LHC-SPS LLRF Upgrade

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History of/Plans for the LARP involvement

- With LARP support and in collaboration with the CERN BE-RF group, SLAC personnel have successfully developed a suite of tools to remotely commission and optimally configure the LHC RF stations (project started in 2008)
  - These tools included detailed models of the LHC RF/LLRF and the beam
  - The tools have been used for commissioning in Nov ’09, Feb ’10, Feb ’11, Feb ’12
  - Both groups (SLAC, CERN) are interested in expanding the capabilities and functions
- Why shift of focus to the injectors?
  - We have 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 $\approx$ 1.5e11 protons/bunch at 50 ns spacing and only 1.2e11 protons/bunch at 25 ns spacing (+higher losses)
  - W. Hofle presented more details on the LIU project yesterday
- We want 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)

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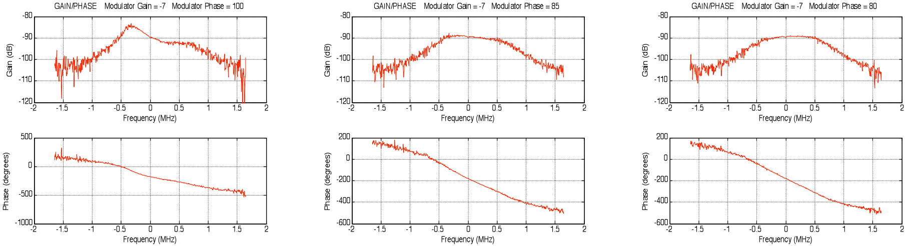
LHC LLRF Commissioning Tools

- The goal was to **remotely** identify the system transfer function, determine the optimal LLRF settings, and implement them
- LLRF is inaccessible with either circulating beam or magnets powered above injection energy
- Remote access is essential and also allows for quick diagnostic tests when needed

LHC LLRF Commissioning Tools

- To achieve the remote configuration:
  - We measure the response of part (or all) of the RF station, to an input burst of noise
  - With the input and output signals we can estimate the transfer function
  - A parameterized linear model is then fit to the transfer function
  - Based on those models, we can adjust LLRF parameters to achieve set gains or phase margins in the feedback loops
  - We then set those parameters in the RF station and re-measure



LHC LLRF Commissioning Tools

- This method enables robust and consistent configuration over all 16 stations and many loops (digital/analog feedback, notch filter for klystron bump 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"

Steps towards (even) higher beam intensity (after LS1 - priority on SPS right now):

- 1-turn feedback phase equalizer setup (could be helpful for currents beyond nominal)
- 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 $\rightarrow$ 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

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SPS RF System Description

200 MHz system

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

800 MHz 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 $(2\text{-}3)\text{x}10^{10}$
- 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

200 MHz 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)

800 MHz 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]

Courtesy E. Shaposhnikova [1]

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

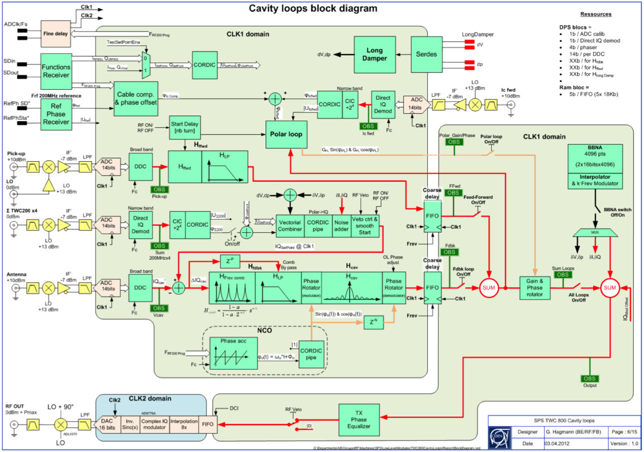
- The corresponding work for the LHC resulted in identifying the few key elements in the LLRF that were critical to limit RF noise, and the sensitivity of beam stability to misalignment in the LLRF parameters [4]
- For example, it was found that a 5 degrees offset in the RF feedback phase severely distorts 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 $\approx 1\mu$s 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 μs 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 LLRF Upgrade: Timeline

- Timeline: 1st prototype tests of 800 MHz in late 2012
- Complex system $\rightarrow$ limited functionality prototype



Courtesy G. Hagmann

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Conclusions/Acknowledgements

- We wish to start the development of a detailed model of the SPS 200-800 MHz RF as part of the LARP collaboration on LLRF. Similar to the past LHC work, regular trips to CERN for exchange and test would be required
- It would include a detailed description of the hardware: Non-linearity (mainly High Level part), noise (both low and high level), misalignments, all LLRF loop, transmission bandwidth etc
- Our SLAC colleagues are interested
- This would serve as a testbed when making technical choices in the LLRF design and help identify needed BW, critical components, expected growth rates, etc as was done for the LHC
- Following the successful LHC strategy, CERN personnel focus on hardware design and testing, whereas the LARP team on the modeling effort

- Many thanks to E. Shaposhnikova, W. Hofle for many helpful discussions and G. Hagmann for the information on the SPS 800 MHz LLRF design.

Thank you for your attention

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