LLRF Models, Tools and Longitudinal Beam Dynamics Studies:

LHC ⇒ *SPS* ⇒

LARP DOE Review June 2012

C. H. Rivetta [1]

LARP LLRF Contributors:

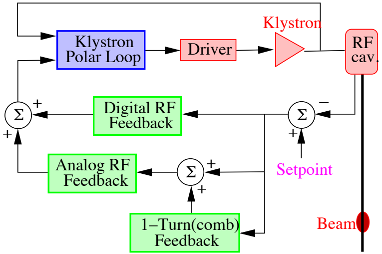
J. D. Fox [1], C. Rivetta[1]
P. Baudrenghien [2], T. Mastorides[2], J. Molendijk[2]

[1]Accelerator Research Department, SLAC
[2]BE-RF Group, CERN

This work is supported by the US-LARP program and DOE contract #DE-AC02-76SF00515

Motivation: LHC LLRF Optimization tools

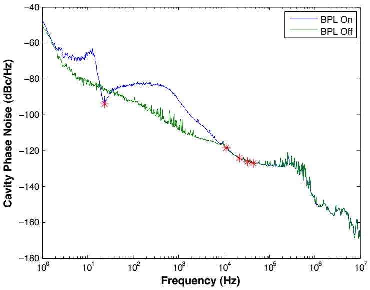
- Investigate the operational limits and impact on beam dynamics from the impedance-controlled RF systems. Look ahead to high current operations, possible upgrades and understand the role of the technical implementation.
  - Based on PEP-II experience, where limits of machine were understood, and overcome, investigate via models and simulation studies new control techniques
- As part of these studies, CERN requested model-based commissioning tools in 2009 - They are part of the beam/LLRF simulation
  - These tools operate remotely and allow identifying the RF station transfer function and designing the feedback loops using model-based techniques.
  - Remote operation was crucial under the new stricter CERN polices preventing tunnel access when the magnets are energized.



- Longitudinal coupled-bunch instabilities - Estimation of stability margins for different RF station configurations.

Motivation: RF Noise Effect on Beam Diffusion Studies

- The noise power spectrum of the RF accelerating voltage can strongly affect the longitudinal beam distribution and contribute to beam motion and diffusion.
    - Increased bunch length decreases luminosity and eventually leads to beam loss due to the finite size of the RF bucket.
- The choices of technical and operational configurations can have a significant effect on the noise sampled by the beam.
- The motivation of this work is
    - To study and validate longitudinal beam diffusion models including the effect of RF station noise and feedback loops
    - To predict how the implementation of the system impacts the longitudinal emittance
    - To identify the sources of noise that are most damaging with the intent to selectively improve the responsible equipment
    - To set a noise threshold for acceptable performance



FY 2010 - 2012 Results

LLRF Optimization tools

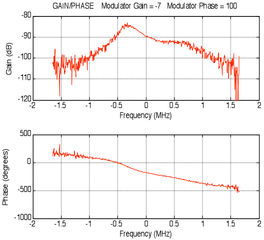
- The LLRF configuration tools have been used by the CERN BE-RF group to remotely commission the LLRF feedback loops of the RF stations during start up in November 09 up to February 12.
  - Tools reduced commissioning from 1.5 days/station to 1.5 hours/station.
  - Model based configuration adds consistency and reliability.
  - 1- turn delay feedback set-up was tested
  - CERN BE-RF group have repeatedly expressed their support and enthusiasm for this collaboration.

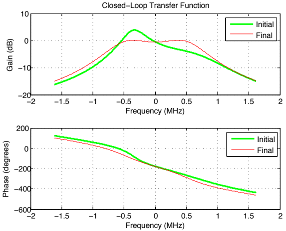
RF Noise Effect on Beam Diffusion Studies

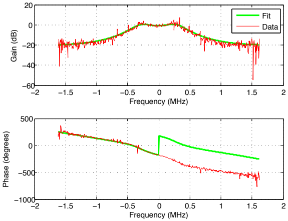
- To better understand the RF-beam interaction we developed a theoretical formalism relating the equilibrium bunch length with beam dynamics, accelerating voltage noise, and RF system configurations
- Conducted measurements at LHC (May 2010 - Nov 2010) which confirmed our theoretical formalism and models

Technical examples: LHC LLRF Optimization Tools

- Tool measures the transfer function of the RF station - Estimates a mathematical model.
- Based on the model, the tool calculates the parameters of the LLRF controller for optimum stability margins
  - This method enables robust and consistent configuration over all 16 stations and many loops (digital/analog feedback, notch filter for klystron parasitic resonance compensation, klystron polar loop)
  - As such, a group of 4-5 CERN engineers work in parallel and commission all stations in a few hours from the "RF group control room"







Technical examples: LHC LLRF Optimization Tools

- The 1-turn delay feedback filter introduced a challenge that is the identification of narrow bandwidth filters over a $\pm 300 kHz$ band.
- New firmware was included in the LLRF to identify the 1-turn delay feedback filter.
- It allows to inject noise and measure the transfer function in a frequency span around particular revolution harmonics.

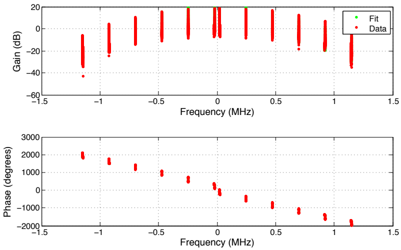


Figure: 1-turn filter characteristic measured around particular revolution harmonics.

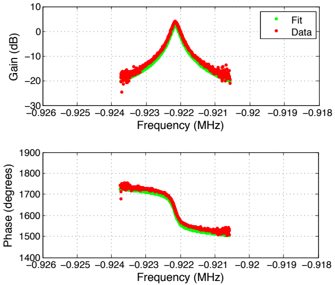


Figure: Detail of 1-turn filter characteristics

LHC LLRF Optimization Tools

Steps toward LHC higher beam beam intensity (after LS1 - priority on SPS right now):

- 1-turn feedback phase equalizer set-up (could be necessary for high-current beam stability, operational margins and configuration flexibility at upgraded currents)
- Control the smooth increase of the High Voltage and Klystron current with beam, from 450 GeV conditions to ramping/physics.
  - Ramping with 25 ns bunch spacing calls for more than the 200 kW that are available from the 50kV/8A (transients compensation)
  - We ramp the DC settings to 56 kV/9A before start ramp, with circulating beam
- RF station configuration with beam. Adjustment without beam ignores detuning and possible drifts → imperfect impedance reduction in physics.
  - So far we set-up the loops without beam. Could be possible to fine-adjust it, with beam, using a noise spectrum with notches on the synchrotron frequency sidebands

Evidence of the limiting factor for the beam current in the LHC Complex is defined by the SPS injector. CERN BE-RF request to LARP, SPS priority during shut-down LS1

- Plans to optimize the operation and LLRF settings in the LHC-RF system are "second priority" and give SPS up grades "first priority".

Toward the operation of the LHC Complex at high current

SPS Upgrade

- Evolve RF Systems-Longitudinal dynamics collaboration with CERN BE-RF group to focus on the critical path to increased LHC complex beam currents, operational flexibility and increased luminosity.
- Why shift of focus to the injectors?
  - LHC complex has reached the maximum number of bunches with 50 ns spacing in the LHC
  - Many challenges for 25 ns operation, mostly on the injector side. The SPS output is 1.5e11 protons/bunch at 50 ns spacing and only 1.2e11 protons/bunch at 25 ns spacing (+higher losses)
- CERN BE-RF group wants to use the skills and expertise developed during this project to:
  - Develop models of the SPS LLRF-beam interaction, which will help with the choices during the SPS LLRF upgrade design process at CERN
  - Automated tools for cavity setting up (non-trivial choices: 200 and 800 MHz cavities etc. Added complexity with respect to LHC effort)

SPS RF System Description

SPS : Double RF System - 200MHz - 800MHz

200MHz system

- Presently 44 and 55 cell cavities (2 each). The future configuration will consist of four 33-cell and two 44-cell cavities

800MHz system

- 2 Traveling wave cavities installed, with 3 sections/cavity, 13 cells/section. Only one cavity used though (2^{nd} cavity idle) pending new power amplifiers (IOTs)
- Required for beam stability above bunch intensity of (2-3)$x10^{10}$ *protons*/*bunch*
- Its phase is locked to the 200 MHz voltage, but the relative phase is programmed during the cycle. Absolute phase is calibrated at the start of each run from beam measurements

Courtesy E. Shaposhnikova [1]

RF-LLRF Upgrade Motivation

200MHz system

- More 200 MHz voltage and therefore 800 MHz will be required for higher intensity beam transfer to the LHC. Low γ_t optics needs even more 200 MHz and 800 MHz RF voltage
- Accurate phase control at 1 deg level also needed (@200 MHz)

800MHz system

- Given the 350 ns cavity filling time and the 8 μs long SPS batch, transient beam loading effects are very obvious in the first 15 bunches. The present LLRF controls the voltage in the centre of the batch only
- It is very difficult to control the 800 MHz voltage phase and amplitude which are essential for beam stability
- Total voltage of 1.5 MV (750 kV/cavity) should be provided in future for high intensity beams
- The 800 MHz could be used for other high intensity beams (CNGS). It could also be used for emittance blow-up
- As part of the SPS effort, the power plant of the 800 MHz are being upgraded, with new IOTs [2]

SPS LLRF Upgrade: Details

- New cavity controller designed for 800 MHz cavities
  - The present system is an all analog design.
  - The new system will include 1-T feedback, feedforward, longitudinal damper (dipole and quadrupole - if needed), longitudinal blow-up and built-in observation
  - The design is much inspired by the LHC 400 MHz LLRF. It profits from synergy with the ongoing 352.2 MHz LLRF design for Linac4
- With the approved SPS 200 MHz upgrade, the full Cavity Controller must be redesigned, including longitudinal damper and feedback coupled on cavities of different length. It will have the same capabilities as the new 800 MHz system
- A detailed model (including beam dynamics, cavity response, transmitter nonlinearities, etc) to predict the influence of technical specifications on beam stability is necessary before the design
  - This is very similar to what was done at SLAC for the LHC LLRF
- More information available from presentations at the 2012 LIU meeting (E. Shaposhnikova [1], E. Montesinos [2], P. Baudrenghien [3])

SPS LLRF Upgrade: Modeling

Three questions are essential

- How much is the beam affected by the LLRF technical choices? Imperfections result in poor transient beam loading compensation, longitudinal stability issues and RF noise driven emittance blow-up
- What is the effect of the High Level imperfections? The non-linearity and frequency response of the power chain must be considered from the start
- What is the importance of imperfections in the LLRF on the overall performances? Typical imperfections are misalignments (slightly RF feedback phase offset for example) or noise figure of the various components
- An answer can only come from a detailed model of the RF chain.

SPS LLRF Upgrade

Example from LHC studies

- The corresponding work for the LHC resulted in identifying the few key elements in the LLRF that were critical to limit RF noise, and the sensitivity of beam stability to misalignment in the LLRF parameters [4]
- For example, it was found that a 5 degrees offset in the RF feedback phase severely distorts the flat response of the closed loop feedback, resulting in a four-fold increase in growth rate of the most unstable coupled-bunch mode driven by the LHC cavity impedance at the fundamental [5]

Differences with LHC effort:

- The modeling effort differs from the LHC in the complexity of the double RF system (200+800 MHz RF) and the beam dynamics issues of interest
  - Collider vs ramping machine: smaller importance of RF noise transient
  - Beam loading: In the LHC the cavities have Å 1μs filling time for a 3.2 μs gap in physics while in the SPS we have 350 ns -700 ns filling time for $a > 10\mu s$ gap
  - The SPS is a relatively fast ramping machine -> changing conditions
  - Multi-cell travelling wave cavities vs. single cell standing wave cavities
  - High QL (60k) superconducting cavities vs. low Q (350 ns filling time) normal conducting TWCs

SPS RF system up-grade: Goal of the Collaboration

Goals

- Develop models of the SPS LLRF-beam interaction, which will help with the choices during the SPS LLRF upgrade design process at CERN
  - This process allowed in the past to consider the interaction of LLRF-RF system and beam dynamics as a unique system.
  - Link LLRF variables to beam dynamics metrics and quantify their impact
  - Impact of imperfections and non-linearities in the system stability and performance. Robustness.
  - Guide choices in the LLRF implementation compatible with the overall specifications and performance of the RF system-beam quality.
- Automated configuration tools for RF system setting-up
  - Remote tool to consistently set the LLRF parameters based on the measured model of the RF system.
- Beam - Nonlinear RF modeling useful to define technical characteristics for future RF systems
  - Base to study the crab cavity LLRF and beam interaction in the future years.

LARP LLRF system project - Plan

Plan

- Evolve focus of LARP-CERN collaboration effort right now - 800MHz system installed end 2012 - Large part of the 200MHz installed and commissioned during 2013-2014 shutdown. 2 additional cavities in 2017.
- Address the studies via simulation, participate in the design of the LLRF and participate in the commissioning of the system. Actively involved in the design and commissioning of the configuration tools.
- SPS development is best addressed via a ramp-up of effort for FY 2013-2014. Excellent project for Ph.D. thesis and Fellows with accelerator measurement component.
- Option 1
  - SLAC FT - 50-75 %
  - Toohig Fellow (Part-time 25 %)
  - 1 Stanford Univ. Graduate Student
- Option 2
  - SLAC FT - 30-50 %
  - Toohig Fellow (Part-time 25-50 %)
  - Post-Doctoral (60-75 %)
  - 1 Stanford Univ. Graduate Student

Conclusions

Conclusions - Future Impact

- We have commissioned the LLRF Optimization tools and conducted beam based studies at LHC to be prepared for operation at high beam currents.
- LHC Complex have reached a limit. More dedicated research and upgrades are necessary in the injectors in order to increase the beam current operation and limits in LHC toward an improvements in Luminosity
- A re-direction of our collaboration with CERN BE-RF group in the area of RF systems-longitudinal beam dynamics developed via the ongoing LARP project seems to be a natural path
- CERN BE-RF group wants to use the skills and expertise developed in current LARP project to:
  - Develop models of the SPS LLRF-beam interaction, which will help with the choices during the SPS LLRF upgrade design process at CERN
  - Automated tools for cavity setting up (non-trivial choices: 200 and 800 MHz cavities etc. Added complexity with respect to LHC effort)
- Many of this new ideas might be implemented as firmware updates to the next-generation LLRF functions in design at CERN and set the base to study RF station - Beam interaction in future systems as crab-cavity project.

Thanks to the audience for your attention!!!, ...Questions?

References

- [1] E. Shaposhnikova, "Introduction and motivation for upgrade of 800 MHz", LIU Meeting, CERN, April 4th 2012. *Link*
- [2] E. Montesinos, "Power aspects: technical, timeline and resources", LIU Meeting, CERN, April 4th 2012. *Link*
- [3] P. Baudrenghien, G. Hagmann, "LLRF for the SPS 800 MHz cavities", LIU Meeting, CERN, April 4th 2012. *Link*
- [4] T. Mastoridis *et. al.*, "RF system models for the CERN Large Hadron Collider with Application to Longitudinal Dynamics", Phys. Rev. ST-AB, 13, 102801 (2010).
- [5] P. Baudrenghien *et. al.*, "The LHC RF System. Is it working well enough?" Chamonix, February 2011.