



## MD 979: Beta-beating measurements on colliding beams

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### Summary

The HL-LHC high brightness beams will give a large  $\beta$ -beating due to the head-on and long-range interactions since a beam-beam parameter of 0.01 per Interaction Point (IP) is expected. The  $\beta$ -beating induced by two head-on collisions reaches 15 %. A third IP, i.e. IP8, could bring the  $\beta$ -beating up to 24% [1]. The aim of the Machine Development (MD) study was to test optics measurements with AC dipole and ADT on colliding beams at injection and to implement a correction of the  $\beta$ -beating due to head-on collision in the two main experiments IP1&5. In this note, we summarize the first results of this test performed in the LHC.

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## 1 Motivation

The current beam-beam parameter in the LHC is slightly higher than design and it is increasing as the quality of the beams delivered by the injectors as well as the brightness preservation in the LHC improve. Future projects such as the HL-LHC and the FCC-hh rely on total beam-beam tune shift up to 0.02 and 0.03, respectively. In such configurations the quadrupolar component of the beam-beam force introduces a  $\beta$ -beating in the order of 15% (Fig. 1), potentially resulting in luminosity imbalance between IPs, collimator cleaning efficiency deterioration and a compromised machine protection. Since such a  $\beta$ -beating goes beyond tolerances, the effect of the beam-beam interactions needs to be understood and if possible corrected. The strong non-linearity of the beam-beam interactions introduces a significant amplitude detuning and a corresponding amplitude dependent  $\beta$ -beating [1]. An optimized correction scheme needs to be investigated.

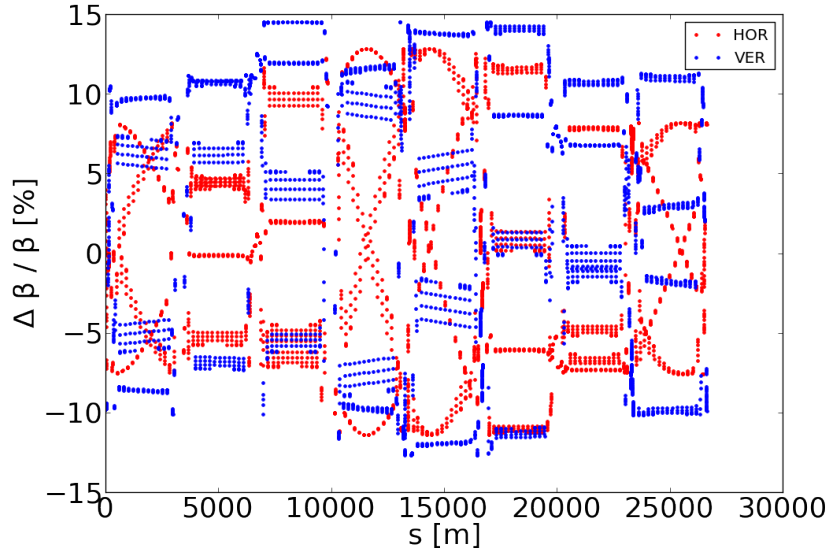


Figure 1: Simulation of horizontal and vertical  $\beta$ -beating due to beam-beam interaction at IP1 and 5 in the nominal HL-LHC configuration [1]

In this report, we explore the possibility of measuring for the first time the  $\beta$ -beating coming from the head-on beam-beam interaction at one IP using forced oscillations with AC dipoles in the LHC. Free and forced oscillations feature a different amplitude dependent tunes and  $\beta$ -beating [2]. The impact of possible corrections to the  $\beta$ -beating and on dynamic aperture is investigated in [3].

## 2 MD Procedure

The MD was carried out the night between the 29<sup>th</sup> and the 30<sup>th</sup> of October 2016. In Fig. 2, an overview of the MD is given. The first part of the MD consisted in two fills (fill numbers 5478 and 5479) with three bunches per beam aiming to find collisions at IP1 only, test the reproducibility of the separation bumps and setup the ADT [4] and AC dipole [5] as exciters. In the second part of the MD (fill number 5480), one pilot bunch (slot number 3080) was injected with corresponding damper settings in Beam 1 and two nominal bunches (slot numbers 2100 and 3080) were injected in Beam 2. Tests were performed at injection energy (450 GeV) since the head-on interaction is independent of the energy and a higher beam-beam parameter could have been reached. The separation was collapsed in IP1 and the transverse damper was turned off on Beam 1. Through the five fills constituting the second part of the MD, AC dipole or ADT excitations with different excitation frequencies and amplitudes were applied. The AC Dipole excitation amplitudes are given in units of the Root Mean Square (RMS) beam size  $\sigma$ . The length of excitations was about 6600 turns for the AC-dipole and 29000 turns for the ADT. The excitation amplitude is ramped during approximately 2200 turns to ensure the adiabaticity of the ramping process [6].

A correction of the  $\beta$ -beating was derived for the LHC lattice at injection energy with head-on beam-beam at IP1 and IP5. It was obtained by matching separately the optic

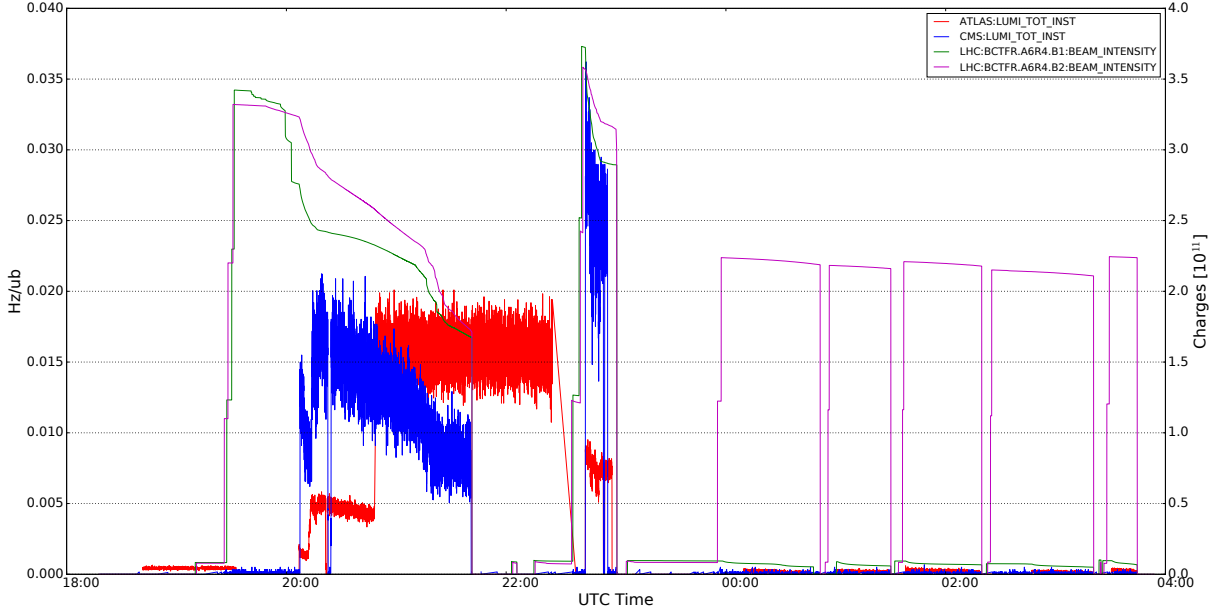


Figure 2: Overview of the MD 979 between 2016-10-29 18:00:00 and 2016-10-30 04:00:00 (UTC Time). The set-up period is shown together with the five fills where the excitations were carried out.

functions on both sides of each interaction region, as well as at the respective IP, to the optics in the lattice without beam-beam elements. The normalized emittance and bunch population were taken as  $2.5 \mu\text{m}$  and  $1.3 \times 10^{11}$ , respectively. The resulting knob consisted of a set of strengths for the quadrupoles Q4 to Q5 on each side of both IPs, as given in Table 1, and it was implemented in the machine during the MD.

## 2.1 Beam parameters

The intensities of Beam 1 and Beam 2 are presented in Fig. 3 (left and right plot respectively) as a function of time.

The horizontal and vertical emittances of Beam 1 and 2 measured with the BSRT system are shown in Fig. 4 (left and right respectively). More detailed analysis of BSRT data by experts is needed since for emittances below  $1.5 \mu\text{m}$ , the accuracy of the measurement cannot be better than 30% [7]. Furthermore, the effect of the  $\beta$ -beating due to the beam-beam collision at the location of the BSRT has to be evaluated since it could increase the uncertainty on the emittance of another 8% for this case (collision at one IP). Besides the growth rates expected, a blow up can be observed at the end of the 3<sup>rd</sup> and 4<sup>th</sup> fills in both beams caused by the too large excitation amplitudes used. The first beam also seems to have blown up during the first fill. Investigations are still in progress in order to determine the cause of it.

The horizontal and vertical beam tunes before collision were 0.31 and 0.32, respectively, the full crossing angle at IP1 and IP5 was  $340 \mu\text{rad}$  and  $\beta^*=11 \text{ m}$ .

IP	Magnet	Strength [ $10^{-5}\text{m}^{-2}$ ]	
		Left	Right
1	Q4	-5.423	8.264
	Q5	-2.374	3.544
	Q6	7.808	-11.802
	Q7	-4.836	7.348
5	Q4	-5.456	8.278
	Q5	-2.366	3.531
	Q6	7.818	-11.807
	Q7	-4.843	7.363

Table 1: Knob for the correction of beta-beating due to head-on beam-beam

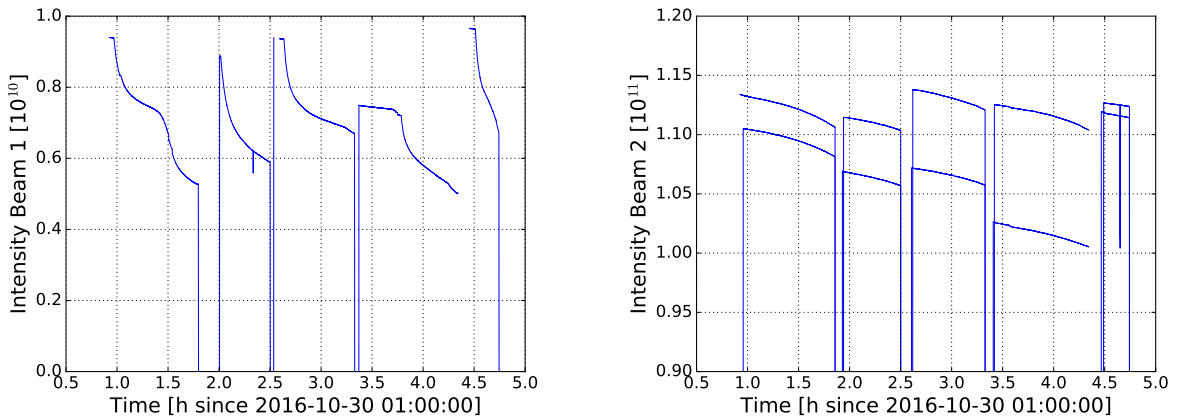
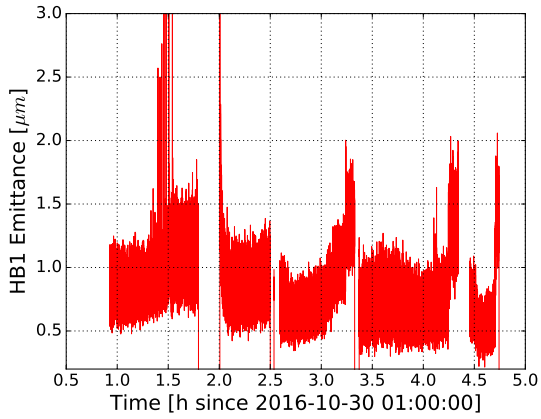
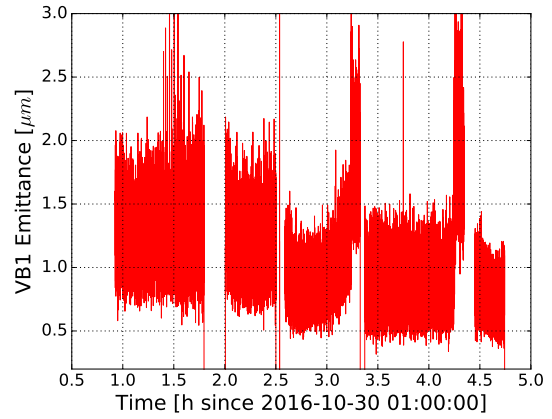


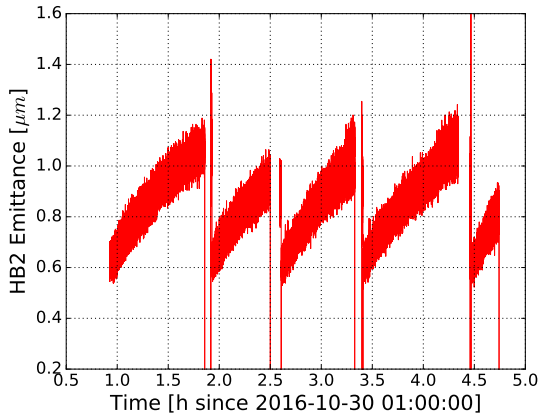
Figure 3: Intensity of Beam 1 (pilot) and Beam 2 colliding bunch



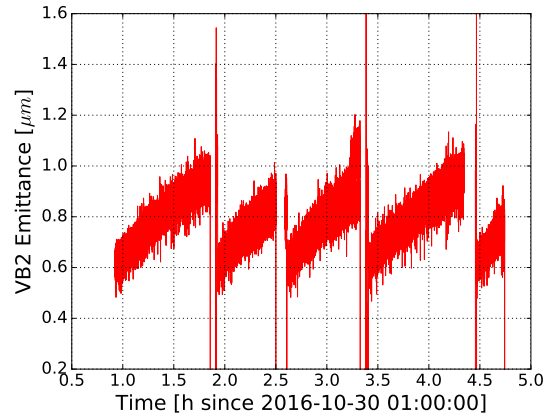
(a) Horizontal normalized emittance of Beam 1



(b) Vertical normalized emittance of Beam 1



(c) Horizontal normalized emittance of Beam 2



(d) Vertical normalized emittance of Beam 2

Figure 4: Horizontal and vertical normalized emittances of Beam 1 and 2 from BSRT measurements as a function of time during the MD

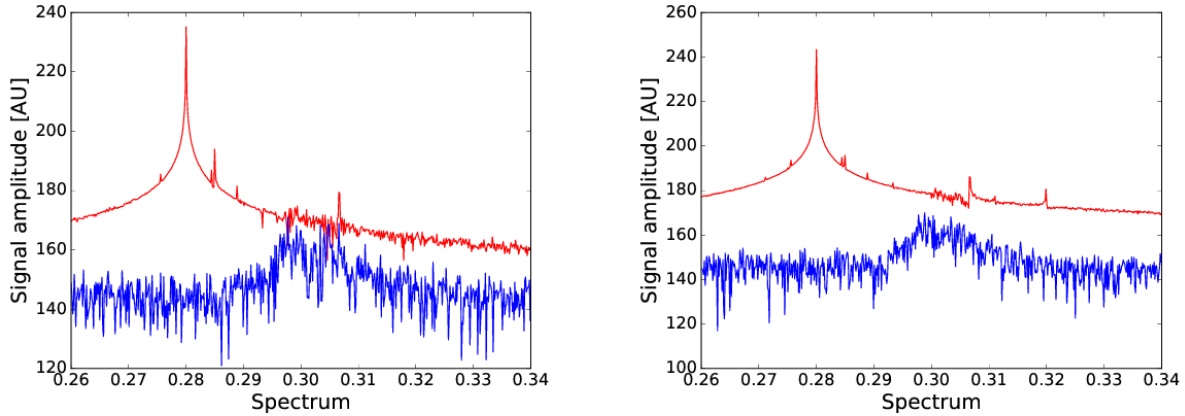


Figure 5: Horizontal spectra of Beam 1 at different ADT excitation amplitude. The vertical excitation amplitude is always  $0.15\sigma_y$  and the horizontal one is  $0.55\sigma_x$  and  $1.19\sigma_x$  for the left and right plot respectively. The blue curve corresponds to the spectrum of the beam just before the ADT excitation whereas the red one to the spectrum during the excitation. The horizontal and vertical ADT excitation frequencies were  $(0.28, 0.285)$ .

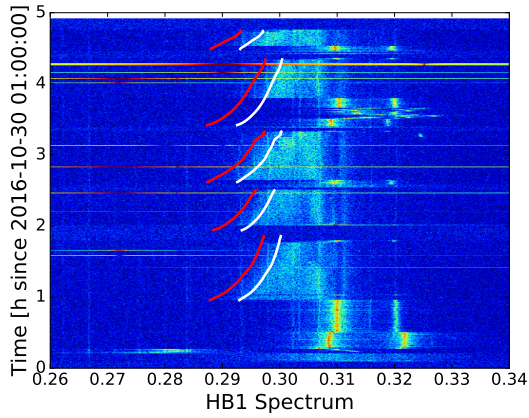
## 2.2 Beam 1 Spectra

Through the five fills, the horizontal and vertical computed beam-beam parameter  $\xi_{bb}$  from the measured intensity (right plot in Fig. 3) and emittances (Fig. 4 (c) & 4 (d)) of Beam 2 had a value between 0.022 and 0.013.

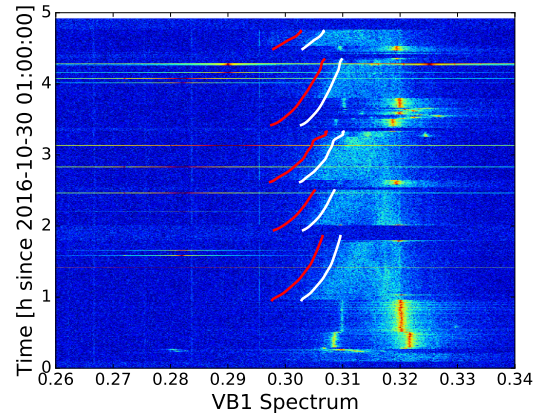
Plots in Fig. 5 show the spectra of Beam 1 from data acquired with the Base-Band Tune (BBQ) during the experiment. The red curve represents the beam spectrum at the moment of the ADT excitation and the blue one represents the beam spectrum just before it. Before the excitation (blue line), the tune spread starts at about 0.292, meaning that the measured beam-beam parameter should be  $\xi_{bb} \simeq 0.018$  which is smaller than what was computed. We compare the beam spectra with excitation (red lines) in order to put in evidence the beam range for a full head-on collision. For the left plot ( $0.55\sigma_x$ ), the continuum spectra from the beam is seen in the tune range 0.295 to 0.31. For a larger excitation amplitude ( $1.19\sigma_x$  in right plot), the continuum spectra is reduced in range (0.3 to 0.31) as expected [2]. In the limit of very large excitation, the frequency spectrum would reduce to a single line at the natural tune as the beam-beam tune shift tends to zero while separation increases.

We show on Figs. 6 (a) and 6 (b), the complete Beam 1 spectrogram during the MD measured from the BBQ. There are two curves on the spectrogram indicating the beam-beam tune shift of the zero amplitude particle due to head-on collision, i.e.  $Q_0 - \xi_{bb}$ . The red one is calculated based on the Beam 2 data presented above without any correction factor while the green one was computed assuming a 20% larger emittance of Beam 2 in both planes (Fig. 4 (c) & 4 (d)) leading to a smaller beam-beam parameter (between 0.0185 and 0.011). The assumption made with a correction factor of 1.2 leads to a maximal tune shift that is more consistent with the BBQ observations.

In Fig. 7, we show zooms of Fig. 6 related to the 1<sup>st</sup> and 5<sup>th</sup> fills in order to highlight the AC-dipole and ADT excitations respectively. The AC-dipole excitations were made on both planes with the same intensity ( $45^\circ$  in x-y excitation planes) whereas the ADT excitations

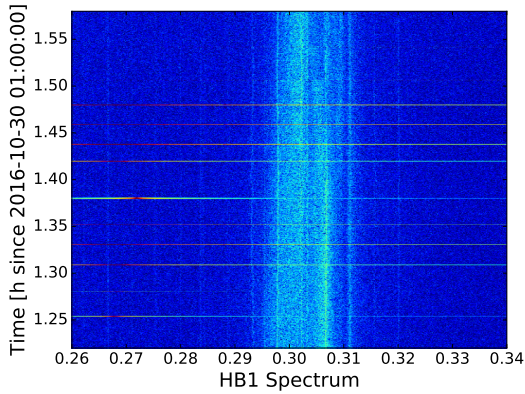


(a) Horizontal Beam 1 spectrum from BBQ

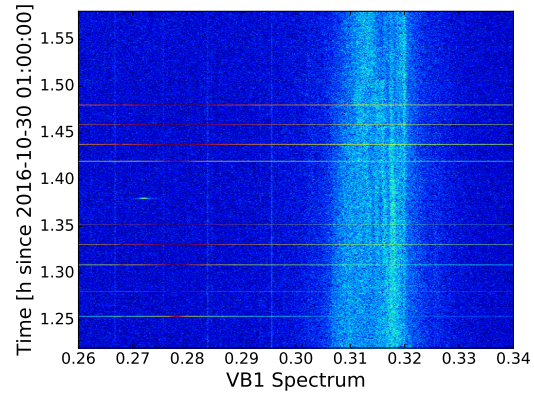


(b) Vertical Beam 1 spectrum from BBQ

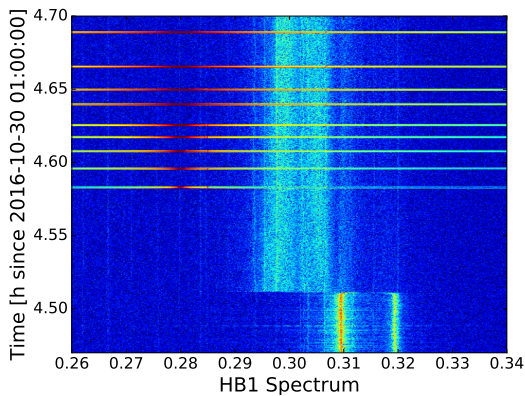
Figure 6: BBQ Spectrograms of the MD for both planes where the red and green curve represent the tune of the zero amplitude particles after beam-beam collision for a correction factor of 1.0 and 1.2 to the emittance of Beam 2 respectively



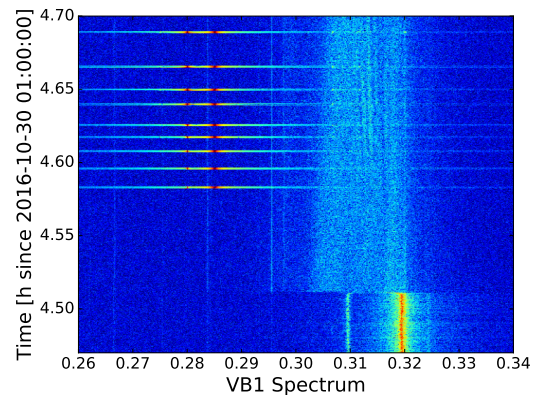
(a) Horizontal AC-dipole excitations (0.268) in 1<sup>st</sup> fill



(b) Vertical AC-dipole excitations (0.278) in 1<sup>st</sup> fill



(c) Horizontal ADT excitations (0.28) in 5<sup>th</sup> fill



(d) Vertical ADT excitations (0.285) in 5<sup>th</sup> fill

Figure 7: Zooms on BBQ from Fig. 6(a) and 6(b)

Excit. device	UTC Time	Amp. [ $\sigma_x$ ]	Amp. [ $\sigma_y$ ]	$f_{excit}^{(x,y)}$	$I_1$ [ $10^9$ ]	$\varepsilon_{n,x}^1$ [ $\mu\text{m}$ ]	$\varepsilon_{n,y}^1$ [ $\mu\text{m}$ ]	$I_2$ [ $10^{11}$ ]	$\varepsilon_{n,x}^2$ [ $\mu\text{m}$ ]	$\varepsilon_{n,y}^2$ [ $\mu\text{m}$ ]	$\xi_{bb,x}$	$\xi_{bb,y}$
AC-dipole	00:15:17	0.10	0.10	(0.268, 0.278)	7.5373	0.8595	1.2649	1.1004	0.8098	0.7518	0.0169	0.0175
	00:16:52	0.29	0.30		7.5142	0.8738	1.2799	1.0999	0.8223	0.7632	0.1660	0.0173
	00:18:33	0.48	0.49		7.4805	0.8833	1.2876	1.0993	0.8362	0.7740	0.0164	0.0170
	00:19:51	0.78	0.79		7.4429	0.8882	1.2835	1.0989	0.8483	0.7821	0.0162	0.0168
	00:21:08	0.78	0.79		7.3980	0.8946	1.2719	1.0984	0.8614	0.7902	0.0159	0.0166
	00:22:14	0.78	0.79		7.3570	0.9049	1.2594	1.0980	0.8735	0.7975	0.0157	0.0164
	00:23:58	1.19	1.21		7.2920	0.9353	1.2448	1.0973	0.8928	0.8098	0.0154	0.0161
	00:25:09	1.19	1.21		7.2424	0.9668	1.2440	1.0968	0.9052	0.8184	0.0152	0.0160
	00:26:14	1.19	1.21		7.1823	1.001	1.2512	1.0964	0.9154	0.8262	0.0150	0.0158
	00:27:29	1.42	1.44		7.0785	1.0423	1.2662	1.0958	0.9254	0.8345	0.0148	0.0156
	00:28:44	1.41	1.44		6.9202	1.0793	1.2832	1.0953	0.9339	0.8420	0.0147	0.0155
	00:30:21	1.81	1.85		6.6263	1.1117	1.2977	1.0945	0.9437	0.8501	0.0145	0.0153
	00:32:27	1.80	1.84		6.1659	1.1213	1.2946	1.0935	0.9571	0.8589	0.0143	0.0151
ADT	00:35:08	0.27	0.27	(0.272, 0.282)	5.7629	1.0992	1.2744	1.0921	0.9769	0.8707	0.0140	0.0149
	00:37:55	0.41	0.41		5.6957	1.0763	1.2641	1.0906	0.9936	0.8853	0.0138	0.0146
	00:39:49	1.19	1.19		5.5563	1.0768	1.2607	1.0895	1.0021	0.8949	0.0137	0.144
	00:42:00	1.30	1.30		5.2769	1.0957	1.2899	1.0881	1.0881	0.9041	0.0135	0.0142

Table 2: Summary of the characteristics of the beams and excitations of the 1<sup>st</sup> fill

were kept constant in the vertical plane ( $0.15\sigma_y$ ) and increased in the horizontal plane (from  $0.27\sigma_x$  to  $1.3\sigma_y$ ). On Figs. 7(a) and 7(b), the excitation frequencies (0.268, 0.278) cannot be deduced at this scale. However, for Figs. 7(c) and 7(d), they are visible on both planes (0.28, 0.285).

Table 2 and 3 contain all the beams and excitations parameters of the 1<sup>st</sup> and 5<sup>th</sup> fills respectively. Further analysis is still ongoing for the other fills.

Forced oscillations differ from free oscillations and to reconstruct the free  $\beta$ -functions, a correction is required depending on the distance between the natural and the excitation frequencies [8]. Three approaches based on the Beam Position Monitors (BPM) were used in order to deduce the natural tune at collision: (i) direct observation of natural tune in the Beam 1 spectrum, (ii) deviation of the RMS  $\beta$ -beating on both sides of the AC/ADT location and (iii) phase advance deviations after AC/ADT location in the segment-by-segment analysis [9, 10]. Beam optics were computed using the N-BPM method [11].

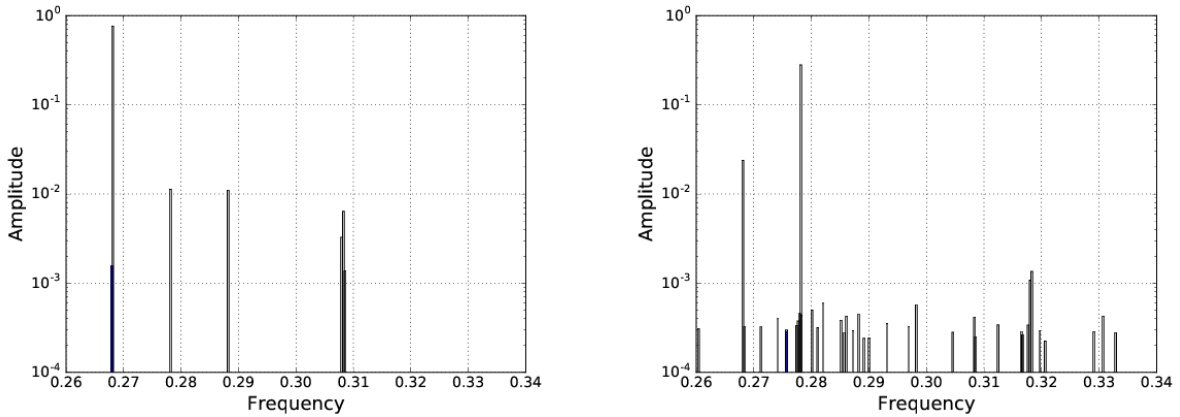
An example of Beam 1 spectrum of the strongest AC-dipole excitation (end of 1<sup>st</sup> fill) from the BPMs data is given in Fig. 8. The signal coming from the AC-dipole on both planes provides the strongest signal in the horizontal spectra. There is also a peak at 0.288 on the horizontal spectrum that is not yet understood. Apart from these excitation peaks, there is another signal that may correspond to the beam natural tune at the frequencies (0.307, 0.317). However, the beam natural tune does not appear in any other spectrum for AC-dipole or ADT excitations.

The RMS method uses the fact that the largest  $\beta$ -beating source for forced oscillations



Excit. device	UTC Time	Amp. [ $\sigma_x$ ]	$f_{excit}^{(x,y)}$	$I_1 [10^9]$	$\varepsilon_{n,x}^1 [\mu\text{m}]$	$\varepsilon_{n,y}^1 [\mu\text{m}]$	$I_2 [10^{11}]$	$\varepsilon_{n,x}^2 [\mu\text{m}]$	$\varepsilon_{n,y}^2 [\mu\text{m}]$	$\xi_{bb,x}$	$\xi_{bb,y}$
ADT	03:34:58	0.27	(0.28, 0.285)	7.9943	0.5077	0.7733	1.1258	0.6959	0.6777	0.0199	0.0201
	03:35:43	0.41		7.9123	0.5176	0.7657	1.1256	0.7076	0.6846	0.0196	0.0199
	03:36:26	0.55		7.8378	0.5333	0.7582	1.1255	0.7201	0.6923	0.0193	0.0197
	03:37:00	0.68		7.7764	0.5452	0.7518	1.1254	0.7306	0.6995	0.0190	0.0194
	03:37:30	0.80		7.7202	0.5515	0.7457	1.1253	0.7401	0.7067	0.0188	0.0192
	03:38:21	0.94		7.6236	0.5463	0.7339	1.1251	0.7558	0.7204	0.0184	0.0189
	03:38:57	1.06		7.5572	0.5298	0.7244	1.1250	0.7660	0.7303	0.0182	0.0186
	03:39:53	1.19		7.4577	0.5019	0.7086	1.1248	0.7800	0.7442	0.0178	0.0183
	03:41:18	1.30		7.2949	0.6055	0.6973	1.1245	0.7984	0.7578	0.0174	0.0179

Table 3: Summary of the amplitude of excitation per devices used for the 5<sup>th</sup> fill. The vertical excitation amplitude remains constant through all this fill and is equal to  $0.15 \sigma_y$ .



(a) Horizontal spectrum with  $1.8\sigma_x$  excitation amplitude (b) Vertical spectrum with  $1.84\sigma_y$  excitation amplitude

Figure 8: Beam 1 spectra of the last AC-dipole excitation ( $f_{excit} = (0.268, 278)$ ) of the 1<sup>st</sup> fill at the BPM.6R2

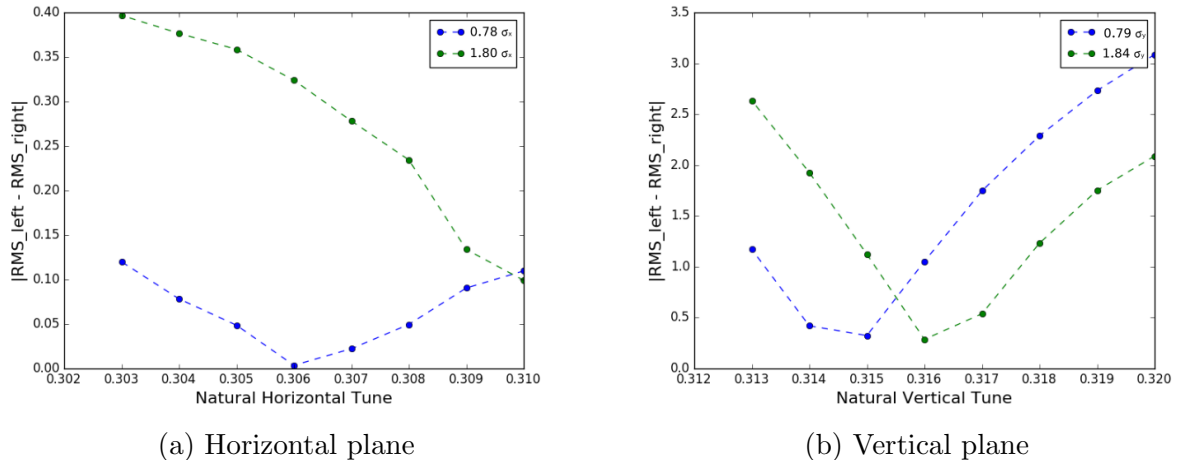


Figure 9: Scan of the natural tune for horizontal and vertical plane. Both lines are for AC-dipole excitations from the 1<sup>st</sup> fill with different excitation amplitudes.

in IR4 ( $s \simeq 3332$  m) should be the AC dipole itself. The best guess of the natural tune should correspond to minimizing the difference of the RMS  $\beta$ -beating between both sides of IP4. This method provides coherent values of the natural tunes for every excitation in the sense that stronger is the excitation amplitude the closer to the initial tunes is the natural tune. Horizontal and vertical scan of the natural tune with two different AC-dipole excitations of the 1<sup>st</sup> fill are in Fig. 9. In the case of the strongest AC-dipole excitation (1.8  $\sigma_x$  and 1.84  $\sigma_y$  on the x-y plane), the natural tunes provided by this method (green plot in Fig. 9(a) and 9(b)) are (0.31, 0.3163), which are similar to the ones from the spectra (Fig. 8): (0.307, 0.317).

The phase advance method aims at finding the natural tune that minimizes the phase advance beating originating in IR4 where the AC dipole is located. This method is applied to the IR4 segment which is treated as an independent transfer line, meaning that the measured optics are used as initial conditions for the simulations and that machine errors occurring in this segment are neglected in the phase propagation. Scans with different natural tunes in the simulations were performed. This method always provided the same results indicating that the best natural tunes were (0.31, 0.32). Further analysis about the simulations and limitations of the model are still in progress.

The  $\beta$ -beating introduced by the beam-beam collision at IP1 ( $s \simeq 20\,000$  m) computed from the BPMs data at the moment of the strongest AC dipole excitation is shown in Fig. 10. For this measurement, Beam 1 had an oscillation amplitude of 1.8  $\sigma_x$  and 1.84  $\sigma_y$  and the frequencies of the forced oscillations were 0.268 and 0.278 on the horizontal and vertical plane respectively. Beam 1 and Beam 2 intensities were  $6.2 \cdot 10^9$  ppb and  $1.1 \cdot 10^{11}$  ppb and their emittances (1.1  $\mu\text{m}$ , 1.3  $\mu\text{m}$ ) and (1.0  $\mu\text{m}$ , 0.9  $\mu\text{m}$ ), respectively. The  $\beta$ -beating due to beam-beam collision remains below 10%.

For the vertical plane, one also notices an important unexpected contribution from IP5 ( $s \simeq 6665$  m in Fig. 10). Further investigations are needed to understand its source.

The predicted  $\beta$ -beating for the zero amplitude particles is shown in Fig. 11 for the above beam parameters where one sees that the maximum  $\beta$ -beating is 10% or 8% without

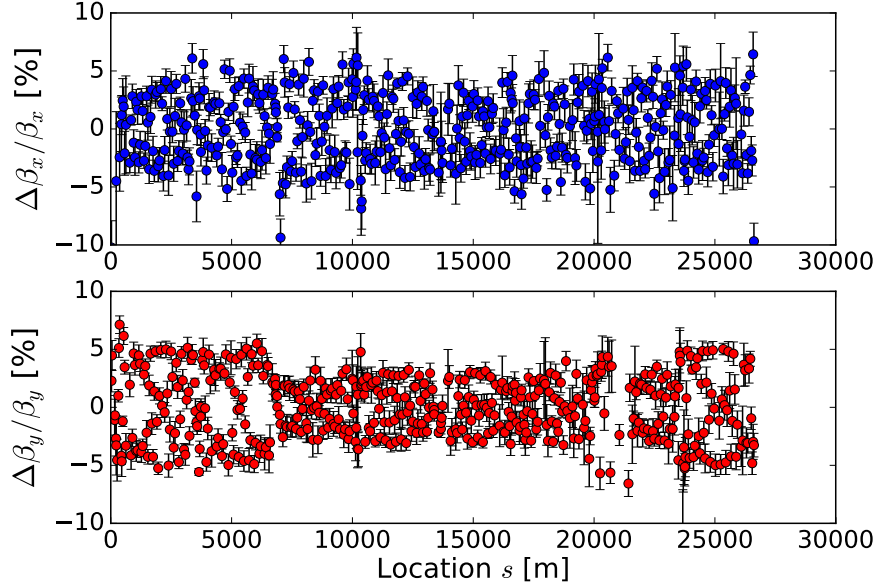


Figure 10: Measured  $\beta$ -beating for  $1.8 \sigma_x$  and  $1.84 \sigma_y$  amplitude particle due to beam-beam interaction at IP1 along the machine computed from BPMs data. This case corresponds to the AC dipole excitation shown on Fig. 8 and to the green plot on Fig. 9. The longitudinal coordinate starts at IP3.

and with the correction factor to the emittance, respectively. However, for a  $2 \sigma$  oscillation amplitude, a reduction of the  $\beta$ -beating of roughly 30% is expected as estimated in [1] leading to a maximum of  $\beta$ -beating of about 8-6%.

The comparison of the  $\beta$ -beating from Figs. 10 and 11 shows that simulations and measurements are of the same order of amplitude. The 20% correction factor to the emittance provides a smaller  $\beta$ -beating as expected that is also more consistent with Fig. 10.

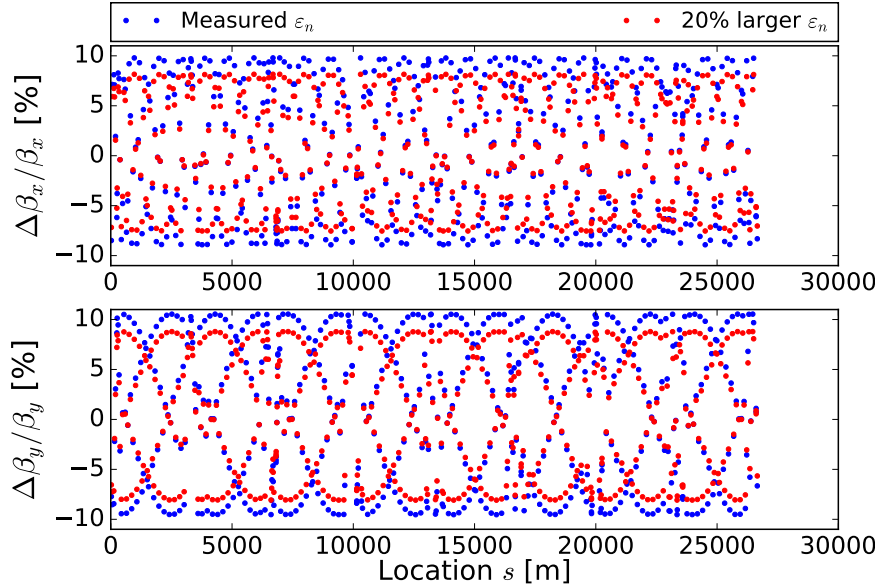


Figure 11: Simulation of  $\beta$ -beating in the LHC due to head-on beam-beam interaction at IP1 at injection energy for zero amplitude particles. Blue points were computed based on the measured normalized transverse emittance and the red ones assuming a 20% larger emittance. The longitudinal coordinate starts at IP3.

### 3 Summary

- Forced oscillations have been induced for the first time in the presence of beam-beam head-on collisions in the weak-strong regime with the aim of measuring optics parameters.
- No emittance growth or particle losses were observed for a wide range of excitation amplitudes up to about  $2\sigma$ .
- The main difficulty to achieve an accurate optics measurement at low excitations is the identification of the natural oscillation frequency, required for the correction of the difference between free and forced oscillations.
- At  $1.8\sigma$  amplitude, however, a clear natural frequency is observed and optics measurements could be accomplished.

### 4 Acknowledgement

We wish to thank the operators of the LHC and its injectors for their kind assistance during the measurements. We acknowledge support from the Swiss State Secretariat for Education, Research and Innovation SERI.

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