LHC RF Station Configuration Tools and Beam Dynamics-RF Station Interaction Modeling

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Introduction

Overview

LHC Longitudinal Beam Dynamics-RF Station Interaction:

- Longitudinal beam dynamics
  - Bunch centroid stability, position and motion
  - Bunch shape and diffusion
- RF stations
  - Optimal station configuration
  - Robustness to perturbations and imperfections

Background - LLRF Architectures

- 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 BOTH the LLRF loops and stability of the beam are necessary conditions.
- The beam current magnitude, the operative conditions of the RF station, interference and noise can induce longitudinal beam instabilities.
- Configuration of the system is critical to achieve optimal performance.

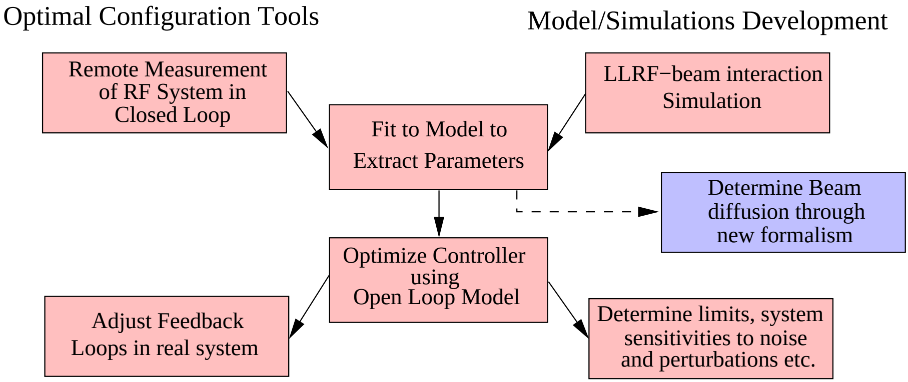
What does our group bring to the LHC?

- The PEP-II and LHC LLRF systems have been presented in [1], [2], among other places.
- The similarities of the systems makes the transfer of knowledge and expertise from PEP-II to LHC straightforward.
- For PEP-II we used LLRF-Beam models to understand limits of accelerator performance, improve reliability, identify technical problems, and develop new control techniques. Tools for the online identification of the RF station model and model based optimal configuration of the controller were developed.
- Tools and models adjustable for the LHC due to the proximity of the architectures.

After the accident in the LHC start-up, these tools have become a priority for the LHC RF group, since new stricter CERN policies prevent tunnel access when the magnets are energized.

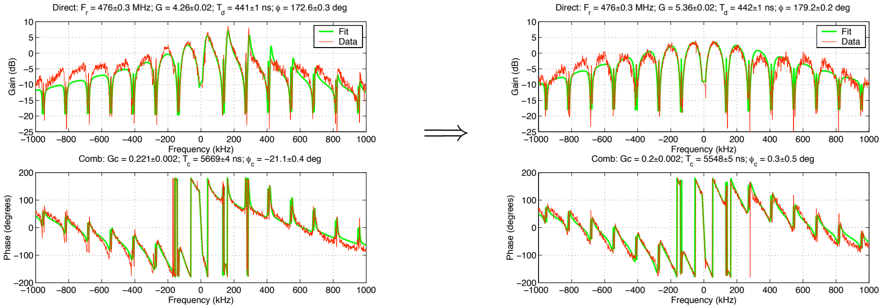
LHC LLRF Effort

Work to date fits into two **related** activities:



- Items in red similar in scope with PEP-II (experience, code, tools updated for LHC). Item in blue unique for LHC.
- Simulation much more detailed than linear model. Includes non-linearities, details omitted in linear model.

PEP-II example



Trips 2008-09

- D Van Winkle (March 2008)
  - Initial Investigations
  - Set up and running with test station at Prevessin
- C Rivetta, D Van Winkle (June 2008)
  - Testing with test station at Prevessin
- D Van Winkle (August 2008)
  - More testing and development at Prevessin
  - First testing with cold cavities in tunnel
  - Fixed LLRF crate synchronization issues to measure system transfer functions.
- C Rivetta, T Mastorides (Nov 2008)
  - Implementation of new “parameter” structure
  - Testing with “fake” cavity at SM18
- D Van Winkle (March 2009)
  - Testing with “fake” cavity at Prevessin
  - Testing with cold cavity SM18

Algorithms

The goal is to have a set of algorithms that will not only align the LLRF remotely during commissioning, but will also provide means for monitoring the system during operations.

In collaboration with the CERN RF group, the following algorithms had been chosen for development. They have now been tested in SM18:

- Nulling Routine
- Align Digital and Analog Phase
- Measure Open Loop and parameterize Open Loop RF station model -> design the controller
- Measure Closed Loop and parameterize Open Loop RF station model -> optimize the controller

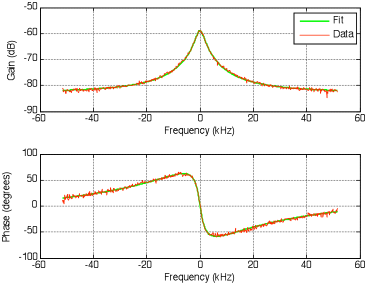
Nulling Routine

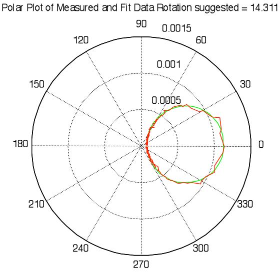
To be able to measure signals in open loop which may contain very high gains, we had to ensure that the overall system was well nulled. Any slight offset could result in an I or Q signal being "railed"

- Null the RF Feedback module offsets
- Null the RF modulator output signal
- Null the carrier in the setpoint module

Digital/Analog Phase Alignment

- The LHC LLRF contains a Digital and an Analog path for feedback.
- It is essential that the digital and analog paths are in phase.
- This algorithm determines the phase between the two paths and adjusts accordingly to achieve zero phase between them.

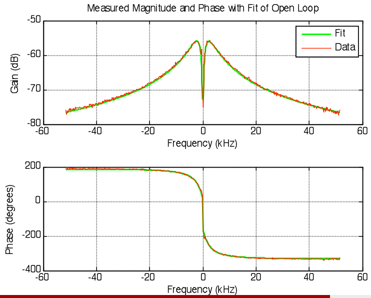


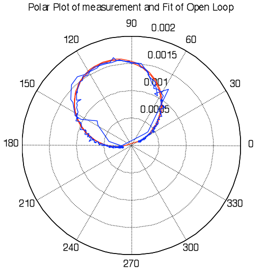


Set Open Loop

- During the tests in SM18 with a real cavity and klystron, it was obvious that we could not get reasonable data with the digital feedback on (value of tests on a real setup).
- Algorithm sets loop phase and gain to satisfy set gain and phase margins.

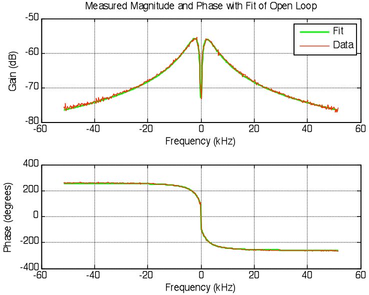
Initial Data

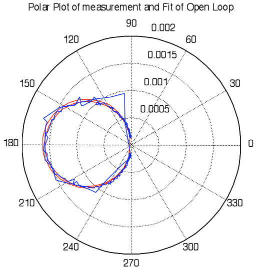




Set Open Loop

Adjusted Open Loop Data

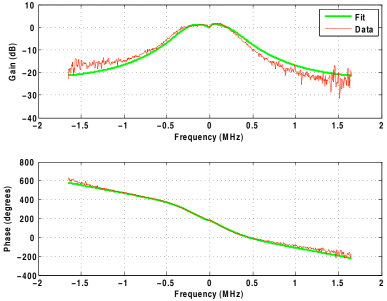




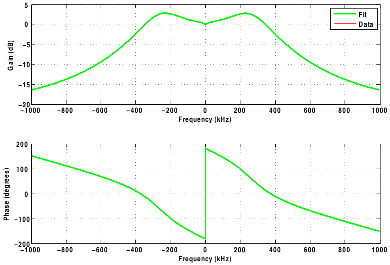
Optimize Closed Loop

The most important algorithm!

Estimates gain and phase adjustments to achieve set gain and phase margins.



Data From SM18 - last week. Asymmetry in the data has not been understood yet.



Modeled response after the suggested “corrections” from the optimization tools.

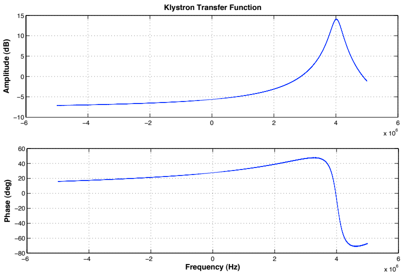
RF Station/Beam Dynamics Interaction Model

- Based on our PEP-II experience on RF-beam interaction, we want to use our models to verify the theoretical predictions of longitudinal motion due to coupled-bunch instabilities for the LHC.
- An additional concern is the significantly lower synchrotron radiation of the protons and the use of klystrons as final amplifiers in the RF stations, which increases the sensitivity of beam emittance and diffusion on RF station perturbations and noise.
- We want to develop a formalism that will allow us to use our models and simulation to study the dependence of the accelerating voltage noise spectrum on the various RF parameters and the technical limitations (such as non-linearities, thermal noise, frequency response etc.) of the LLRF system components.
- Once this is achieved, we can study optimal configurations and algorithms.

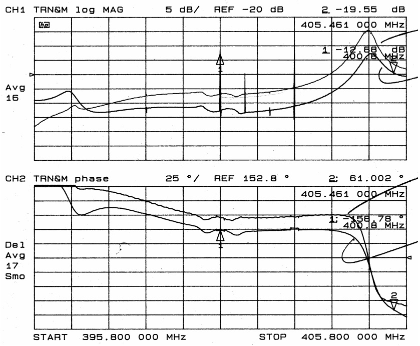
What has been achieved

- Adapted Simulation for LHC parameters and architecture
- Verified simulation with all commissioned components

Klystron Transfer Functions



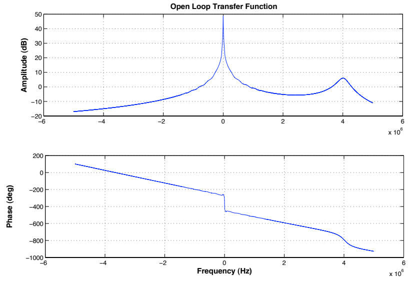
SLAC Simulated Klystron Transfer Function



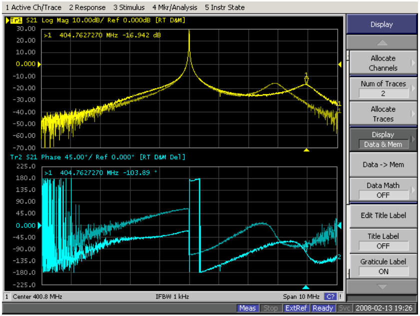
LHC Measured Klystron Transfer Function

Initial Results from Simulation

Open Loop RF Station Transfer Functions



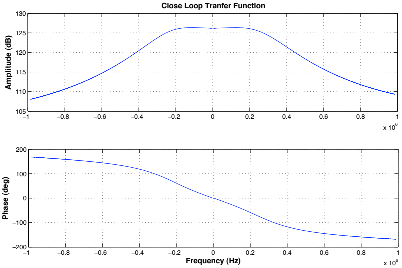
SLAC Simulated Open Loop RF station Transfer Function



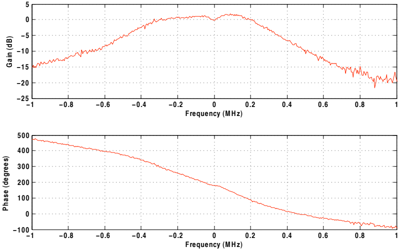
LHC Measured Open Loop RF station Transfer Function (two different RF stations)

Initial Results from Simulation

Closed Loop RF station Transfer Functions



SLAC Simulated RF station Closed Loop Transfer Function



LHC Measured RF station Closed Loop Transfer Function

Effect of RF noise on beam emittance

- J. Tuckmantel at CERN has estimated the maximum allowed phase noise from the RF system to 0.17° rms or 1.15 ps [3].
  - The phase noise for the RF system in the absence of beam has been measured to 24 fs, **for a particular setting of the LLRF feedback loops**.
- The f_s crosses 50 Hz during the ramp. J. Tuckmantel has also simulated this effect [4], predicted non-negligible effects, and recommended an alternative ramping scheme with much smaller effects on the beam shape.

Effect of RF noise on beam emittance

- We would like to confirm J. Tuckmantel's findings with our simulation, which allows us to include the effect of:
  - Coupling between the bunches due to the RF system impedance $Z(\omega)$
  - Changes of the noise floor level due to different gains in the LLRF feedback loops (analog, digital, and polar loops)
  - Voltage non-linearity – since σ_z is comparable to $\lambda_{RF}/4$
- To achieve that we are working on:

In Development

Current Work

- Develop a formalism to estimate the effect of RF noise on longitudinal emittance including beam-RF interaction and beam coupling
- This step is essential, because it is connecting our developed work and experience with a useful metric for the LHC.
- We are hoping to complete this by mid-2009

With this formalism and the existing simulation and models we hope to:

- Estimate the total system noise, diffusion coefficients, and $Z(\omega)$ for any LLRF configuration using our simulation
- Determine the beam distribution using the Fokker-Planck equation and apply the perturbation formalism to include the effect of coupling [5].

Further Plans for LHC Models and Simulation

Once we have a formalism that ties RF noise with essential beam characteristics, we want to:

- Analyze the sensitivity of beam emittance and diffusion on various RF parameters.
- Estimate the noise floors and their impact on machine performance
- Study the technical implementation characteristics, technology limits
- Determine optimal control algorithms and configurations

Future Plans

LLRF Commissioning and optimal configuration tools

- Expand configuration tools for CERN use, including full LLRF controller (Direct and 1-Turn Feedback loops)
- Participate in commissioning measurements
- Finish Closed Loop measurement and fitting
- Add Klystron Polar Loop configuration
- Calibrate the measurements with the system (currently there is an unknown attenuation factor)
- Measure with beam

Future Plans

RF Station/Beam Dynamics Interaction Model

- Validation of simulation when all systems operational
- Longitudinal emittance analysis
- In depth beam/model verification
  - Estimation of noise floors and impact on machine performance
  - Study of technical implementation characteristics, technology limits
  - Estimation of system limits
- Use simulation and commissioning experience to test alternative LLRF implementations

- [1] C. Rivetta *et. al.*, “Modeling and Simulation of Longitudinal Dynamics for Low Energy Ring-High Energy Ring at the Positron-Electron Project”, Phys. Rev. ST-AB, 10, 022801 (2007) and SLAC-PUB-12374, February 2007.
- [2] T. Mastorides *et. al.*, “Analysis of Longitudinal Beam Dynamics Behavior and RF System Operative Limits at High Beam Currents in Storage Rings”, Phys. Rev. ST-AB, 11, 062802 (2008) and SLAC-PUB-13287.
- [3] J. Tuckmantel, “Synchrotron Radiation Damping in LHC and Longitudinal Bunch Shape”, LHC Project Report 819, June 2005.
- [4] J. Tuckmantel, “Simulation of LHC Bunches under Influence of 50-Hz multiple Lines on the Cavity Field”, LHC Project Note-404, June 2007.
- [5] A. Chao, “Physics of Collective Beam Instabilities in High Energy Accelerators”, Wiley Series in Beam Physics and Accelerator Technology, 1993.