LHC BEAM DIFFUSION DEPENDENCE ON RF NOISE: MODELS AND MEASUREMENTS*

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Abstract

Radio Frequency (RF) accelerating system noise and non-idealities can have detrimental impact on the LHC performance through longitudinal motion and longitudinal emittance growth. A theoretical formalism has been developed to relate the beam and RF loop dynamics with the bunch length growth [1]. Measurements were conducted at LHC to validate the formalism, determine the performance limiting RF components, and provide the foundation for beam diffusion estimates for higher energies and intensities. A brief summary of these results is presented in this work.

INTRODUCTION

During a long store, the relation between the energy lost to synchrotron radiation and the noise injected to the beam by the RF accelerating voltage determines the growth of the bunch energy spread and longitudinal emittance. Since the proton synchrotron radiation in the LHC is very low, the beam diffusion is extremely sensitive to RF perturbations.

The theoretical formalism presented in [1], suggests that the noise experienced by the beam depends on the cavity phase noise power spectrum, filtered by the beam transfer function, and aliased due to the periodic sampling of the accelerating voltage signal V_c. Additionally, the dependence of the RF accelerating cavity noise spectrum on the Low Level RF (LLRF) configurations has been predicted using time-domain simulations and models [2]. In this work, initial measurements at the LHC supporting the above theoretical formalism and simulation predictions are presented.

BEAM DIFFUSION DEPENDENCE ON RF NOISE

According to the theoretical formalism, the growth rate of the longitudinal bunch length should be proportional to the beam sampled noise power P_n. Since the beam is a very high Q resonator at the synchrotron frequency f_s, P_n is effectively proportional to the sum of the power spectral density around $f_s + k \cdot f_{rev}$ where f_{rev} is the revolution frequency and k an integer.

The time-domain simulations include models of the noise from the cavity controller (LLRF), but not from the RF reference loop. A simplified block diagram of the system is shown in Figure 1, which shows these two main contributions to cavity noise.

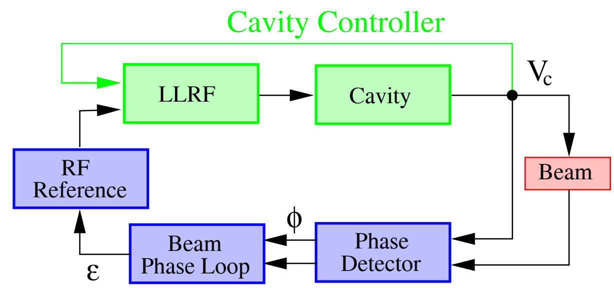

Figure 1: Simplified block diagram of the RF system with Beam Phase Loop.

Cavity Phase Power Spectral Density

Based on the time-domain simulations, a cavity phase noise spectrum similar to the one shown in Figure 2 was anticipated. This spectrum is defined by the superconducting cavity and the the LLRF feedback system in closed loop.

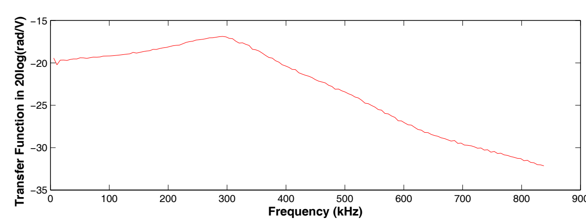

Figure 2: Estimated transfer function between modulator input and cavity phase.

Measurements of the power spectral density of the RF stations during operations with 3.5 TeV beam showed that the total power P_n is in fact dominated by low frequency noise around f_s. Tests suggested that this low frequency noise was introduced by the 400.8 MHz RF reference, as can be seen in Figure 3. It is obvious from this figure that the cavity sum noise follows the 400.8 MHz reference up to approximately 300 Hz. At higher frequencies, the noise is dominated by the LLRF controller.

The phase power spectral density of cavity 2B1 is shown as an example in Figure 4. The beam sampling frequencies for $k \in [0\ 4]$ are marked for reference. During all the measurements presented in this work, at least 98% of the noise power was attributed to the single contribution at f_s.

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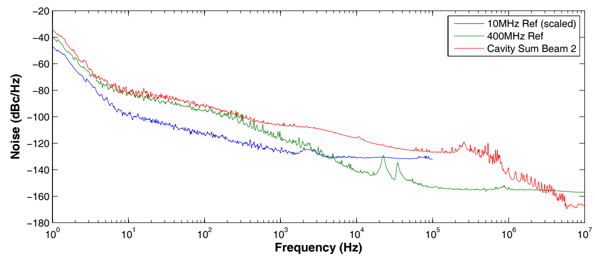

Figure 3: Beam 2 cavity sum and RF reference-BPL OFF

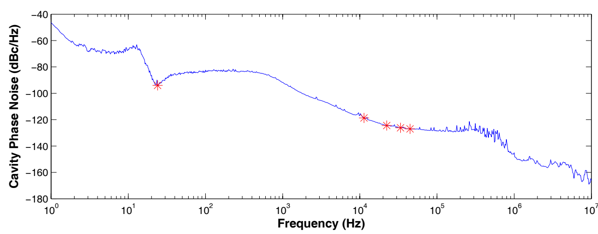

Figure 4: Cavity phase noise for cavity 2B1 with 1.5 MV, Q of 60k, 3.5 TeV beam.

Beam Phase Loop

The notch seen at the synchrotron frequency of about 23 Hz, is introduced by the Beam Phase Loop (BPL), a narrow bandwidth loop that synchronizes the average beam phase over a turn with the RF phase, via adjustments of the 400.8 MHz reference, as shown in the simplified block diagram in Figure 1.

As such, it leads to a major performance improvement. Figure 5 shows the substantial reduction of the phase error ϵ at f_s with the BPL closed. Furthermore, Figure 6

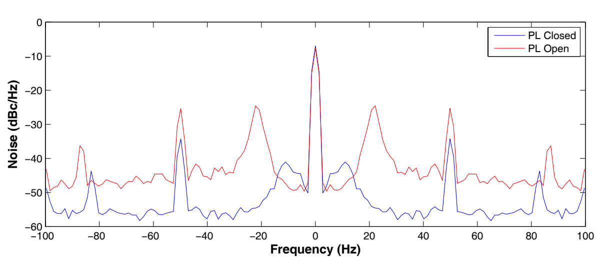

Figure 5: Beam 1 phase error with BPL on/off.

shows the significant change in bunch length growth when the BPL was turned off at the later stage of this measurement. Bunch length data used in this work were provided by the Beam Quality Monitor [3].

Beam Diffusion Studies

Dedicated measurements were conducted to better quantify the relationship between the sampled noise power and the bunch length, and also to better understand the effect

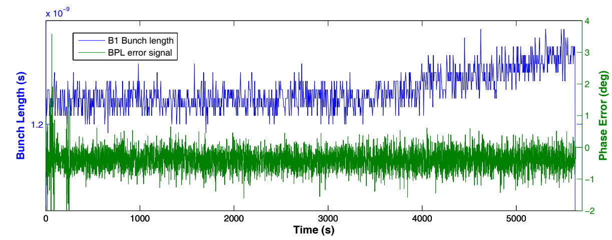

Figure 6: Beam 1 bunch length and BPL error signal ϵ with time. BPL turned off at $t = 4000$ seconds.

of the BPL. During these measurement, the LHC was operating at 3.5 TeV, with non-colliding, single bunch of 9e9 intensity per ring. Figure 7 shows the cavity phase noise

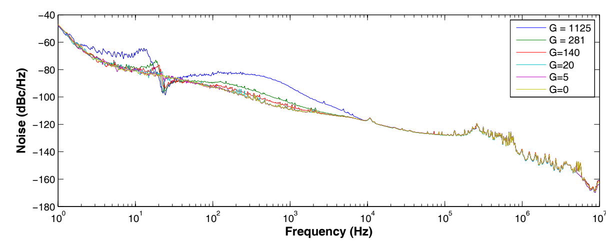

Figure 7: Cavity 6B2 phase noise spectral density with BPL τ^{-1}.

spectral density as a function of the BPL inverse time constant τ^-1. Increasing the BPL τ^{-1} clearly decreases the noise at f_s. It is interesting to note that noise around f_s actually goes up, with no effect on beam dynamics though. Therefore, the rms noise value is not a valuable metric for beam dynamics performance. To show the effect near

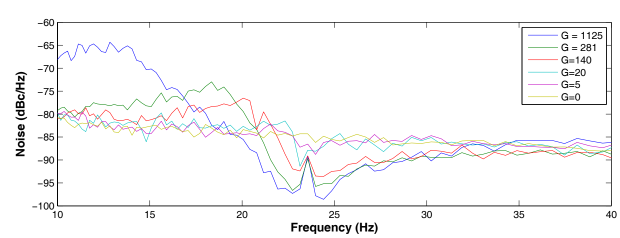

Figure 8: Cavity 6B2 noise spectral density with BPL τ^{-1}.

f_s the image has been enlarged near the synchrotron frequency (Figure 8).

The approximate bunch length growth rate $d\sigma_z/dt$ for each τ^{-1} setting is reported in Table 1 for Beam 1 and Table 2 for Beam 2. An estimate of the total power sampled by the beam is also shown. Unfortunately, since this power is dominated by the power spectral density around f_s, the accuracy of this estimate is limited by the instrument resolution, as seen in Figure 8. Still though, one can see the clear correlation between noise power and longitu-

Table 1: Bunch Growth Rate Dependence on BPL τ^{-1} and Noise Power for B1

BPL τ^{-1}	**Sampled Noise (μrad)**	$d\sigma_z/dt$ (ps/hr)
1125	-	19
562.5	12.3	19
70	13.7	19
10	30.6	71
2	40.5	315
0	53.7	426

dinal emittance growth. It is also obvious that the bunch

Table 2: Bunch Growth Rate Dependence on BPL τ^{-1} and Noise Power for B2

BPL τ^{-1}	**Sampled Noise (μrad)**	$d\sigma_z/dt$ (ps/hr)
1125	15.8	14
281	17.6	14
140	24.3	14
20	27.3	14.5
5	43.8	189
0	61	301

length growth is strongly related to the τ^{-1} of the BPL. Furthermore, it seems that for a BPL τ^{-1} of more than approximately 30, there is no significant improvement in beam diffusion. More careful studies will be necessary to exactly quantify this level. Finally, the bunch length growth for Beam 1 seems to be higher than that for Beam 2 for the same levels. This discrepancy is probably due to the limited accuracy of the noise estimation as shown in Figure 8 or of the bunch length growth estimation shown in Figure 9.

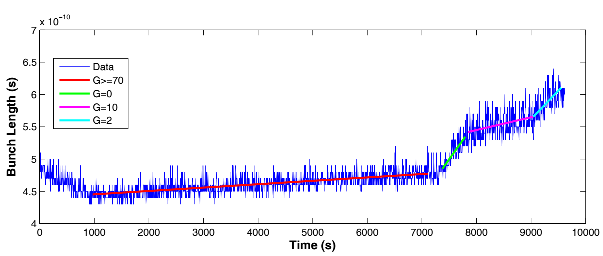

Figure 9: Beam 1 bunch length growth with different BPL gains.

SIMULATION VALIDATION

The cavity phase power spectral density was measured to establish its expected dependence on the controller gain and to validate the time-domain simulation. As shown in Figure 10, the simulation agrees very well with the measurement. Since the RF reference noise contribution is not modeled in the simulation, there is a discrepancy at very low frequencies when the reference is the dominating noise source. The bump at 250 kHz is being investigated.

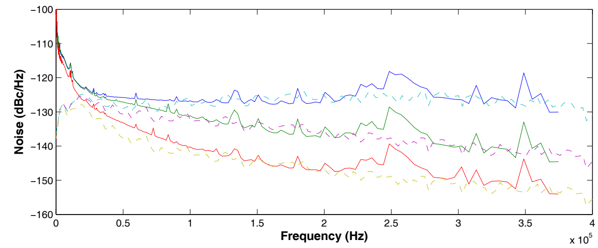

Figure 10: Cavity phase power spectral density with controller attenuator setting from 4B2 (solid lines) and simulation (dashed lines).

It is obvious from this figure that the simulation provides a good representation of the RF cavity for frequencies higher than a few kHz. As such, it can be very useful in predicting the system behavior for various RF configurations, estimating the coupled-bunch instabilities, and determining the contribution of the phase noise to beam diffusion around $f_s + k \cdot f_{rev}$ for $k > 0$.

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 cavity phase noise power spectral density around $f_s + k \cdot f_{rev}$, as predicted in [1]. It was discovered that the noise power is dominated by a single contribution at f_s, which in turn depends strongly on the 400.8 MHz reference. It was also shown that the time-domain simulation presented in [2], provides a close representation of the RF system behavior.

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