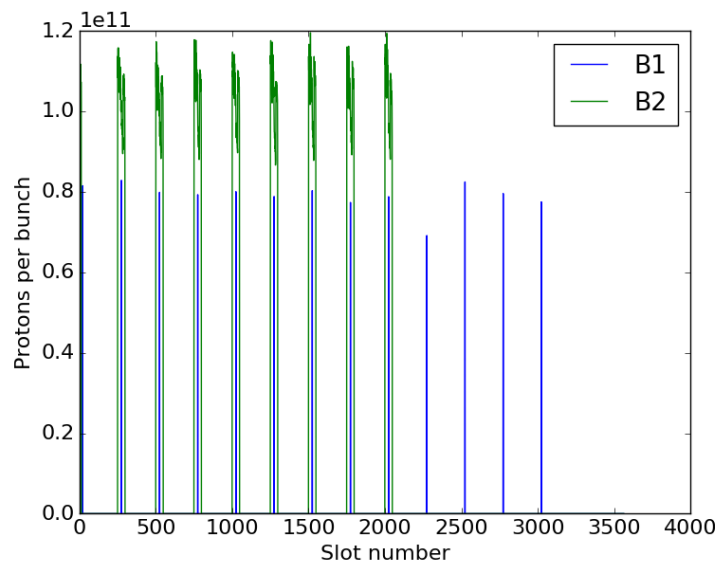


Fig. 1: Bunch-by-bunch intensity for Beam 1 (blue line) and Beam 2 (green line).

thresholds estimated from the previous MD (3290) with no sign of instabilities due to the BTF excitation

itself at flat top energy. Unfortunately some problems with the BTF application occurred: it was not possible to set-up the excitation amplitude through the GUI due to an update of the INSPECTOR so we could only change the excitation by using FESA and no excitation in the vertical plane could be applied due to bad phasing in this plane. Therefore the BTF measurements were acquired only in the horizontal plane of Beam 1.

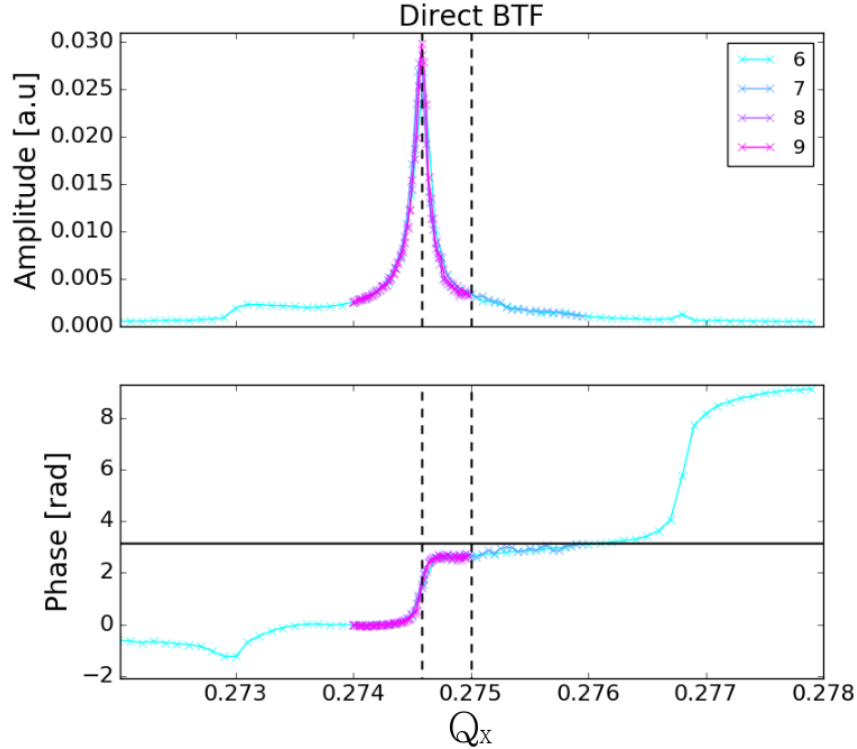


Fig. 2: Various BTF acquisitions (different colors) for Beam 1 (horizontal plane) at flat top energy in the same configurations. The chromaticity was reduced to 2.5 units during the measurements. The solid black line corresponds to the phase value of  $\pi$ . The first dashed black line at the peak of the BTF amplitude corresponds to the measured coherent tune while the second one in the middle of the two synchrotron sidebands represents the incoherent bare tune.

Measurements were performed at flat top energy after the correction of the linear coupling in the machine. The current of the Landau octupoles were increased to 546 A in order to maximize the beam stability. We lowered the chromaticity to 2.5 units in order to minimize the synchrotron sidebands in the BTF response. An example of the acquired BTF response at flat top energy is shown in Fig. 2 where various BTF measurements (different colors) for Beam 1 (horizontal plane) were acquired in the same configuration. The solid black line corresponds to the phase value of  $\pi$ . The first dashed black line at the peak of the BTF amplitude corresponds to the measured coherent tune while the second one in the middle of the two synchrotron sidebands represents the incoherent bare tune. As visible there was present a negative coherent tune shift w.r.t. to the bare tune of  $\Delta Q_{coh} \approx 3.4 \times 10^{-4}$ . This suggested that the impedance was modifying the response of the BTF [6–8]. Indeed the application of the fitting function shown in Fig. 3 is not giving satisfactory results if we consider only the detuning from the octupole magnets. In order to study the impact of the impedance in the BTF response, simulations using the COMBI code have been carried out. The results of the simulations are shown in Fig.4 where the BTF responses for a chromaticity value of 2.5 units ( $Q_s = \pm 0.002$ ) including the 2018 impedance model and octupoles powered with a current 546 A (as during the measurements) are plotted for various bunch intensities. The black line corresponds to the analytical case without impedance evaluated using the PySSD code and it is found to be similar to the case with smaller bunch intensity ( $0.05 \times 10^{11}$  p/bunch, the light blue line), and therefore with a lower impedance level, meaning that in this case the impedance contribution in the response is negligible. By increasing the bunch intensity the absolute value of the

coherent tune shift increases as expected (Fig.4). Figure 5 shows the coherent tune shifts evaluated from the simulated BTF response including the 2018 wake field model (the light blue line) and the wake field evaluated from the collimator settings as during the MD (the orange line). As visible, in order to reproduce the observed tune shift in the measured BTF ( $\Delta Q_{coh} \approx 3.4 \times 10^{-4}$ ) at flat top energy, one has to increase the bunch intensity up to  $1.2 \times 10^{11}$  p/bunch. This translates into a factor 1.5 on the impedance w.r.t. measurements. This value is in agreement with independent impedance measurements in the LHC for the horizontal plane of Beam 1 [9]. A first attempt to directly compare the measured BTF response to simulations is shown in Fig. 6 where the measured BTF response at flat top energy (red line) is compared to simulated BTF responses for various chromaticity values including in the model the impedance and the Landau octupole detuning for 546 A as during measurements. A factor 1.5 stronger impedance has been used as measured in the LHC. For completeness the analytical case without impedance is also plotted (black line). As visible the coherent tune shift is also fully reproduced. The shape of the measured BTF is fully recovered for a chromaticity of 1.0 units (the light blue line), a smaller value w.r.t. the measured one that was about 2.5 units.

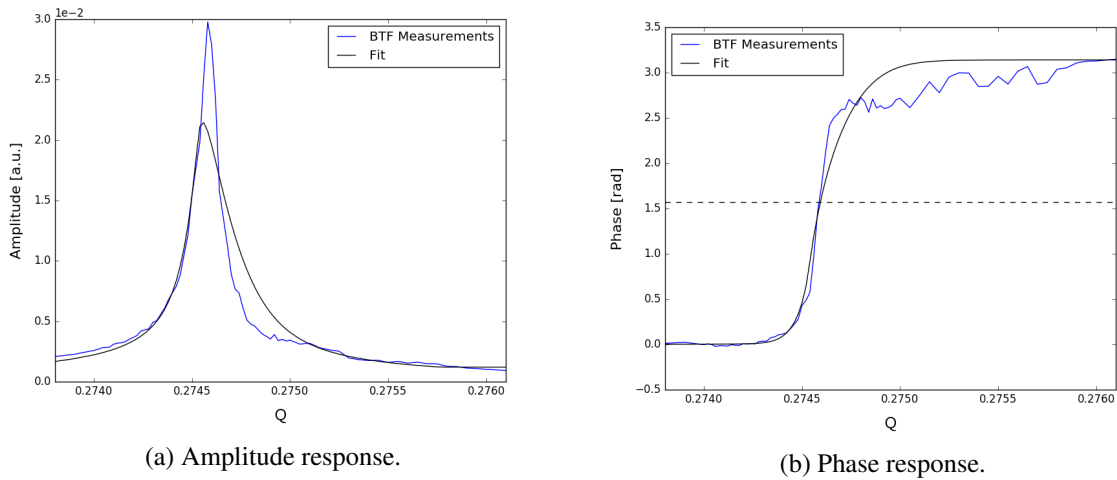


Fig. 3: Measured (the blue line) and fitted BTF response (the black line) w.r.t. the semi-analytical case evaluated by the PySSD code including the detuning with amplitude provided by 546 A octupole (as during the BTF measurements).

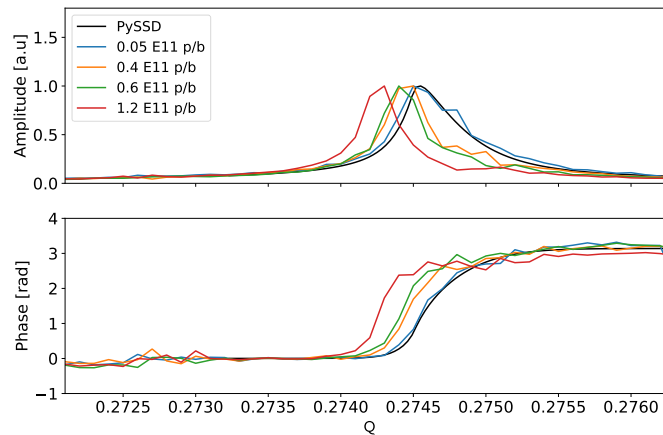


Fig. 4: Simulated BTF response for a chromaticity value of 2.5 units ( $Q_s = \pm 0.002$ ) including the 2017 impedance model and octupoles powered with a current of 546 A (as during the measurements) for various bunch intensities. The black line corresponds to the analytical case without impedance evaluated using the PySSD code.

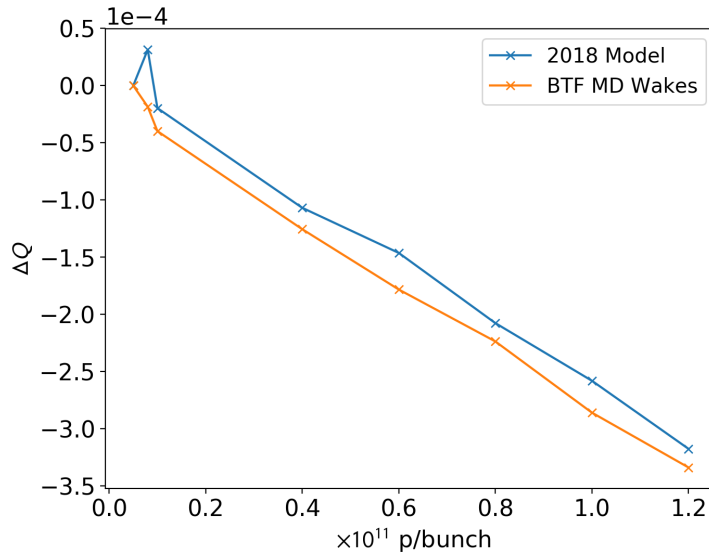


Fig. 5: Coherent tune shifts evaluated from simulated BTF response including the 2018 wake field model (light blue line) and the wake field evaluated from the collimator settings as during the MD (orange line).

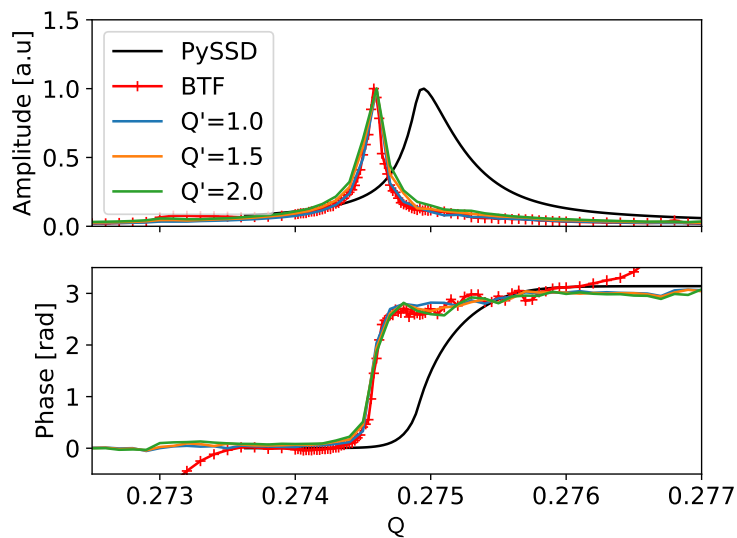


Fig. 6: Measured BTF response at flat top energy (red line) compared to simulated BTF response for various chromaticity values including in the model the impedance and the Landau octupole detuning for 546 A (as during measurements). For completeness the analytical case without impedance is also plotted (black line).

Unfortunately during the second part of the MD we could not reach the betatron squeeze due to some problems with the tune application that crashed. We therefore decided to continue the studies injecting white noise with the ADT. We injected white noise on the single bunches of Beam 1 (for few minutes) and measured the BTF after the noise was applied. When the noise was applied losses were observed and instabilities occurred for higher noise amplitude when exciting through the BTF. Figure 7 shows the horizontal BBQ spectrum for Beam 1 while injecting white noise and while acquiring BTF measurements. By increasing the noise level by 20% the beam was unstable right after the BTF excitation (Fig. 7). Further studies and simulations are necessary to explain this behavior and understand the limitation of the models in this configuration.

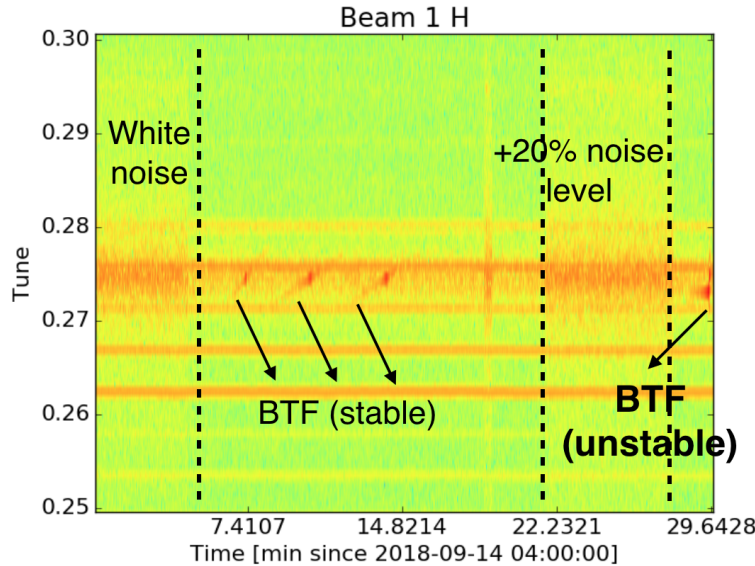


Fig. 7: Horizontal BBQ spectrum for Beam 1 while injecting white noise and acquiring BTF measurements.

## 2.2 MD carried out in Block 4

The second part of the MD was carried out during MD Block 4 on October 30<sup>th</sup>, 2018. First we performed the setup of the BTF system at injection energy for both planes of Beam 1 on INDIVS bunches of low intensity. Then we injected 3 lower intensity INDIVS in Beam 1 and 2 trains of 48 nominal bunches on Beam 2. However, due to a mismatch of the sextupoles in sector 34 (somehow a hidden leftover from a previous MD) we could not ramp the energy to reach the flat top for which a dump was needed to solve the problem. After the dump, we could not re-inject trains in Beam 2 due to a RF cavity problem in the PS. Waiting for recovery, we decided to acquire BTF measurements at injection energy with lower intensity INDIVS on both beams as a function of the octupoles (7 A, 13 A) and chromaticity ( $Q' \approx 3$ ,  $Q' \approx 1$ ). Since trains could not be recovered in time, we decided to proceed injecting 3 lower INDIVS in both beams, allowing for head-on studies, but not long-range as foreseen. At flat top, we reduced the impedance by opening the secondary and primary collimators (TCSPM and IR7 TCSGs at  $15\sigma$ , IR7 TCP settings at  $6\sigma$ ). At the end of the squeeze we collided the beams simultaneously in IP1 and IP5. The chromaticity was reduced in order to reduce the synchrotron sidebands in the BTF response, then measurements were performed with beams separated from 0 to  $6\sigma$  in several steps. Figure 8 shows the measured BTF amplitude responses in the presence of head-on collisions in IP1 and IP5 for different offsets at the IPs. As visible in fully head-on collisions the amplitude response is wider, meaning that the tune spread is the largest one, while at  $1.45\sigma$  the amplitude response is the narrowest. Therefore, the tune spread results to be reduced, confirming the presence of a minimum of Landau damping at this separation as expected [1, 10]. Tune shifts are also observed while separating the beams. Figure 9 shows the measured tune shifts from the BTF response (blue and green dotted lines) with beams in head-on collisions in IP1 and IP5 as a function of the beam to beam separation at the IPs (in units of the rms beam size) and compared to MAD-X expectations (the blue and green dashed lines). The blue and green shadows include a  $\pm 10\%$  error on the chromaticity value while the grey shadows also include a  $\pm 10\%$  error on the crossing angle at the IPs. The agreement is better for smaller offsets at the IPs while the measurements deviate from expectations for separations above  $2\sigma$ .

At  $1.5\sigma$  separation, we performed an octupole scan reducing the current from 565 A to 376 A, and then to 94 A as shown in Fig.10. A tune shift is visible while lowering the octupole current. However is not clear why the tune spread seems to be reduced for an octupole current of 550 A (the blue line) looking at the width of the BTF amplitude response. Further analysis is required to confirm this behavior.

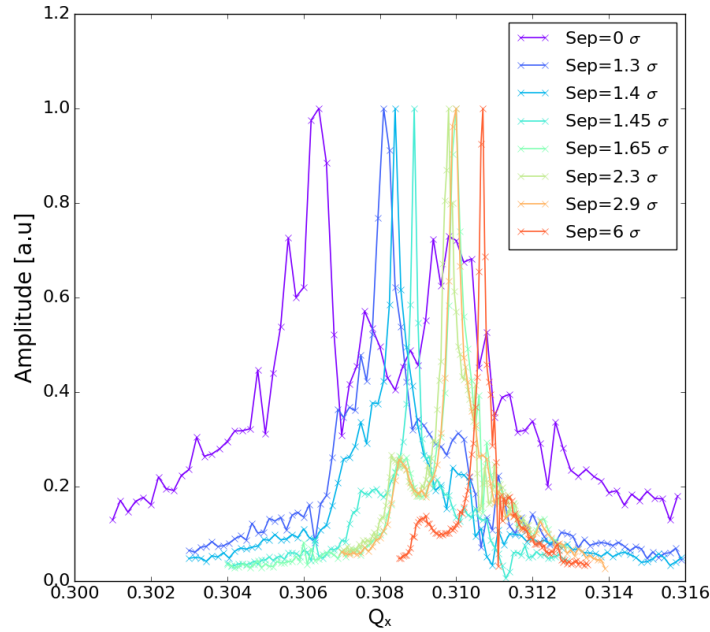


Fig. 8: Measured BTF amplitude responses with head-on collisions in IP1 and IP5 for different offsets at the IPs.

### 3 Summary

The MD procedure and preliminary results of the BTF measurements have been presented in this note. No instabilities triggered by the BTF excitation itself were observed during these MDs showing that BTF measurements at flat top energy are possible. However some limitations were observed for the reconstruction of the Stability Diagram at flat top energy: the impedance contribution has to be reduced (lower intensity bunches and retracted collimators) otherwise the BTF response is modified and measurements of the Stability diagrams cannot be achieved by using the fitting method. In the MD time window, no instabilities were observed while acquiring the BTF measurements in the presence of low amplitude white noise. However for higher noise levels the beams became unstable while exciting through the BTF. The

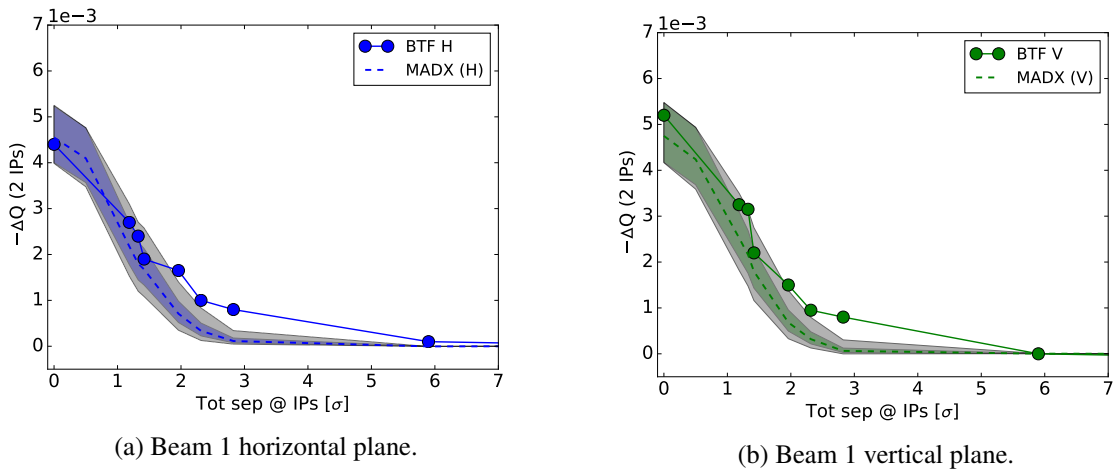


Fig. 9: Measured tune shifts from the BTF response (blue and green dotted lines) with beams in head-on collisions in IP1 and IP5 as a function of the beam to beam separation at the IPs, compared to MAD-X expectations (the blue and green dashed lines). The blue and green shadows include a  $\pm 10\%$  error on the chromaticity value while the grey shadows also include a  $\pm 10\%$  error on the crossing angle at the IPs.



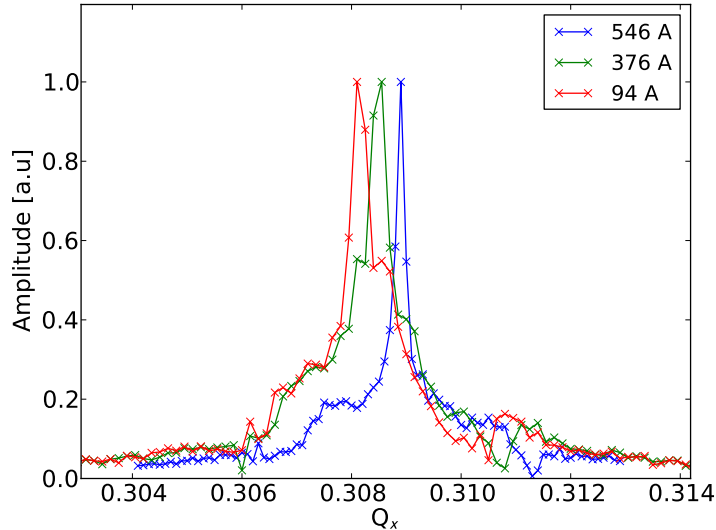


Fig. 10: Measured BTF amplitude responses with head-on collisions in IP1 and IP5 for a parallel offset at the IPs of  $1.5\sigma$  for different octupole currents.

full understanding of the mechanisms remains to be addressed. Further analysis is needed including COMBI simulations in the presence of white noise together with a detailed analysis of the beam profiles while injecting the noise.

During the second MD, BTF measurements were acquired in the presence of beam-beam head-on interactions. The measurements have been acquired as a function of the parallel separation at the IPs. The expected minimum of stability at  $1.5\sigma$  has been measured by BTFs. However a direct comparison with expectations needs to be addressed. For this, multi-particle simulations (COMBI) with a full implementation of the crossing angle at the IPs will be necessary. During the parallel separation scan at the IPs, tune shifts were measured and compared with the expected tune shifts from MAD-X simulations with a satisfactory agreement within the considered errors.

#### 4 Acknowledgements

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