LLRF studies at LHC - models, anticipated beam dynamics and emittance effects

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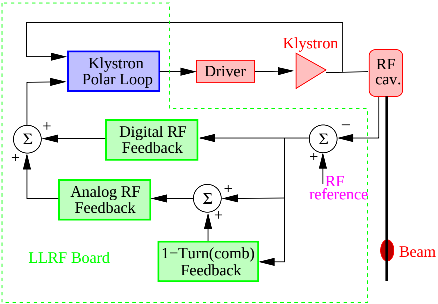
RF Station/Beam Dynamics Interaction



- The longitudinal beam dynamics is mainly defined by the impedance and associated circuitry of RF stations.
- The stable operation requires the control of higher-order mode impedances as well as the precise control of the accelerating fundamental impedance.
- Impedance controlled LLRF architectures modify the impedance seen by the beam with feedback techniques. This system has multiple dynamic loops. Stability of the complete system is necessary condition.

System stability

To achieve stability of the operation point of the complete system, multiple parameters have to be set:

- Cavity voltage and detuning, RF feedback gain and phase, one-turn feedback delay, and more..
- Trade-offs exist between RF station and beam stability margins.
- We want to investigate the effect of RF system configurations and parameters on the longitudinal beam dynamics and related stability margins, for both single bunch (beam diffusion) and collective effects (coupled-bunch instabilities).
- Our models and simulations for the LHC architecture, parameters, and technical implementation [2], were used for these studies.

What are we studying?

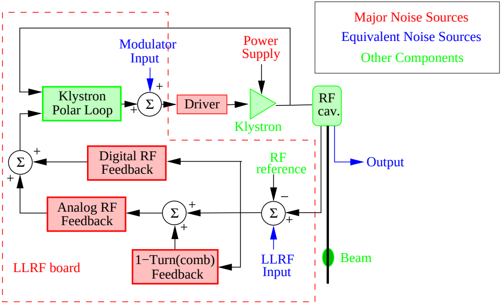
- The noise power spectrum of the RF accelerating voltage strongly affects the longitudinal beam distribution and contributes to beam motion and diffusion.
- The choices of technical and operational configurations in the RF system can have a significant effect on the noise sampled by the beam.
- The beam and RF dynamics are often studied as two independent systems. We want to express their interaction as one dynamic system to fully understand the system performance.
- We want to set the RF noise levels in the LLRF system (thresholds) for each operational scenario of the RF station such that they define a constant bunch length during beam store.

Formalism

- We initially looked into using the Fokker-Planck equation to express the beam diffusion
- This treatment fails to include the effect of beam and RF station dynamics on the noise sampled by the beam, as well as the aliasing effects due to the beam periodicity. It is also limited to sources of white noise
- To address the need to fully understand the RF station-beam interaction we have developed a theoretical formalism relating the equilibrium bunch length with the beam dynamics, the RF system configurations, and the noise sources in the RF station [1]
- It should be noted that with this treatment, the individual noise sources can be shaped or colored noise sources.

Noise Sources

- The major noise sources in the RF system include components in the LLRF boards, the klystron driver amplifier, the klystron power supply, and low frequency sources.
- For the beam diffusion effects, we focus on wideband sources, in particular the LLRF noise and the klystron driver amplifier.



- We refer the noise of the modulator or the LLRF boards in two points to analyze their effect on the cavity accelerating voltage phase noise. The cavity voltage amplitude noise is not significant for beam dynamics.

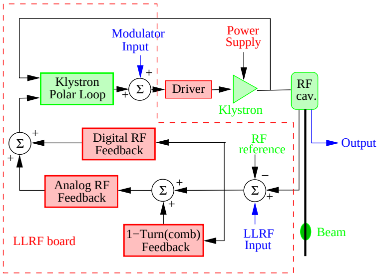
Methodology

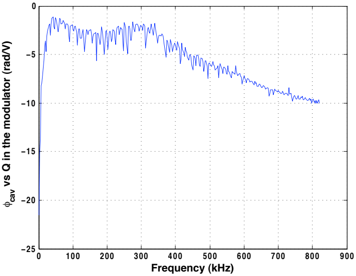
- Analyzing the total contribution of the individual noise sources distributed in the hardware in the accelerating voltage phase noise, it is possible to define maximum levels or thresholds in the spectral power densities for those sources, such as the bunch length is constant during storage (steady state situation).
  - Each individual source will contribute differently to the total phase noise. It is defined by the transfer function between the noise source and the cavity.
  - The transfer function is dependent of the configuration or operation condition of the RF station and feedback loops.
  - This analysis can be conducted using the models and simulation developed for the LHC RF station.
- Using the above information, we can also estimate the anticipated growth rate of the bunch length.

Noise Rejection Estimation

To achieve this:

- We set our simulation to the configurations of interest and measure the transfer function between the noise source (I/Q channel) and the phase of the cavity voltage





Initial Results

- We compare our estimated thresholds for various RF configurations, during ramp or physics, and for different beam currents
  - A few examples are shown on the next slide
- We see some sensitivity to channel, noise source, LLRF configuration, as expected.
- Very low thresholds for ramp, which is not a reason for concern though, since the beam is kept in this condition for a very short time
- Our initial thresholds for the collision energies are slightly lower than the estimated noise levels, so a slow beam growth is anticipated. We are working on estimating the expected bunch length growth rate.
- These results are for a 7 TeV beam, we are working on our 3.5 TeV estimates.

Initial Results (Physics)

Configuration	$V_{Modulator}$		V_{LLRF}	
	i	q	i	q
Physics 0.5 A	1.0553	0.2709	0.0301	0.0180
Physics 0.3 A	2.1131	0.2095	0.1166	0.0177
Non-optimal Physics 0.3 A	2.4136	0.1839	0.0301	0.0180

Table: Modulator and LLRF noise threshold in $\mu\mathrm{V}/\sqrt{\mathrm{Hz}}$ for physics configurations.

Validation

Before we move forward with more analytic studies, we want to validate:

- the estimation of the noise sources, by measuring the actual RF system
- the correlation between the phase noise of the accelerating cavity voltage and the LLRF noise sources
- our formalism, by correlating the bunch length behavior during a store with the accelerating voltage phase noise

Measuring the Noise Sources

- A prototype test system in Prevessin was measured to determine the LLRF noise, both remotely from SLAC, and at CERN by John Molendijk.
  - The tests show good agreement with our estimated noise levels from the schematics/layout. The measurements will be repeated next week using a RF system similar to the one in the tunnel (CERN SM18).
- Using the noise measurements in the LLRF and the phase noise measurement of the accelerating cavity voltage, it will be possible to validate the noise model for the RF station

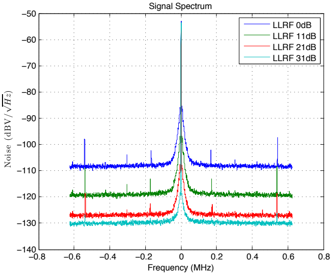


Figure: Power spectral density at the output of the LLRF.

Bunch length RF noise correlation measurements

- Additional measurements are planned for the beginning of May
- The bunch length will be tracked during a store
- Measurements of the RF cavity phase noise will be conducted in the same time period
- The results will be compared with our anticipated bunch length growth.

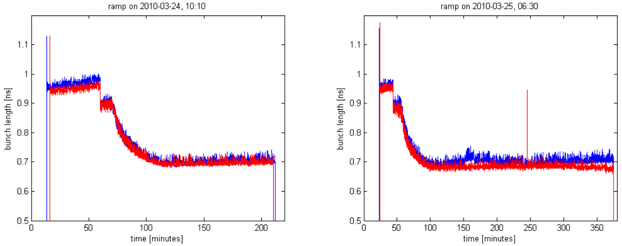


Figure: Bunch length growth (image from Giulia Papotti at CERN).

Goals

- Various studies have been conducted to evaluate the longitudinal coupled-bunch instabilities at the LHC [3], [4].
- These studies though do not include the cavity fundamental impedance or do not consider the effect of the LLRF impedance reduction feedback system.
- Using the time-domain simulation and related models it is possible to estimate the effective impedance presented to the beam by the RF station for any configuration.
- The coupled-bunch instabilities can then be computed to study the bunch centroid stability, position, and motion due to multi-bunch coupling as a function of the RF configurations.
- As a starting point, the LLRF was set to the values suggested from the RF tools and "half-detuning" algorithm, including changes in the 1-turn feedback. Studies of sensitivity to individual parameters were conducted.

Modal Growth Rates-Tune Shifts

- Using the estimated impedance and assuming a gaussian bunch, the growth rate σ_l and tune shift $\Delta\omega_l$ can be computed for each coupled-bunch mode l

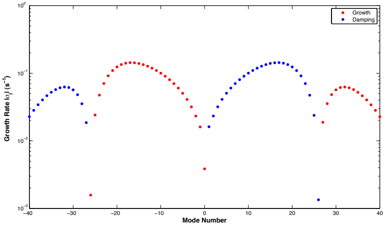


Figure: Modal Growth Rates for configuration Ramp 0.3 A – One-turn Feedback is off.

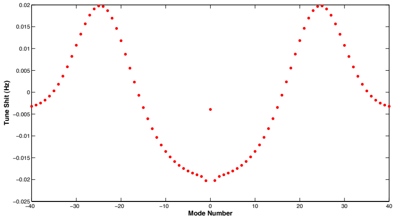


Figure: Tune shift for configuration Ramp 0.3 A – One-turn Feedback is off.

Stability Criterion

- Growth rates in the order of seconds (slow compared to revolution period)
- But, the synchrotron radiation damping time is in the order of hours
- No bunch-by-bunch feedback, so stability determined by Landau damping
- Stability criterion [5], [6], [7]

$$\sigma_l < \frac{\Delta\omega_s}{4}$$

where $\Delta\omega_s$ is the synchrotron frequency spread within the bunch.

Results

- The fastest growth rate is at least a factor of twenty smaller than the stability criterion threshold for all configurations
- Changes of the LLRF configuration have significant effects on the modal growth rates though (optimal tuning is very important)
- Growth rates are inversely proportional to beam energy and almost proportional to beam current
- Therefore, operation with higher currents at the 3.5 TeV beam energy leads to reduced operational margins. Optimal setting of the RF station is even more important in this case.

Future/Conclusions

Beam Diffusion Studies

- With our simulation, models, and now theoretical tools (formalism), we are in a great position to estimate the effect of RF configurations, alternative designs, or next generation systems on the LHC longitudinal dynamics.
- Validation measurements in the next month are very important for the accuracy of our future estimates/studies
- Results can be helpful for noise allocation and specification of technical components in future designs

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