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MD3310 – Complex tune shift measurement at flat-top in the LHC

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Summary

This note summarises the MD3310 activity. The goal was to measure the complex tune shift as a function of intensity in the LHC at 6.5 TeV. The session took place in the night of 17 June to 18 June 2018 as part of the MD block 1. Bunches of various intensities were injected and once at top energy, they were excited with the transverse damper (ADT). From the excitation signal, the tune of each bunch can be computed. Two fills were planned, the first to be performed with low bunch intensities, the second with high bunch intensities. Unfortunately, due to a magnet trip, only the first one was successfully completed.

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1 Introduction

The High Luminosity upgrade of the LHC requires brighter beams to reach its luminosity target. These new beams will be challenging from the coherent stability side, notably from impedance induced effects. The current LHC impedance model, on which the HL-LHC model is based, must therefore be compared to (and refined with) dedicated measurements. In this respect, one of the main observables related to the transverse beam coupling impedance in accelerators is the tune shift versus intensity [1, 2].

For the measurement in the LHC, the transverse damper (ADT) was used to coherently excite the bunches. Bunches can be kicked individually, and the excitation gain and time profile can be finely controlled [3]. The turn by turn oscillation signal was then recorded using the ADT ObsBox [4] and the tune for each bunch was computed from the turn by turn, bunch by bunch data.

2 Procedure and Beam Conditions

The MD activity was carried out in the night of 17 June to 18 June 2018 [5], during fills 6816, 6817 and 6818. The injection scheme `Single_20b_0_0_0_Instabilities` was used for all fills. Figure 1 shows an overview of the MD.

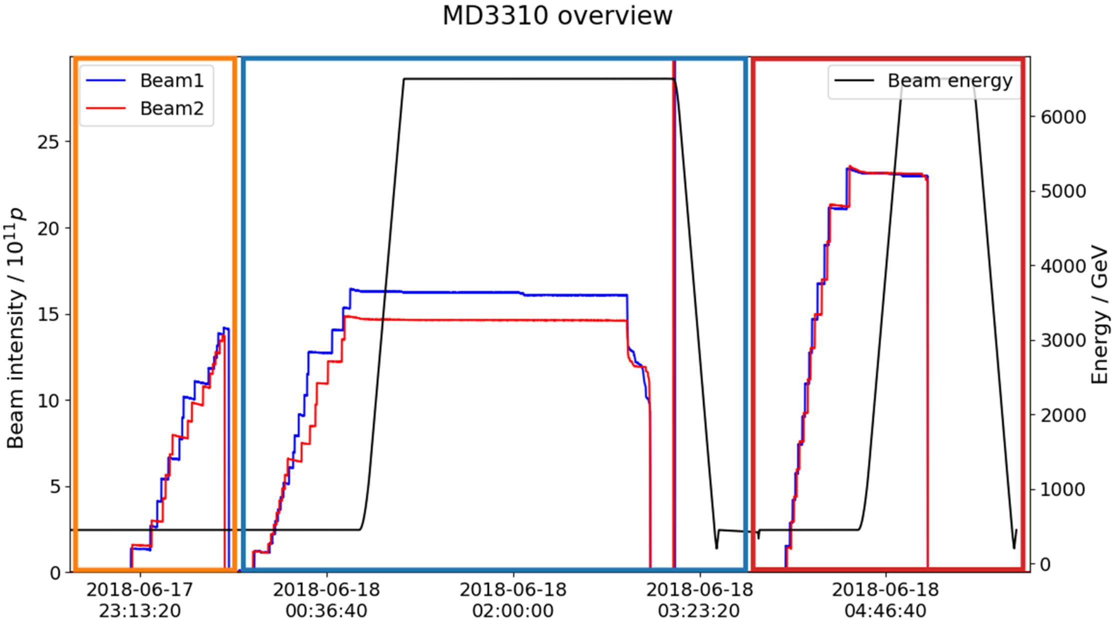

Figure 1: Beam 1 intensity (blue curve) and Beam 2 intensity (red curve), alongside beam energy (black curve) during the MD activity. At the start of the MD (highlighted in orange), the beam was dumped because of a too low bunch intensity. Measurements could be performed in the second fill afterwards (highlighted in blue). The third fill with higher intensity bunches was dumped by a corrector magnet trip (highlighted in red).

The first fill was dumped during the injection process by interlocked BPMs in point 6. The interlock was caused by a bunch having too low intensity.

The second fill had bunches in both beams with intensities ranging from 0.5×10^{11} protons per bunch (p.p.b) to 1.4×10^{11} p.p.b. It was ramped to the top energy of 6.5 TeV, after the "combined ramp and squeeze" sequence and before the tune change. The octupole current at top energy was set to 450 A. Once the top energy was reached, the bunch excitation with the ADT was set up. The chromaticity was also reduced by 6 units in both beams and planes in steps of 2 units, to a target $Q' = 9$. The ADT damping gain was also reduced to 0.03 in LSA to improve the excitation signal, but coherent instabilities in B2 required to revert the setting. The bunches were kicked $\sim$ 15 times to obtain enough statistics. During the measurement, the full bunch lengths were comprised between 1.05 ns and 1.1 ns. Once the individual tune measurement was performed, the transverse damper (ADT) was switched off and the octupole current was reduced to 0 A to trigger an instability.

The third fill had bunches in both beams with intensities ranging from 1.4×10^{11} p.p.b to 2.1×10^{11} p.p.b. It could be ramped to top energy with octupole current setting of 527 A at top energy. However the fill was lost after reaching top energy due to a magnet trip.

3 Data Treatment and Results

The tune was computed with the turn by turn transverse position of each excited bunch, recorded with the ADT ObsBox [4]. PySUSSIX [6], a Python wrapper of the SUSSIX code [7] was used to compute the tune. The first 400 turns after the bunch excitation were used.

Despite the large amplitude kicks from the ADT, data for B1 bunch remained noisy, especially for low intensity bunches. For B2 however a clear shift with intensity can be observed. Figure 2 shows the average tune for each measured bunch as a function of intensity. The dashed line shows the linear fit of the tune shift, weighted by the errors on each data point. Data for certain intensity points were discarded because of higher noise.

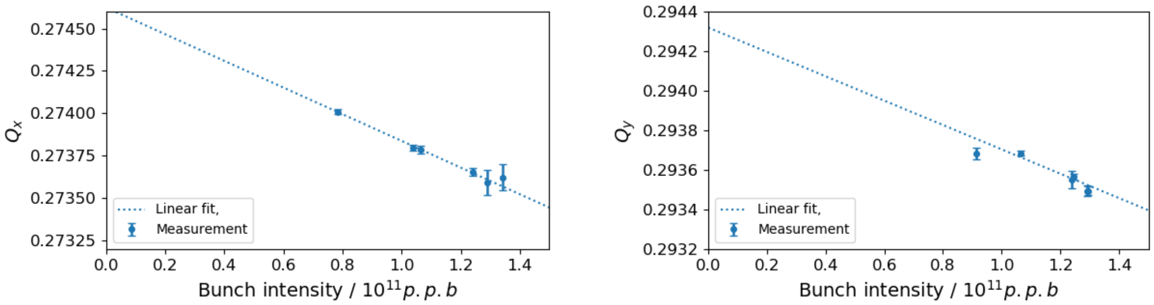

Figure 2: Measurement for Beam 2, horizontal plane on the left and vertical plane on the right. The linear fit is plotted in dashed line and the fit parameters are given in Tab. 1

Table 1: Fit parameters obtained from the data, using a non-linear least square algorithm. The error on each measurement are taken into account to obtain the error on the fitted tune shift. Here N_b is the bunch intensity in p.p.b.

Plane	Fit
B2H	$Q_x = 0.2746 - (7.9 \times 10^{-15} \pm 0.5 \times 10^{-15})\, N_b$
B2V	$Q_y = 0.2943 - (6.2 \times 10^{-15} \pm 0.7 \times 10^{-15})\, N_b$

Results can be compared to DELPHI [8] simulations performed with the LHC impedance model. The tune shifts simulations were performed using the LHC 2018 impedance model, with the collimator gaps at the time of the MD retrieved from the LHC logging database. A chromaticity $Q' = 8$ (close to the target chromaticity of 9 during measurement), a transverse damper gain $g = 0.01$ and a full bunch length of 1.08 ns were used. The effect of the quadrupolar impedance on the tune shift was accounted for by using Sacherer formula: both dipolar ΔQ_{dip} and quadrupolar ΔQ_{quad} tune shifts are computed. The correction factor to account for the quadrupolar impedance is then the ratio $(\Delta Q_{dip} + \Delta Q_{quad}) / \Delta Q_{dip}$. It is then applied to DELPHI simulations, which can account only for the dipolar impedance. In the horizontal plane, the tune shift computed with DELPHI is reduced by 23 % because of the quadrupolar impedance. In the vertical plane it is reduced by 6 %. The simulated values with the correction factor for quadrupolar impedance are reported in Tab. 2.

Table 2 reports the linear fit of the measured tune shift as well as the error on the fit parameter. Measurements are found to be 25 % higher for the horizontal plane. For the vertical plane, agreement between simulations and measurements is good.

Table 2: Simulated and measured tune shift versus intensity for Beam 2. The following columns report the tune shift slope values normalised to the synchrotron tune $Qs = 1.9 \times 10^{-3}$ and a bunch intensity of 10^{12} p.p.b computed with DELPHI. "Sim." column reports DELPHI simulations results. "Corr. factor" column is the correction factor to account for the quadrupolar impedance effect to be applied on the "Sim." column. The following column shows the simulation results with the correction factor applied. "Measured" column is the measurement result obtained by linear regression of the tune shifts measured at different intensities, with the corresponding errorbar.

Plane	Tune shift / 10^{-12} p.p.b $\times Q_s$			
	Sim.	Corr. factor	Sim. w/ quad.	Measurement
B2H	-4.3	0.77	-3.3	-4.1 ± 0.3
B2V	-3.5	0.94	-3.3	-3.2 ± 0.4

After the tune shift measurement, the bunches were made unstable to measure their instability growth rate. The ADT was first switched off by trimming its gain in LSA: bunches with intensities above 10^{11} p.p.b. became unstable, while other lower intensity bunches became unstable only when reducing the octupole current slowly to 0 A. Some bunches remained however stable: the damper gain trimmed in LSA might have left the ADT with a residual power, or residual tune spread might have been present, therefore providing some damping.

The measured growth rates are plotted in Fig. 3, alongside simulation results. Measurement data from beam 1 and beam 2 bunches were merged. For the simulations with DELPHI, the damper gain was assumed to be $g = 5 \times 10^{-4}$ to simulate a residual damping from the ADT. A locally linear trend of the instability growth rate versus intensity can be observed. The measured growth rate is within a factor of two compared to simulations: for example at $N_b \sim 1.4 \times 10^{11}$ p.p.b, the measured growth rate is $\sim 1 \times 10^{-4}$, whereas simulations predict 0.6×10^{-4}.

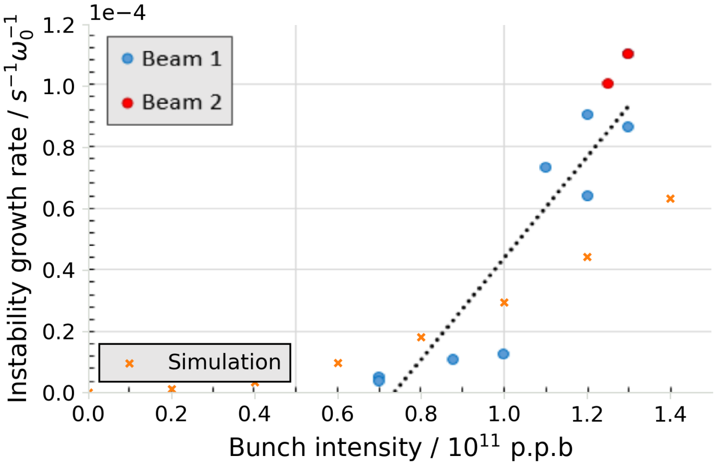

Figure 3: Instability growth rate measurement (red and blue dots) compared to DELPHI simulations (orange crosses). The growth rate were normalised to the beam angular revolution frequency ω_0.

In the future the tune shift measurement could be improved by:

- performing the measurement first at injection energy, which would allow to gain time and streamline the procedure before a measurement at top energy. The machine could also be refilled in case of emittance blow-up or bunch lengthening. A lost fill would also be less impacting.

- optimizing the bunch excitation. During the MD chromaticity and damper gain were reduced to improve the signal quality. This however can lead to instabilities compromising the beam quality. The impact of octupole current and chromaticity on the measured tune shift should be assessed in more details.
- performing the measurement with higher bunch intensities, as was originally foreseen for this MD activity.
- increasing the statistic by kicking the bunches several times to reduce the uncertainty on the tune value. However tune drift along time should also be taken into account in this case.

The growth rate measurements could as well be improved by ensuring there is no residual damper gain and probing as well the lower intensity region ($N_b < 0.6 \times 10^{11}$ p.p.b).

4 Conclusion

The MD activity and outcome were reduced with respect to the original plan as only one fill with low to nominal intensity bunches could be performed, and data remained noisy for the low intensity bunches, especially on Beam 1.

However, for Beam 2 a linear tune shift with intensity could be measured with sufficient accuracy. Good agreement between simulations and measurements was observed in the vertical plane. In the horizontal plane the measured shift was 15% to 30% higher than predicted by simulations.

The growth rate were measured switching off the damper gain (by an LSA trim) and reducing the octupole current to 0 A. A residual damping (or a residual tunespread from lattice non-linearities) was likely present, since not all the low intensity bunches became unstable. Nevertheless, a first comparison with simulations suggests a factor of about 2 higher growth rates than predicted.

With improvements to the measurement procedure, the measurement could be performed again, especially in the future profiting of the installation of new low impedance collimators.

In addition the measurement could also be done at injection energy where the loss of a fill or bunch instabilities would be less impacting, at the price of more open collimator settings.

Acknowledgements

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