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MD3308 – Growth rate versus chromaticity measurement at injection

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Summary

This report summarises the results of MD3308 on the measurement of the instability rise time as a function of chromaticity in the LHC. The measurement was held in the MD block 3 of 2018, on the afternoon of the 14th of September. With nominal bunches at the injection energy, the horizontal and vertical chromaticities were trimmed in the negative range from ∼-40 to -2 units. The transverse damper (ADT) was switched off to let an instability develop. The turn-by-turn position signal was then recorded with the ADT ObsBox. From these signals, the rise-time was deduced and compared to a prediction derived from the LHC impedance model.

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1 Introduction

Instability measurements are a way to evaluate the machine impedance and compare it to the model. The LHC impedance is overall higher at top energy because of the tighter collimator gaps required for betatron cleaning. However measurements at top energy are more demanding because of time and machine protection constraints. A parametric scan, e.g in chromaticity, is therefore difficult to perform with the beams at top energy.

Staying at injection energy allows scanning a variety of beam parameters. From theory, simulations and measurements, chromaticity is known to affect the instability rise time of a bunch [1, 2]. The rise time is also dependent on the bunch intensity and the real part of the machine impedance. At injection energy, the impedance contribution is shared between the collimators and the cold beam screen [3]. Measuring the instability rise time for different values of the horizontal and vertical chromaticities for both beams can therefore give information on the real part of the LHC impedance model.

2 Procedure and Beam Conditions

The measurement was performed on the afternoon of the 14th of September 2018 [4]. A single nominal bunch was injected in both rings. The filling scheme `Single_20b_0_0_0_Instabilities` was used. Buckets 851 and 901 were used throughout the MD activity such that the two bunches did not collide and had no long range interactions. The chromaticity was trimmed in one plane to a negative value, keeping the other at a positive value. A negative chromaticity for a machine operating above transition energy would ensure a strong mode 0 instability, easier to measure and to compare to predictions. During the first part of the MD the ADT gain value was trimmed to a very low value in LSA. However the ADT modules were still set on a residual damping. In some cases the instability was not developing properly. After a remote intervention of the RF experts at 19:00, the procedure was modified to switch off completely the ADT modules to let the instability develop. Measurements after 19:10 were done with this modified procedure. The instability caused intensity losses: more than 90% of the bunch intensity was lost in a few seconds. The ADT modules were then switched back on. The remaining intensity was scraped using the ADT blow-up capability, avoiding to explicitly dump the beam changing the operational beam mode. The new bunch was then injected in the same bucket as the previous one. The main beam parameters used in the MD activity are reported in Tab. 1.

Parameter	Value
Fill number	7171
Bunch intensity	$\sim 1.2 \times 10^{11}$ p.p.b
Bunch length τ_b	$1.1\,\mathrm{ns} \leq \tau_b \leq 1.3\,\mathrm{ns}$
Bunch emittance ε_n	$0.8\,\mu\mathrm{m} \leq \varepsilon_n \leq 1.3\,\mu\mathrm{m}$
Octupole current	0 A
TDI half-gap	Closed at 3.8 mm

Table 1: LHC beam set-up for the measurement.

The bunch emittance evolution during the MD is plotted in Fig. 1. The horizontal emittance was comprised between 0.8 µm and 1.3 µm and the vertical emittance between 0.8 µm and 1.1 µm. Emittance growth can be observed when the bunch was kept for longer periods. After 19:10 and the procedure adaptation described beforehand, the bunches were kept for shorter periods in the accelerator, and the emittance remains around 1 µm. Larger values correspond to the blow-up caused by instabilities.

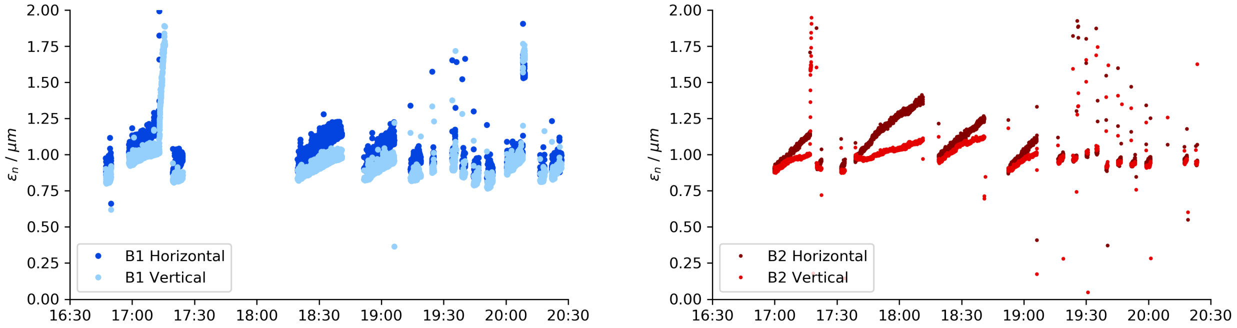

Figure 1: Bunch emittance versus time for beam 1 (left) and beam 2 (right). Horizontal plane data is plotted with a darker colour.

The bunch length evolution is also plotted in Fig. 2. Lengthening can be observed when the bunch remained for longer periods of time. After 19:10, and with the procedure change, the bunch stayed in the machine for shorter periods, and the bunch length was ∼1.1 ns.

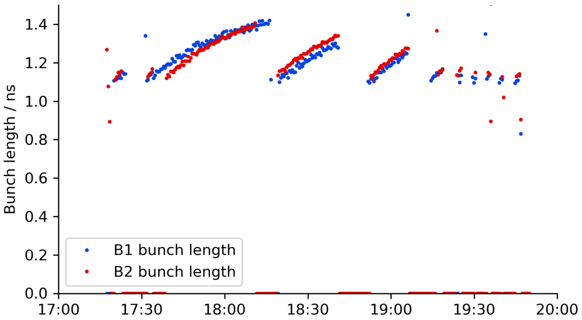

Figure 2: Bunch length evolution versus time for beam 1 and beam 2.

Figure 3 shows the MD overview, with the intensity in Beam 1 and Beam 2 as well as the energy which remained constant during the MD. After the procedure adaptation, the measurement procedure went smoothly and multiple points with $Q'_{H,V} \in [\sim -40; -2]$ were taken. The measurement times are given in Tab. 2 along with the chromaticity set in the machine and the bunch intensity. The method to start the instability (trimming the ADT gain in LSA or switching off the ADT modules) is also given. The availability from the injectors and the LHC was excellent, as can be observed in Fig. 3.

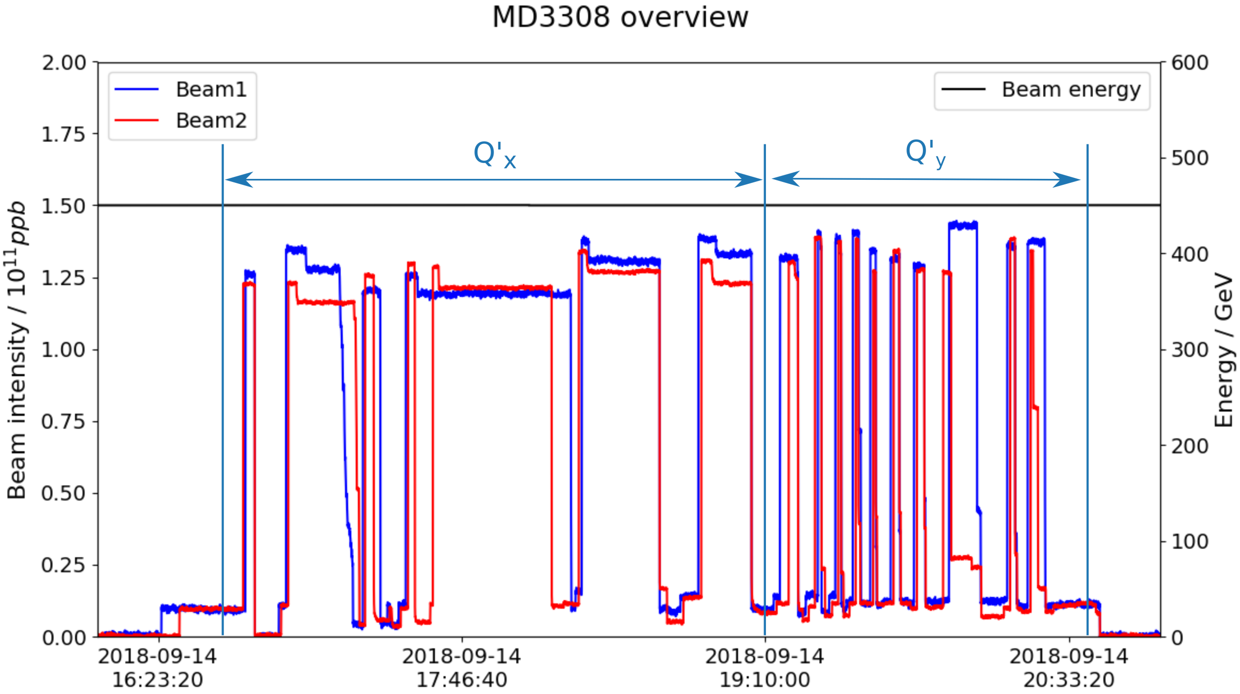

Figure 3: Beam 1 (blue curve) and Beam 2 (red curve) intensity, alongside beam energy (black curve) during the MD activity.

3 Data Treatment

The instability signal was recorded with the ADT ObsBox [5] and allowed to record the turn-by-turn, bunch-by-bunch transverse position over 32000 turns. The instability rise time was deduced from an exponential fit of the instability data, as shown in Fig. 4. The range was limited to the part where the instability was developing, before intensity losses occurred. Since the instability growth rate (i.e. the inverse of the rise time) depends, to a first approximation, linearly on the bunch intensity [1, 6], it was then normalised to a bunch intensity of 10^{11} protons per bunch. It also allows for an easier comparison to the simulation results.

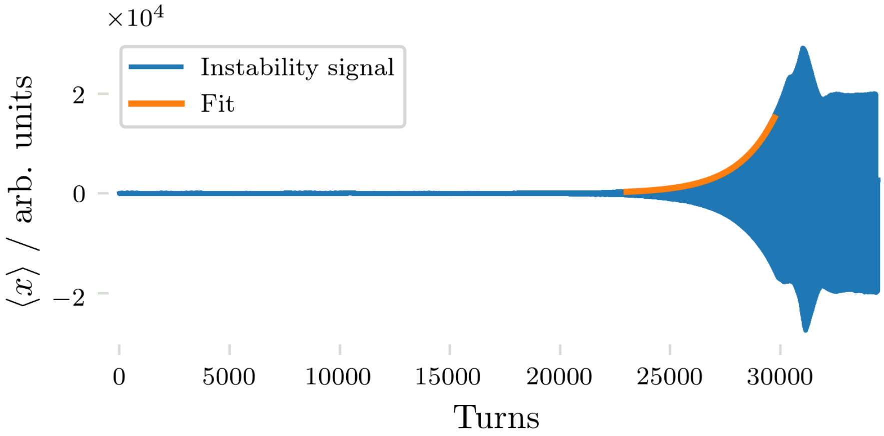

Figure 4: Example of an instability signal saved with the ADT ObsBox. The transverse position at the ADT pick-up is saved turn-by-turn, over 32000 turns. An exponential fit at the beginning of the unstable part of the signal is performed to obtain the rise time.

4 Results

The measurement results are summarised in Fig. 5 for the horizontal plane and Fig. 6 for the vertical plane. Dots indicate the measurements and solid lines indicate simulation results obtained with the Vlasov solver DELPHI [7], using the LHC impedance model at injection energy [8].

The TDI half-gap of 3.8 mm are taken into account in the impedance simulations, as well as the MKI. The dashed line also shows the simulation results applying a factor of 2 reduction to the simulated rise times. Table 2 details the rise time for each measurement point, and also provides the measured bunch intensity to which the rise time is scaled. Parameters used for DELPHI simulations are reported in Tab. 3.

In the case of Beam 1 vertical plane at large negative chromaticities, the instability appears to be slower than predicted. For these points the exponential fit on the instability data was poorly conditioned since the instability growth was not uniform. An example of a poor instability signal is given in Fig. 7. In this case the instability develops between turns 23000 and 27000, but the instability shows a variation in growth rate, characterised by the two slopes visible on the signal. Non-linear effects caused by the large negative chromaticity values and the fact that the machine optics is not corrected in this region could be as well playing a role. This aspect could be improved in the future with dedicated optics characterisation. For the horizontal plane, the rise times are about 2 times faster than predicted from simulations. For Beam 1, the data quality is poorer as observed from the large error bars for chromaticities close to zero. In this case, the issue might be caused by the damper gain setting applied during the first part of the MD, since some measurement were made with a residual damping.

We conclude that, for Beam 2 and Beam 1 in the horizontal plane, the measured rise times are within a factor of 2 faster than simulation results as summarised in Tab. 4. The measurement of Beam 1 in the vertical plane is likely to be optimised.

Beam/Plane	Time	Q'	Intensity / 10^{11} p.p.b	Rise time / s	Procedure
B1H	17h24	-5	1.17	0.6(2)	LSA trim
	18h40	-14	1.23	0.11(2)	LSA trim
	19h06	-4	1.26	0.3(1)	LSA trim
	19h18	-9	1.19	0.10(2)	Modules off
B2H	17h22	-5	1.23	0.33(3)	LSA trim
	17h33	-10	1.22	0.15(2)	LSA trim
	18h11	-4	1.18	0.18(2)	LSA trim
	18h40	-14	1.24	0.11(1)	LSA trim
	19h06	-4	1.19	0.41(6)	LSA trim
	19h18	-9	1.21	0.15(1)	Modules off
	19h25	-19	1.31	0.078(4)	Modules off
	19h30	-29	1.28	0.071(6)	Modules off
B1V	19h25	-19	1.28	0.08(4)	Modules off
	19h40	-10	1.25	0.24(8)	Modules off
	19h46	-15	1.20	0.21(4)	Modules off
	19h53	-20	1.18	0.2(2)	Modules off
	20h08	-31	1.21	0.5(1)	Modules off
	20h18	-26	1.22	0.30(4)	Modules off
B2V	19h40	-10	1.18	0.19(3)	Modules off
	19h46	-15	1.25	0.24(3)	Modules off
	19h53	-20	1.20	0.13(4)	Modules off
	20h01	-31	1.22	0.096(8)	Modules off
	20h23	-36	1.19	0.17(2)	Modules off
	20h24	-36	1.21	0.18(4)	Modules off

Table 2: Measurement time and chromaticity set in the machine. The plane indicated corresponds to the one for which the chromaticity was trimmed. The measured bunch intensity and the ADT switch off procedure corresponding to the measurement time are also indicated. Before 19:10, the ADT gain was trimmed in LSA, after the ADT modules were switched off.

Parameter	Value
Energy	450 GeV
Bunch intensity	1×10^{11} p.p.b
Number of bunches	1
Full bunch length	1.2 ns
Tune H/V (fractional)	0.275/0.295
Momentum compaction factor α_p	3.48×10^{-4}
Chromaticity range	$[-40; -2]$
Damper gain	0
Impedance model	`LHC_inj_450GeV_B1_2017`

Table 3: DELPHI simulation parameters used for the study.

5 Conclusion

The instability growth rate measurement at injection energy proved to be successful despite the short measurement time frame and the workarounds needed for the ADT. A large range

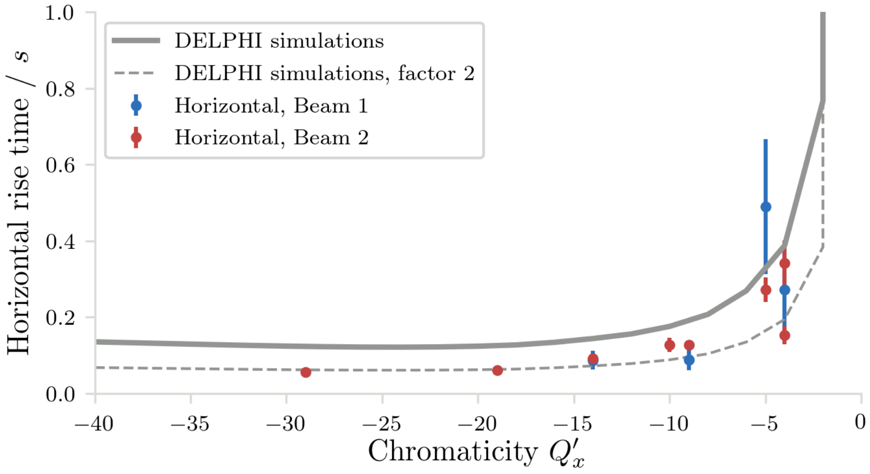

Figure 5: Instability rise time versus chromaticity in the horizontal plane. Dots represent the measurements for Beam 1 (blue) and Beam 2 (red) and the solid line represents DELPHI simulation results using the LHC impedance model. The dashed line represents the computed rise time reduced by a factor of 2.

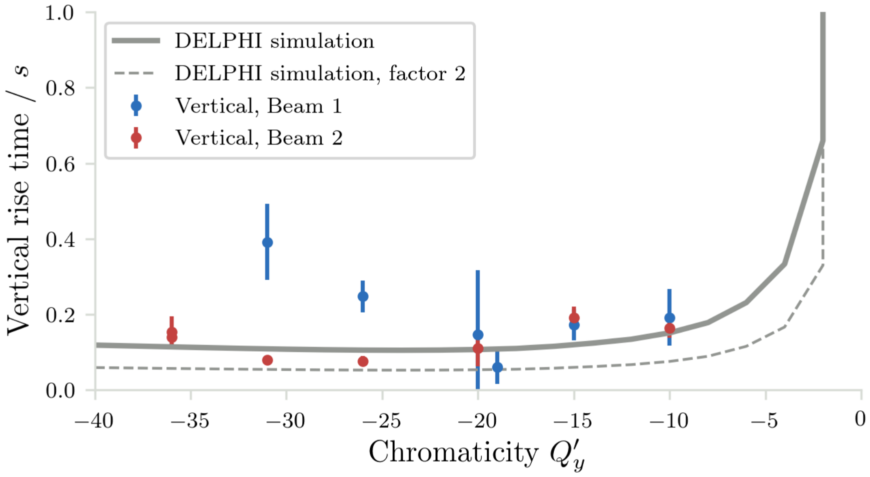

Figure 6: Instability rise time versus chromaticity in the vertical plane. Dots represent the measurements for Beam 1 (blue) and Beam 2 (red) and the solid line represents DELPHI simulation results using the LHC impedance model. The dashed line represents the computed rise time reduced by a factor of 2.

of chromaticities could be measured with both beams and planes. Clear instability signals were recorded, with however some edge case at large negative chromaticities. Rise times were found to be faster of about a factor of 2 with respect to predictions, in particular for Beam 1 and Beam 2 in the horizontal plane. Beam 1 in the vertical plane showed large error bar and additional measurements are needed. Similar measurements are planned in the future, together with a careful optics characterisation, especially at large negative chromaticity, and damper set-up. In order to disentangle the source of the discrepancy between measurements and predictions based on the LHC impedance model, the relative weight of the beam screen and collimators impedance will be investigated. This can be performed opening the collimator jaws within machine safety limits.

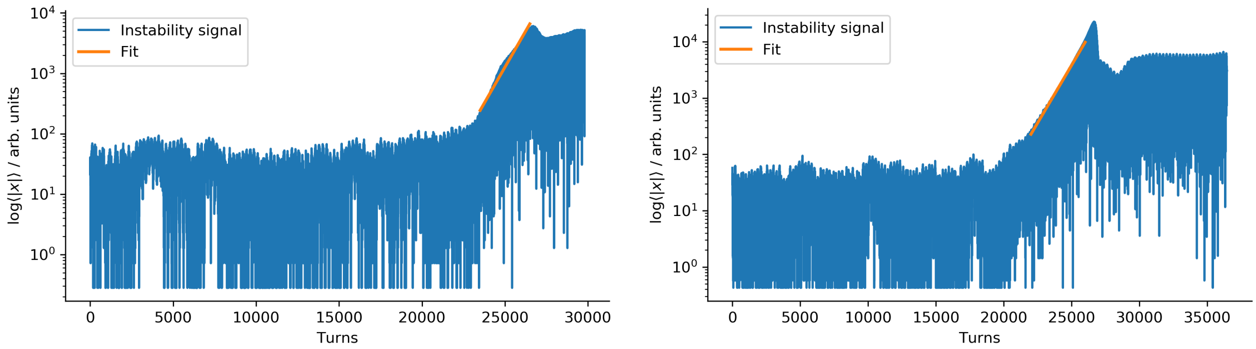

Figure 7: Example of an instability signal with a growth rate which is not uniform during the instability (B1V at $Q' = -19$) on the left plot. For comparison the right plot shows an instability with a growth rate remaining the same during the instability (B2V at $Q' = -10$).

Beam	Plane	Ratio	Error on ratio
B1	Horizontal	0.6	0.2
	Vertical	1	0.4
B2	Horizontal	0.5	0.03
	Vertical	0.9	0.1

Table 4: Averaged measurement to prediction ratios for the instability rise time. The average value is weighted by each measurement error.

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