# SPS LLRF Models

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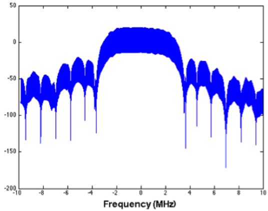
# Introduction

- Frequency and time domain models of the existing 200 MHz and new 800 MHz LLRF systems are being developed.
- The frequency domain model will allow us to:
  - study the stability margins of the RF loop
  - develop tools to commission, optimally setup, and operate the new LLRF
  - determine the limitations of the implementation
- The time domain model focuses on the RF-beam interaction.
  - The results from this model will be very important to set the specifications for the design and the parameters of the LLRF system
  - The model will allow us to assess the system stability and achieved beam loading compensation along the batch
  - Also study the effect of the 200 and 800 MHz alignment.

# Frequency domain model; summary

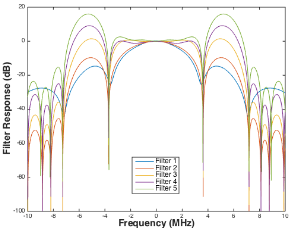
- The single-station model (in Matlab) is complete. It includes:
  - The existing 200 MHz and the new 800 MHz LLRF system
  - Comb filters at $f_{rev}$ and $f_s$, low-pass filter, one-turn delay, and the cavity model using the actual coefficients implemented in the FPGA (800 MHz system).
- The model was validated during the early commissioning of the 800 MHz upgraded system, accurately reproducing the open loop response and closed loop gain and phase margins.
- The 800 MHz system response (gain/bandwidth) has not been optimized yet. As the hardware is re-configurable, it is planned to upgrade the processing from the results of the on-going study.




Complete open loop response (simulation).

# Frequency domain model; first studies

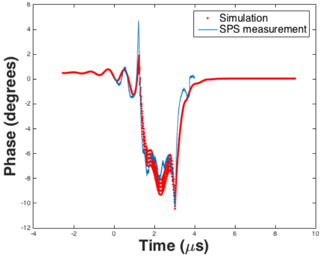
- The model was then used to estimate the stability margins:
  - For different feedback filters
  - As a function of one-turn delay settings
  - During the ramp as $f_{RF}$ changes with respect to the cavity resonant frequency.
- The results show:
  - A need for an accurate loop phase function during the ramp. Functions were updated as a result.
  - Extreme sensitivity to delay with the proposed high gain filter.
  - Aligning zeros of cavity model in feedback and real cavity is essential for loop stability, since it significantly reduces the range of stable delay settings.




Open loop response with different feedback filters.

# Time domain model; summary

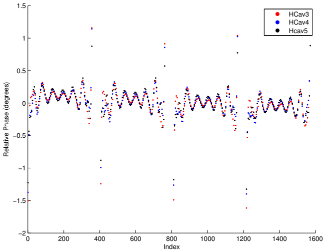
- The time domain model is being developed in Simulink.
- It includes all the components modeled in the frequency domain.
- Beam loading effects on bunch phase along a bunch train have been compared between measurements and simulations with good agreement. Some adjustments are still necessary though.




Beam loading along a batch. Single cavity model.

# Time domain model; next steps

- The next step will involve investigating the beam loading effect along the batch as a function of the LLRF parameters.
- There are many degrees of freedom: gain and bandwidth for two systems (200 and 800 MHz), relative gains of feedback and feedforward, one-turn delay.
- A major objective for these studies is to provide the hardware designers with the necessary LLRF specification to minimize the transient beam loading along the batch.




Beam loading with different feedback filters.

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2. Frequency Domain Model
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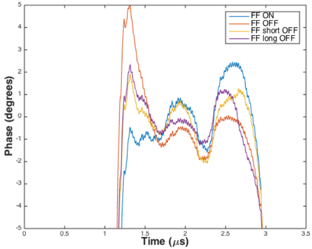
4. **Measurements**
5. Summary and Future Steps

# Measurements: Feedforward.

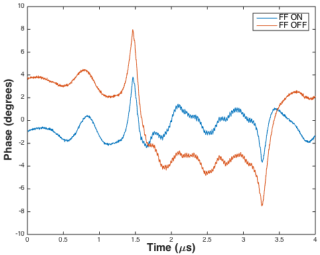
- With Thomas' help, measurements were conducted a year ago (72 b., 25 ns)
- We measured beam and cavity phase with and without the feedforward (off in short cavities, long cavities, or all cavities). Measurements at flat bottom.
- The data are very useful for the validation and final tuning of the models.
- In addition though, they already provided some insight to the kind of issues we should study and be aware of.
- For example, it seems that we might have too much gain in the feedforward.



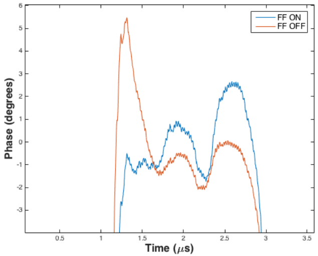

Beam phase for various settings.

# Measurements: Feedforward vs. Feedback.

- Feedforward ON reduces the peak to peak phase error (4.8°) from the Feedforward OFF case (7.4°).
- BUT, the peak to peak error is less when the feedforward is off for either short or long cavities (short cavities FF OFF 4°, long cavities FF OFF 5°).
- The model will allow us to understand this behavior and then investigate the optimal feedforward gain.




Short cavity phase.




Beam phase.

# Summary and Future Steps

- A frequency domain model of SPS LLRF has been developed and validated.
- This model will help to define stability margins vs. feedback gain in the system and understand the impact of the delay in the RF station stability
- The model will also assist with the setting up of the 3-section cavities and new transmitters
- A time domain model is under development and will provide results related to the transient beam loading, beam stability and longitudinal bunch position.
- This model will allow us to determine optimal settings for the SPS LLRF with regards to transient beam loading reduction.
- It would also be interesting to study the possible impact of coupling between cavities of different lengths.

## Acknowledgments

- I would like to thank Greg Hagmann for the useful information provided during the model development.

Thank you for your attention!