SPS 800 MHz RF Models

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1. Introduction
2. Frequency Domain Model
3. Frequency Domain Validation
4. Time Domain Model
5. Conclusions

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

- We have two 3-section (39 cells) traveling wave cavities installed. Only one used in operation (2nd cavity idles)
- Required for beam stability above bunch intensity of (2-3)x$10^{10} protons/bunch$. Bunch shortening mode.
- New LLRF has been developed and is under test. Two MDs conducted in the last month. The modeling and simulation work presented in this talk is complementary to that effort and analyze the impact of the hardware limitations in the system.

Introduction

SPS RF/LLRF Upgrade Motivation

- Given the 350 ns cavity filling time and the $8\mu s$ long SPS batch, transient beam loading effects are very obvious in the first 15 bunches. No attempt to compensate the transient beam loading.
- 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.
- Total voltage of 1.5 MV (750KV/cav) should be provided from the 800 MHz system in the future for high intensity beams.
- Accurate phase control at 1 deg level also needed (@800 MHz).
- New cavity controller designed for 800 MHz cavities
  - It includes 1-T feedback, feedforward, longitudinal damper (dipole and quadrupole - if needed), longitudinal blow-up, built-in observation and the power plant upgraded with new IOT.
  - the 800 MHz RF system could be used for longitudinal damping and emittance blow-up
- 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. This up-date will be done between LS1 and LS2.

SPS RF system upgrade: 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 (LHC, PEP-II) [1], [2], [3].
  - 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 which will probably share fundamental technical characteristics.

SPS LLRF Upgrade: Modeling

Four 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 imperfect controlled longitudinal emittance blowup, as the synchrotron frequency varies along the bath.
- 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
- What is the impact of the misalignment between the 200 and 800 MHz RF systems caused by uncompensated transient beam loading? → Imperfection on the capture losses in the LHC and effects on the longitudinal blow-up.

SPS LLRF Upgrade: Modeling

Initial goals

- The answer to all those questions starts with the development of a model of the system.
- Models can be analyzed in time domain (mostly beam stability and beam loading compensation) or frequency domain (mostly RF loop stability).
- It can increase the system designers' understanding of the impact of imperfections and noise in the stability and performance of the RF station and beam.
- Determine optimal operating settings for the LLRF.

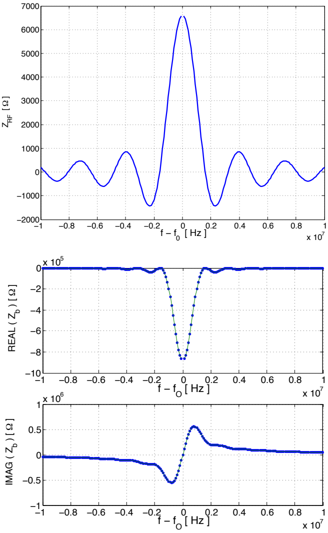
SPS RF system: Model

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 $V_b = Z_b I_b = -\frac{L^2 R_2}{8}\left(\left(\frac{sin\tau/2}{\tau/2}\right)^2 - 2i\left(\frac{\tau - sin\tau}{\tau^2}\right)\right) I_b$

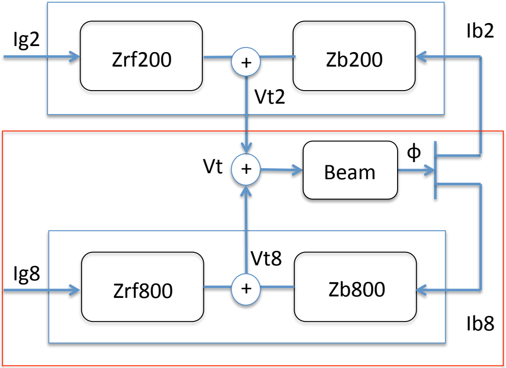
- The forward transfer impedance $Z_{RF} = V_{RF}/I_g$ and the beam transfer impedance $Z_b = V_b/I_b$ are different.



SPS RF System: Model

RF system model

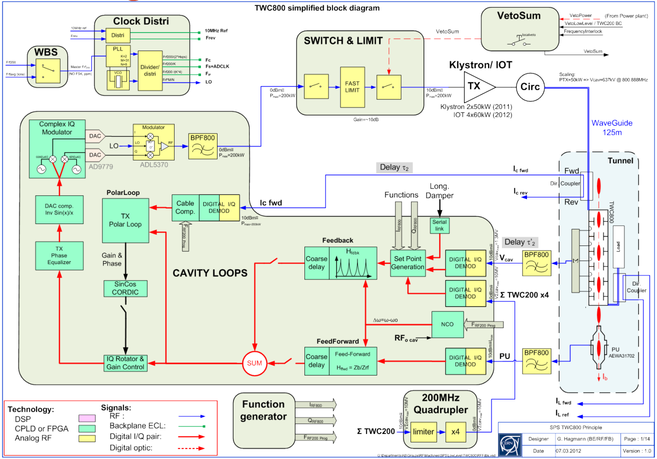
A generic block diagram of the RF system, including a rigid model for the beam dynamics is



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

SPS LLRF System

Block diagram



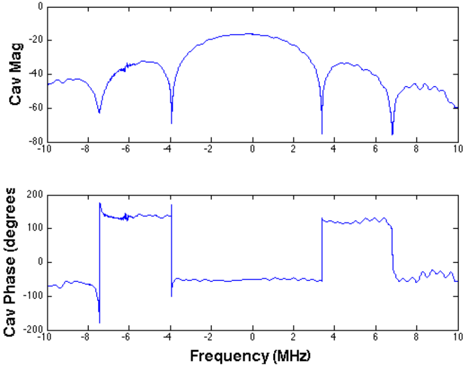
Block diagram of the 800MHz LLRF upgrade.

Designed by G. Hagmann, P. Baudrenghien - CERN

Components Modeled

Cavity

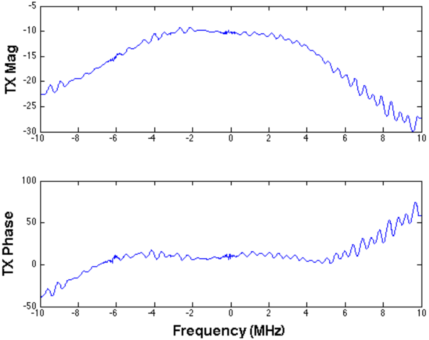
- The cavity impedance presented to the power generator, Z_{RF} is identical to the measured response of the system and is shown below:



Components Modeled

Transmitter

- The IOT is identical to the measured response from the test stand

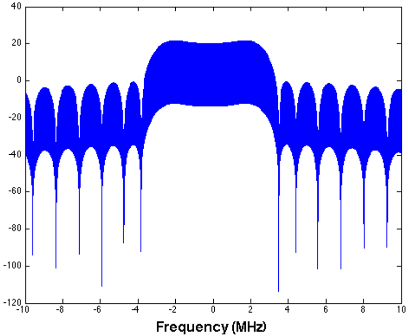


- The RF chain is calibrated so that the gain, from LLRF digital output to LLRF digital input is 1 at the RF frequency. That chain includes modulator, power amplifier, waveguide, cavity, antenna sum, cables back to LLRF and demodulator.

Components Modeled

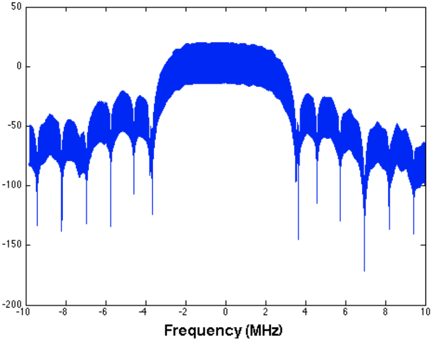
Cavity Controller

- The cavity controller includes the comb filters at f_{rev} and f_s, the low-pass filter, the one-turn delay, and the cavity model for adjusting the filter's sign using the actual coefficients implemented in the FPGA.
- The feedback response is shown below, using the low gain cavity model in the feedback chain.

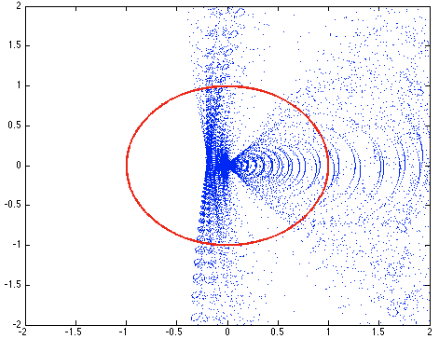


Stability margins

- The feedback gain is then set to 20 dB which achieves a gain margin of 13 dB at flat bottom, as shown in the figure below. The corresponding phase margin is about 72° degrees.
- The feedback response is shown below, using the low gain cavity model in the feedback chain.



RF station - Open Loop transfer function



Open Loop polar plot - Critical point for stability $-1 + i0$

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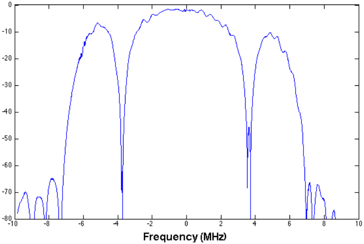
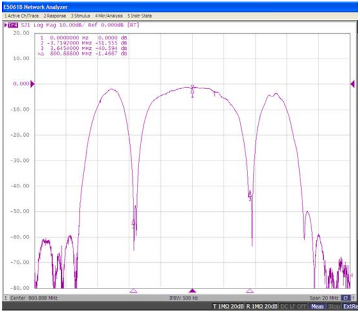
Validation (October 15th 2014 MD)

- The frequency domain model was validated with data from an SPS MD on October 15th 2014.
- First, the model was compared to data in the absence of comb, showing good agreement.





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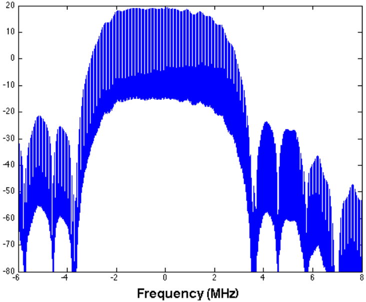
S21 Log Mag 10.00dB/ Ref 0.000dB [RT]
 1    0.0000000 Hz    0.0000 dB
 2   -3.7192000 MHz -51.555 dB
 3    3.6454000 MHz -40.594 dB
>Δ  800.88800 MHz  -1.4667 dB
```

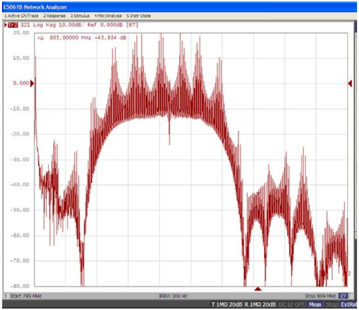
1 Center 800.888 MHz IFBW 500 Hz Span 20 MHz

T 1MΩ 20dB R 1MΩ 20dB DC LF Off

Validation (October 15th 2014 MD)

- The open loop response was compared with combs as well.

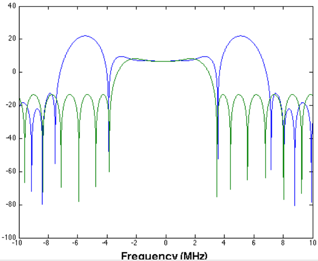




- The loop was then closed and almost identical stability margins results in the measurements and the model (13 dB gain and 73° phase margin).

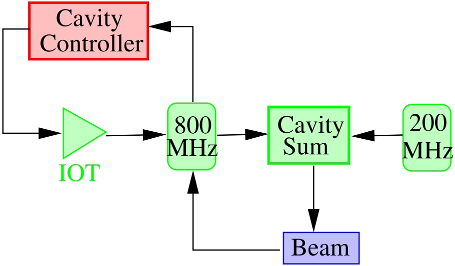
Stability Margin Sensitivity

- After validating the model, the stability margins were estimated for two proposed feedback filters (shown below):
  - As a function of the one-turn delay setting
  - During the ramp as f_{RF} changes with respect to the cavity resonant frequency f_o.
- The results show:
  - A need of accurate loop phase function with ramp. Functions were updated as a result of model findings.
  - Extreme sensitivity to delay with the high gain proposed filter.
  - Aligning zeros of cavity model in feedback and real cavity is essential for loop stability, otherwise delay setting is extremely critical.



Time Domain Model

- In development.
- Includes same components as feedback model *plus* the beam.
- Will be used to investigate the expected transient beam loading for various Cavity Controller settings.
- Validation not possible yet: marginal transient beam loading at flat bottom, beam unstable at flat top during last MD



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Conclusions

- A frequency domain model of the complete 800MHz RF station has developed and validated with the recent measurements conducted at the SPS ring.
- The studies help to define stability margins vs. feedback gain in the system and understand the impact of the delay in the RF station stability
- Based on a In-phase/Quadrature formalism, a model of the RF power stage has been developed to study the beam transient response in time domain.
- The complete model of the RF station, including the LLRF feedback, is under development and will provide results related to the transient beam loading, beam stability and longitudinal bunch position.
- One important point from these studies is to answer to the hardware designer what is RF station closed loop bandwidth required to minimize the transient beam loading along the batch.

Thank you for your attention

Thanks

- Thanks to G. Hagmann, P. Baudrenghien and other collaborators at CERN.

References

- C. Rivetta, T. Mastorides, J.D. Fox, D. Teytelman, D. Van Winkle, “Modeling and Simulation of Longitudinal dynamics for Low Energy Ring-High Energy Ring at the Positron-Electron Project", Physical Review Special Topics Accelerators and Beams, Volume 10, Issue 2, February 2007.
- T. Mastorides, C. Rivetta, J.D. Fox, D. Van Winkle, D. Teytelman, “Analysis of Longitudinal Beam Dynamics Behavior and RF System Operative Limits at High Beam Currents in Storage Rings", Physical Review Special Topics Accelerators and Beams, Volume 11, Issue 6, June 2008.
- T. Mastorides *et. al.*, “RF system models for the LHC with Application to Longitudinal Dynamics", Phys. Rev. ST Accel. Beams 13, 102801 (2010).