LLRF models, SPS RF upgrade plans

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Introduction

Toward the operation of the LHC Complex at high current

- Evidence of limiting the beam current capability in the LHC Complex is defined by SPS injector.
- Many challenges for 25ns operation, most on the injector side. The SPS output is $\simeq$ 1.5e11 protons/bunch at 50ns spacing and only 1.2e11 protons/bunch at 25 ns spacing.
- Future target: 2.2e11 protons/bunch at 25 ns spacing in HiLumi LHC.
- Collaboration with CERN BE-RF group in the area of RF systems-longitudinal beam dynamics under the LARP support was redirected to increase the beam current operation and limits in the LHC Complex toward an improvements in Luminosity.
- 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 (Two RF systems (200MHz-800MHz)

SPS RF System Description

200MHz

- Presently two 4-section (44 cells) and two 5-section (55 cells) traveling wave cavities.
- Controlled using feed-forward and one-turn delay feedback to minimize the RF station impedance.
- Used as longitudinal damper at injection. Noise injection for longitudinal emittance blow-up in the energy ramp
- The future configuration will consist of four 33-cell and two 44-cell cavities.

800MHz

- Two 3-section (39 cells) traveling wave cavities installed. Only one active (2nd cavity idle)
- Required for beam stability above bunch intensity of (2-3)x10^{10} *protons/bunch*. Bunch shortening mode.
- Its phase is locked to the 200MHz voltage, but the phase is programmed during the cycle. Absolute phase is calibrated at the start of each run from beam measurements.
- no compensation of transient beam loading at present

SPS RF/LLRF Upgrade Motivation

- Given the 350 ns cavity filling time and the 8μs 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.
- More 200MHz voltage and therefore 800MHz 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.
- Total voltage of 1.5 MV (750KV/cav) should be provided in the future for high intensity beams.
- Accurate phase control at 1 deg level also needed (@800 MHz).
- Accurate phase control could be used for other high intensity beams (CNGS). It could be used for emittance blow-up.
- As part of the SPS effort, the power plant of the 800 MHz are being upgraded, with new IOT
- the 800 MHz RF system could be used for longitudinal damping and emittance blow-up

SPS RF/LLRF Upgrade Motivation

LLRF Upgrade

- New cavity controller designed for 800MHz cavities
  - It includes 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 400MHz LLRF.
- With the approved SPS 200MHz 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 800MHz system.

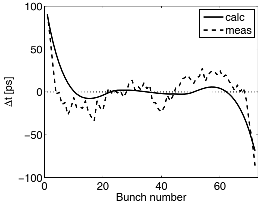
SPS RF system up-grade: Goal of the Collaboration

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, noise, bandwidth 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 Harmonic RF System in LHC.

Double Harmonic RF System at SPS: Previous studies

- Previous years, E. Shaposhnikova, T. Argyropoulous, T. Bohl, J. Tuckmantel, et.al. conducted complete measurement and studies to quantify the impact and performance of the installed Double Harmonic RF system in the SPS.
- Those studies are the base to define the upgrade in the SPS 200-8000MHz RF system.
- They pointed out that the variation of the final emittance along the batch is the result of the modification of the synchrotron frequency distribution due to the effect of beam loading in the double harmonic RF system.



Bunch position variation along the batch ($V_{200} = 4.5$MV, $V_{800} = 0.5$MV). This error modifies bunch length and the synchrotron frequency distribution along the batch.

T.Argyropoulos, et.al. HB2010

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
- Impact of misalignment between 200 and 800 MHz RF systems caused by uncompensated transient beam loading. Imperfection on the capture losses in the LHC.
- An answer can only come from a detailed model of the RF chain.

SPS RF system: Model

Traveling Wave Cavities

- The generator current I_g will create an accelerating voltage $V_{RF} = e^{i\phi_s} L\sqrt{\frac{Z_o R_2}{2}}\frac{sin\tau/2}{\tau/2} I_g = e^{i\phi_s} Z_{RF} I_g$, with $\tau = T_d(\omega - \omega_o)$.
- The beam current I_b traveling along the cavity axis will induce a voltage $V_b = Z_b I_b = -\frac{L^2 R_2}{8}\left(\left(\frac{sin\tau/2}{\tau/2}\right)^2 - 2i\left(\frac{\tau - sin\tau}{\tau^2}\right)\right) I_b$
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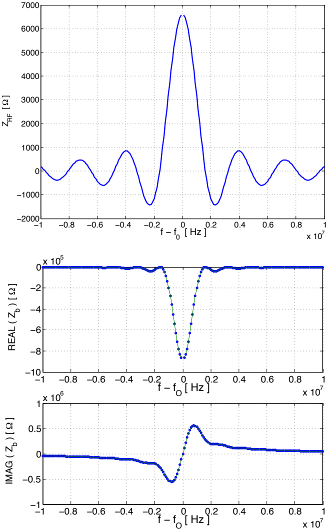
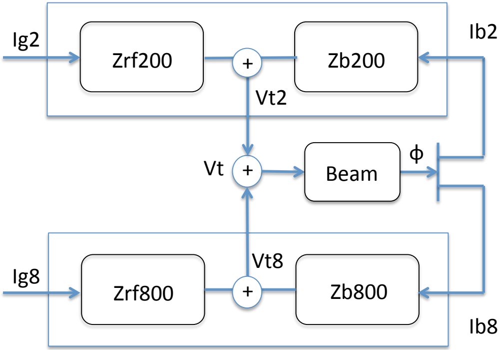
- The forward transfer impedance $Z_{RF} = V_{RF}/I_g$ and the beam transfer impedance $Z_b = V_b/I_b$ are different.



SPS RF System: Model

RF system model

A generic block diagram of the RF system, including a rigid model for the beam dynamics is



The 200MHz and 800MHz cavities are modeled using two different impedances Z_{RF} and Z_b

SPS RF System: Model

Traveling-Wave Cavity Model : In-Q

- To include the effect of non-linearities in the LLRF-RF stage, it is necessary a time domain model of the system
- The cavity dynamics can be modeled using IN-Q formalism
  - It describes the relationship between the modulations of the generator/beam signals and the modulations of the accelerating/beam induced voltage signals
-

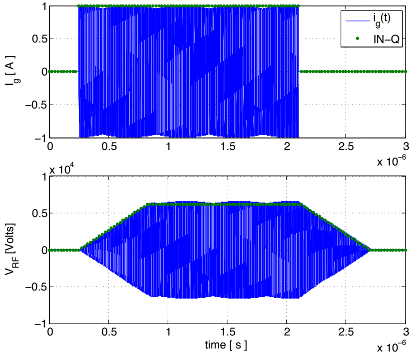
$$\begin{aligned} i_g(t) &= Re\{(I_{gIN}(t) + i.I_{gQ}(t))e^{i\omega_c t}\}; \\ v_{rf}(t) &= Re\{(V_{rfIN}(t) + i.V_{rfQ}(t))e^{i\omega_c t}\} \end{aligned}$$

- In frequency domain $s = i.\omega$

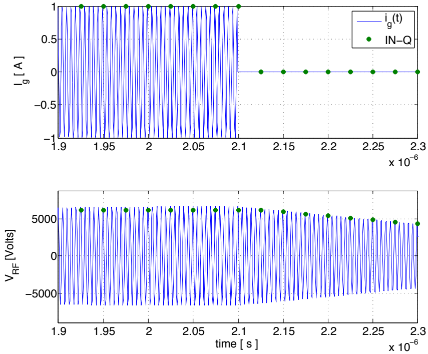
$$\begin{bmatrix} V_{rfIN}(s) \\ V_{rfQ}(s) \end{bmatrix} = \begin{bmatrix} Z_{11}(s) & Z_{12}(s) \\ Z_{21}(s) & Z_{22}(s) \end{bmatrix} \begin{bmatrix} I_{gIN}(s) \\ I_{gQ}(s) \end{bmatrix}$$

SPS RF System: Model

Traveling-Wave Cavity, IN-Q Model : RF Voltage at 200.222 MHz



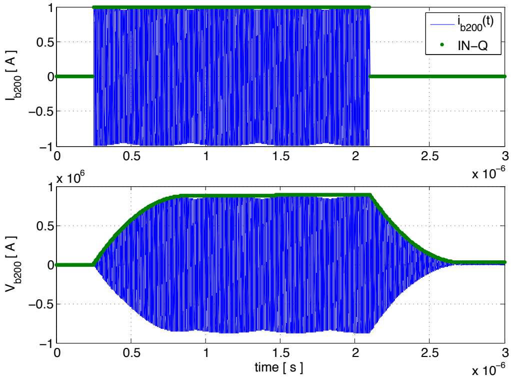
Cavity voltage response to a burst of RF input power. Comparison between IN-Q model and real time domain signal



Details at the end of the RF input power

SPS RF System: Model

Traveling-Wave Cavity, In-Q Model : Beam Induced Voltage



Beam induced voltage in the cavity due to a batch of $1.8\mu s$ duration. Comparison between IN-Q model and time domain signal. $I_{b200}(t)$ is the harmonic component at 200.222 MHz.

SPS LLRF System

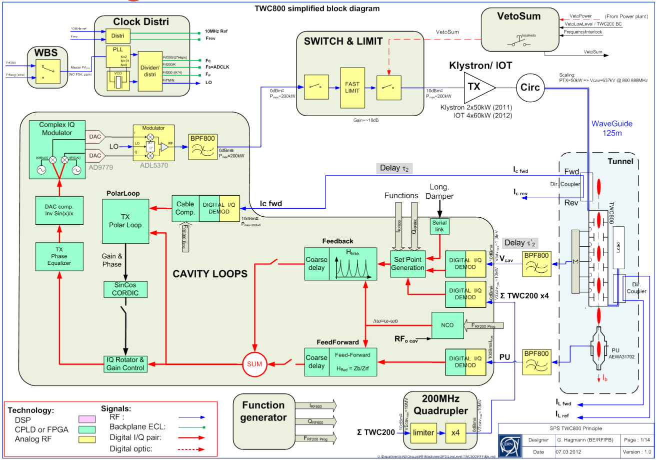
LLRF Basic Functions

Next step in the modeling is to include the LLRF feedback (Feedforward - 1-Turn delay Filter). The LLRF basic features are:

- Strong RF feedback to reduce impedance at the fundamental (transient beam loading and beam stability).
- Given the loop delay in the SPS installation, this can be achieved implementing a One-Turn delay feedback
- A feedforward path to reduce further the beam induced voltage
- Local feedback around the power driver to make the feedback/feedforward channel insensitive to gain /phase variations in the power stage, and locally reduce the noise.
- A channel to modulate amplitude/phase of the cavity voltage as actuator for longitudinal feedback.

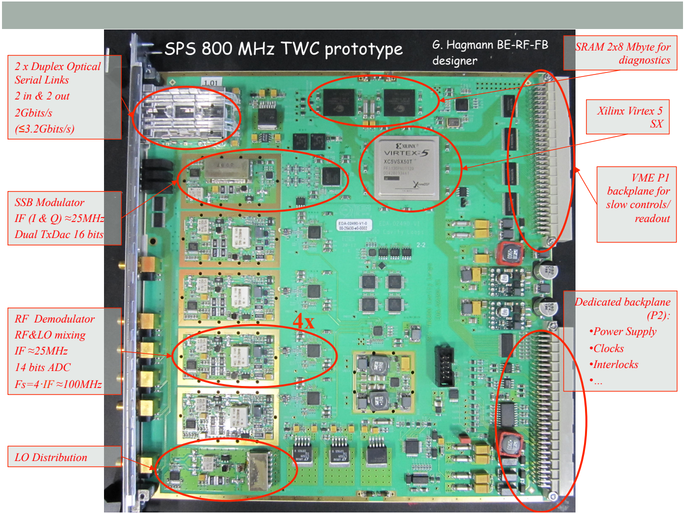
SPS LLRF System

Block diagram



Block diagram of the LLRF and RF power systems

SPS LLRF 800MHz System



LLRF 800 MHz board developed at CERN

Model Validation - Future Studies

- The 800 MHz LLRF will be installed for SPS during - after long shutdown LS1. The 200 MHz LLRF upgrade will be started after LS1, profiting from the 800 MHz LLRF work.
- Based on the studies and measurements conducted by E. Shaposhnikova, T. Angyropoulos, et.al at the SPS, validate the time-domain model of the RF system using a rigid model to represent the beam dynamics.
- Evaluate the beam stability margins predicted by the model and define the limitations / improvement in the longitudinal beam dynamics modeling.
- Evaluate the impact of non-linearities and imperfections in the LLRF-High Level RF system in the beam stability.
- Contribute to the development of LLRF firmware and define tools to set the parameters of the LLRF controller (Similar to the LHC configuration tools)

Future Plans

- We started the modeling with minimum men-power. J. Cesaratto (Toohig Fellow) will join with 25% of his time after the kicker report for SPS wide band feedback is completed.
- Ramp up the collaboration for next FY up to 1FTE
- Option 1
  - Add another Toohig Fellow (Part-time 25-50 %)
  - 1 Stanford Univ. Grad.Student
- Option 2
  - CERN Marie Curie Fellow
  - 1 Stanford Univ. Grad.Student

References

1 E. Shaposhnikova, "Introduction and motivation for upgrade of 800MHz", LIU Meeting, CERN, April 4th 2012.

2 P. Baudrenghien, G. Hagmann, "LLRF for the SPS 800MHz cavities:, LIU Meeting, CERN, April 4th 2012.

3 T. Argyropoulos, et. al. "Controlled Longitudinal Emittance blow-up in a double harmonic RF system at CERN SPS", Proc. of HB2010

4 E. Shaposhnikova, "Longitudinal Instabilities in the SPS and Beam Dynamics issues with high harmonic RF systems", Proc HB2012

- T. Mastorides et. al., "RF system models for the CERN Large Hadron Collider with Application to Longitudinal Dynamics", Phys. Rev. ST-AB, 13, 102801 (2010).

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