

# STUDIES OF RF NOISE INDUCED BUNCH LENGTHENING AT THE LHC\*

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## Abstract

Radio Frequency (RF) noise induced bunch lengthening can strongly affect the Large Hadron Collider (LHC) performance through luminosity reduction, particle loss, and other effects. This work presents measurements from the LHC that better quantify the relationship between the RF noise and longitudinal emittance blowup and identify the performance limiting RF components. The experiments presented in this paper confirmed the predicted effects on the LHC bunch length growth.

## BEAM DIFFUSION WITH RF NOISE

Following [1] and [2], the bunch length growth rate can be estimated by

$$\begin{aligned} \frac{d\sigma_\tau^2}{dt} &= \frac{d\sigma_\phi^2}{\omega_{RF}^2 dt} = \frac{\omega_s^2}{2\pi\omega_{RF}^2} S_\phi(f_s) \\ &= 2\sigma_\tau \frac{d\sigma_\tau}{dt} \end{aligned} \quad (1)$$

where  $\omega_{RF}$  is the RF angular frequency,  $\omega_s = 2\pi f_s$  is the angular synchrotron frequency, and  $S_\phi(f)$  is the phase noise spectral density experienced by the beam (in  $\text{rad}^2/\text{Hz}$ ).

Since the beam is a very high Q resonator at the synchrotron frequency  $f_s$ , the beam sampled power  $P_n$  is dominated by the noise power spectral density around  $kf_{rev} \pm mf_s$  where  $f_{rev}$  is the revolution frequency,  $k$  an integer, and  $m$  is the azimuthal mode number ( $m = 1$  for dipole modes,  $m = 2$  for quadrupole modes etc). In this work we focus on  $m = 1$ , since this mode dominates the diffusion of the bunch core, with the LHC bunch length (250-375 ps) small compared to the bucket width of 675 ps.

## LHC MEASUREMENTS

Dedicated measurements with protons [3] and ions were conducted to better quantify the relationship between the sampled noise power and the bunch length, and also to better understand the effect of the BPL.

### Protons

In this study, the Beam Phase Loop (BPL)<sup>1</sup> gain was varied which had a significant effect on the noise power spec-

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<sup>1</sup>The Beam Phase Loop (BPL) is a narrow bandwidth loop that acts on the VCXO to damp out barycentric longitudinal motion around the synchronous phase. As such, it damps out longitudinal motion around

tral density around  $f_s$  ( $k = 0$ ), and consequently the noise power sampled by the beam. The wideband spectral density for RF station 6 of Beam 2 (RF station 6B2) is shown in Fig. 1, as a function of the BPL gain.

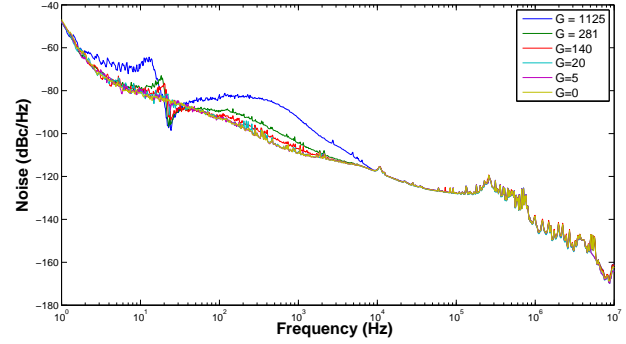


Figure 1: RF station 6B2 noise spectral density with BPL gain.

Figure 2 shows the effect of the BPL gain settings on the longitudinal bunch length for Beam 2.

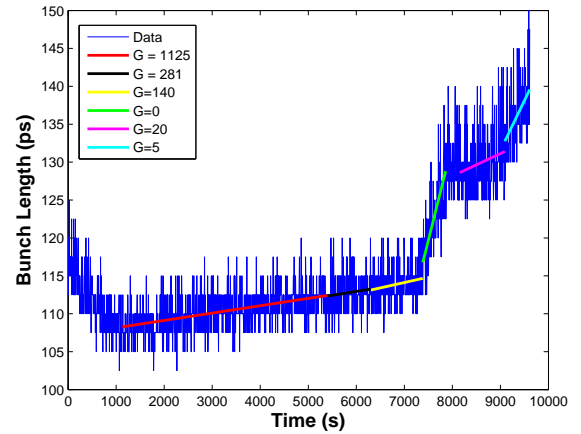


Figure 2: Beam 2 Bunch Length with time.

The growth rate of the longitudinal bunch length can be approximated from these figures. Using Eq. 1, and the measured accelerating voltage noise spectrum it is then possible to compute the estimated bunch length growth rate for each setting and compare with the measured growth rates. Results are presented in Table 1 for Beam 2 (results for Beam 1 are omitted due to space limitations). One can see the

the synchronous phase, motion driven by noise in the RF system or other mechanisms.

Table 1: Bunch Growth Rate Dependence on BPL Gain and Noise Power for B2

BPL gain	Estimated	Measured	
	$d\sigma_\tau^2/dt$ (ps <sup>2</sup> /hr)	$d\sigma_\tau^2/dt$ (ps <sup>2</sup> /hr)	$d\sigma_\tau/dt$ (ps/hr)
0	19000	22500	91
5	12800	12900	47
20	5500	2800	8
140	2900	1200	5
281	1250	800	4
1125	1000	800	3

clear correlation between the scaled bunch length as estimated by Eq. 1 and the longitudinal emittance growth. As expected, the agreement is better for higher noise levels, since at those points the Intra-Beam Scattering (IBS) contributions are insignificant and there is less uncertainty in the bunch length growth estimation.

### Ions

Through these initial measurements, it was evident that the growth rate of the bunch length is strongly related to the accelerating voltage phase noise power spectral density around  $f_s + kf_{rev}$ , as predicted in [4]. For a more quantitative and accurate study, a technique was developed to inject noise of controllable amplitude in a narrow band around the synchrotron sidebands of a set revolution harmonic ( $k = 1$  for these measurements). Measurements were then conducted in November 2010 using ions at 3.5Z TeV, with four equidistant non-colliding bunches of  $7 \cdot 10^9$  intensity per ring. The initial bunch length was approximately 160 ps for both beams. The total RF voltage was set to 12 MV. The bunch emittance was blown up transversely to reduce IBS.

Noise was injected in one RF cavity per ring for this measurement, with a bandwidth of 10 Hz from  $f_s - 10$  to  $f_s$ . The injected noise power level was varied during this measurement. Figure 3 shows the power spectral density of the various levels of injected noise around  $f_{rev} + f_s$  and Figure 4 shows the resulting bunch length growth for Beam 1, with linear fits for each noise level.

The bunch length growth in ps/hr can be determined by the slope of the linear fit. Of course, the accuracy of these estimates are limited by the length of each time segment and the granularity of the BQM measurements. Table 2 shows the results for both beams (the negative numbers in the end are due to substantial beam loss). In the early stages of this measurement (up to the first -76 dBc/Hz level in bold), the bunch is short enough that the growth is dominated by IBS. This background level of about 40 ps/hr is present until the bunch grows sharply from 210 ps to 240 ps and is mostly attributed to IBS. As the bunch grows longer, the background growth (from IBS plus the nominal RF noise) drops to about 20 ps/hr. It is also evident

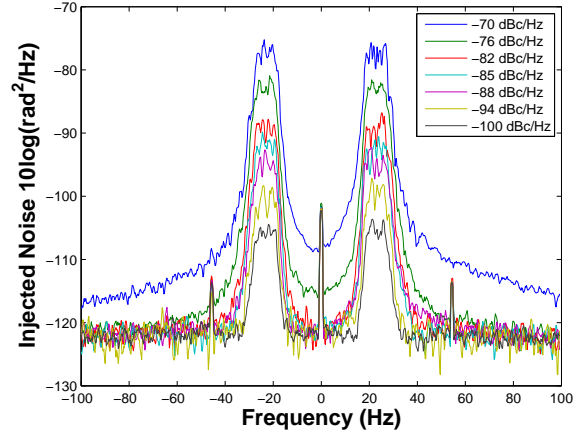


Figure 3: Levels of injected noise around  $f_{rev} + f_s$ . Horizontal axis shifted by  $f_{rf} + f_{rev}$ .

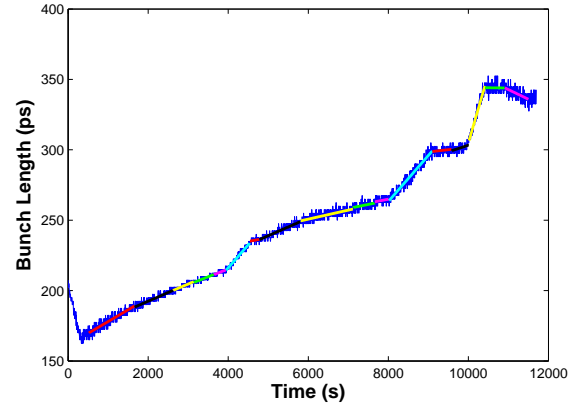


Figure 4: Beam 1 bunch length growth

that the threshold for the injected noise is between -82 and -85 dBc/Hz; since in the former case there is no noticeable change from the background level, whereas in the latter there is a measurable increase in the bunch length growth rate.

The estimated growth from Eq. 1 is shown for all the noise levels higher than or comparable to the noise threshold. There is good agreement with the measurements. The reported values are  $d\sigma_\tau/dt$  rather than  $d\sigma_\tau^2/dt$ , so there is an additional dependence to  $\sigma$ .

## LHC RF NOISE THRESHOLD

Since the bunch length growth rate  $d\sigma/dt$  is approximately proportional to the RF noise power, it is possible to estimate a noise threshold to reach a growth rate of 2.5 ps/hr (or equivalently a  $4\sigma$  growth rate of 10 ps/hr). This rate achieves an acceptable lifetime and is comparable to the IBS growth.

Table 2: Bunch Length Growth as a Function of the Power Spectral Density (PSD) of the Injected Noise – Referred to a Single Sideband (SSB)

PSD (dBc/Hz)	B1 $d\sigma_\tau/dt$ (ps/hr)	B2 $d\sigma_\tau/dt$ (ps/hr)	Estimated (ps/hr)
background	60	72	
-100	45	40	
-94	44	34	
-88	42	39	
-82	41	68	40
<b>-76</b>	<b>119</b>	<b>128</b>	150
background	19	30	
-82	45	49	35
background	23	20	
-85	21	26	20
background	20	6	
-76	119	140	125
background	12	16	
-76 at $3f_s$	35	-6	
-70	352	580	380-450
background	-1	1	
-70 at $3f_s$	-49	-52	

At the time of the proton measurements the noise injection capability was not implemented. As a result, the highest RF noise level for the proton data occurred when the BPL was off, with a SSB noise PSD of approximately -85 dBc/Hz at the fundamental band ( $k = 0$ ). In this case, the fundamental band is dominating, so we do not need to include the other contributions at  $f_s + kf_{rev}$ . A bunch length growth rate of about 100 ps/hr was measured with this configuration. Therefore, to achieve 2.5 ps/hr the SSB noise power spectral density should be approximately **-101 dBc/Hz**. This noise threshold is per cavity and assumes *uncorrelated* noise sources [5].

During the ion measurements, the injected noise power is larger than the nominal RF station noise, so that the bunch length growth rate  $d\sigma/dt$  is approximately proportional to the injected noise power, *if the noise is significantly large to be the dominant contribution over IBS*. For this reason and since the beam loss is not too high to affect the accuracy of the estimate, the SSB PSD level of -76 dBc/Hz is used for the noise threshold estimate. At that noise level, the growth rate was estimated to about 130 ps/hr. Scaling to 2.5 ps/hr, we get a threshold of approximately -93 dBc/Hz *for a single cavity* (SSB). The threshold adjusted for all 8 RF cavities is then **-102 dBc/Hz**. Not surprisingly, the estimates for protons or ions are in close agreement.

The cumulative PSD from the double synchrotron sidebands around each of the 30 revolution harmonics between  $f_{rev}$  and the end of the closed loop cavity bandwidth (approximately 300 kHz) is approximately -110 dBc/Hz according to the LHC measurements. With the BPL on, the

noise contribution at the  $f_s$  is reduced below this level. Therefore, the LHC RF noise is about 9 dB lower than the noise level for 2.5 ps/hr growth rate, assuming the 2010 LLRF configuration.

## CONCLUSIONS

Dedicated measurements were conducted in the LHC to gain insight in the effect of RF noise to the longitudinal beam diffusion. It was evident that the growth rate of the bunch length is strongly related to the accelerating voltage phase noise power spectral density around  $f_s + kf_{rev}$ , as predicted in [4]. The noise threshold for 2.5 ps/hr growth was estimated to -101 dBc/Hz (SSB flat noise spectral density from  $f_s$  to the edge of the closed loop bandwidth). A 9 dB margin is achieved with the current RF configuration and the BPL on.

With this formalism it is now possible to estimate the effect of different operational and technical RF configurations on the LHC beam diffusion. This formalism could also be useful for the design of future RF systems and the budgeting of the allowed noise.

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