Development of an FPGA-based Cavity Simulator for Testing RF Controls

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This work was supported by the EIC Project and the U.S. Department of Energy, Contract DE-SC0012704.

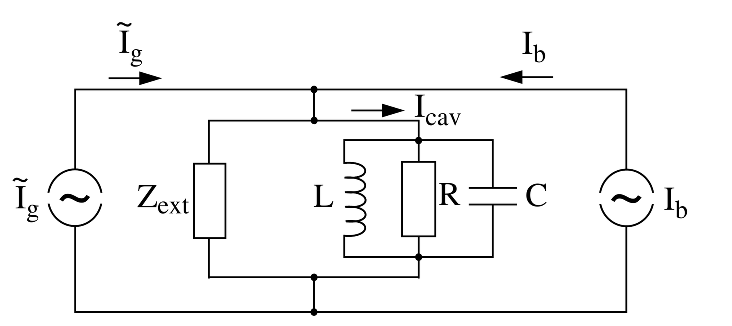
1. Abstract

LLRF is used to precisely control the amplitude and phase of the RF field in cavities. Often times, access to test the control algorithms with RF equipment, especially in the presence of beam, is limited or beyond reach. In such cases, testing must be done through computer modeling or simulations. Computer modeling is often too slow and difficult to interface with the LLRF hardware. Analog or digital cavity simulators are preferred as they allow for interaction with the LLRF controls platform in real-time, and compared to their analog counterparts, FPGA-based digital cavity simulators allow for a more adjustable and sophisticated implementation. The newly developed FPGA-based cavity simulator includes the cavity electrical model, the cavity mechanical model including Lorentz Force Detuning and microphonics, an amplifier model which can simulate real amplifier nonlinearities, and a beam model. The simulator will be validated using measurements from BNL's CeC 500 MHz NCRF cavity and the CeC 704 MHz 5-cell SRF cryomodule.

2. Implementation

Electrical Model

The cavity electrical model can be described by a RLC-type resonant circuit. Then the RF drive and beam serve as sources of excitation for the circuit. The model is shown below:



$$\frac{1}{R_L C} = \omega_{1/2}$$
$$\frac{1}{LC} = \omega_0^2$$
$$Q_L = R_L\sqrt{\frac{C}{L}}$$

The cavity voltage is described by:

$$\ddot{V}_C + \left(\frac{\omega_0}{Q_L}\right)\dot{V}_C + (\omega_0^2)V_C = \omega_{\frac{1}{2}}\left(\frac{2\beta}{1+\beta}V_f + R_L I_b\right)$$

Using the results from [2] and the following approximation:

$$\dot{x} \approx \frac{x[n]-x[n-1]}{T_s} \qquad (1)$$

The cavity can be implemented as a complex low-pass filter at baseband, defined by:

$$\begin{bmatrix} V_I[n] \\ V_Q[n] \end{bmatrix} = \begin{bmatrix} 1-T_s\omega_{1/2} & -T_s\Delta\omega \\ T_s\Delta\omega & 1-T_s\omega_{1/2} \end{bmatrix}\begin{bmatrix} V_I[n-1] \\ V_Q[n-1] \end{bmatrix} + T_s\omega_{1/2}\vec{u}[n]$$

Mechanical Model

According to [4], the cavity mechanical model can be represented using resonators. Specifically, the k'th mechanical mode is described by the following differential equation:

$$\Delta\ddot{\omega}_k + \left(\frac{\omega_k}{Q_k}\right)\Delta\dot{\omega}_k + (\omega_k^2)\Delta\omega_k = -\omega_k^2 K_k E_{acc}^2 + \phi_{microphonics}$$

Due to the low frequency of the mechanical resonances (< 1 kHz), the same approximations used for the cavity electrical model cannot be used to implement the mechanical model. Instead, the second order equation is converted to 2 first order differential equations defined as:

$$x_1 = \Delta\omega_k$$
$$x_2 = \Delta\dot{\omega}_k$$

$$\dot{x}_1 = x_2$$
$$\dot{x}_2 = -\left(\frac{\omega_k}{Q_k}\right)x_2 - \omega_k^2 x_1 - \left(\omega_k^2 K_k E_{acc}^2 + \phi_{microphonics}\right)$$

Again, using eq (1), the digital implementation for the mechanical model is found. The final equations are not shown here.

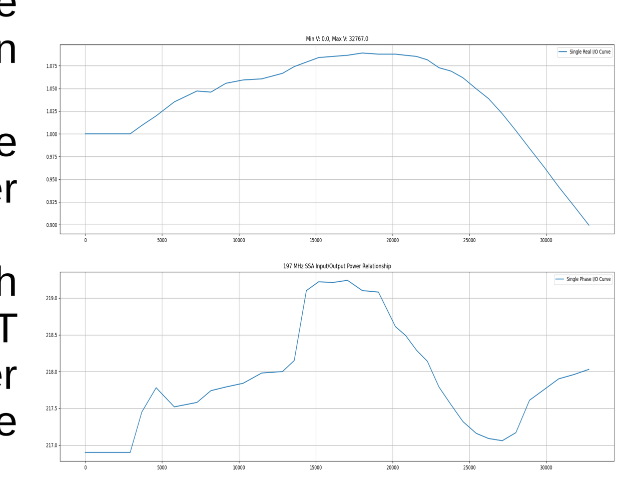
The microphonics are generated by a linear-feedback shift register (LFSR) which generates pseudo random bit values.

Amplifier Model

The simulator models both the frequency response and saturation behavior of the amplifier.

The amplifier frequency response is simply modeled by a lowpass filter with an adjustable cutoff frequency.

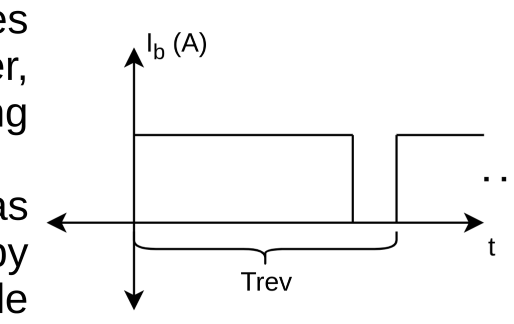
Non-linearities associated with saturation are modeled using a LUT that stores data from real amplifier measurements. The magnitude of the drive signal is used to index this LUT.



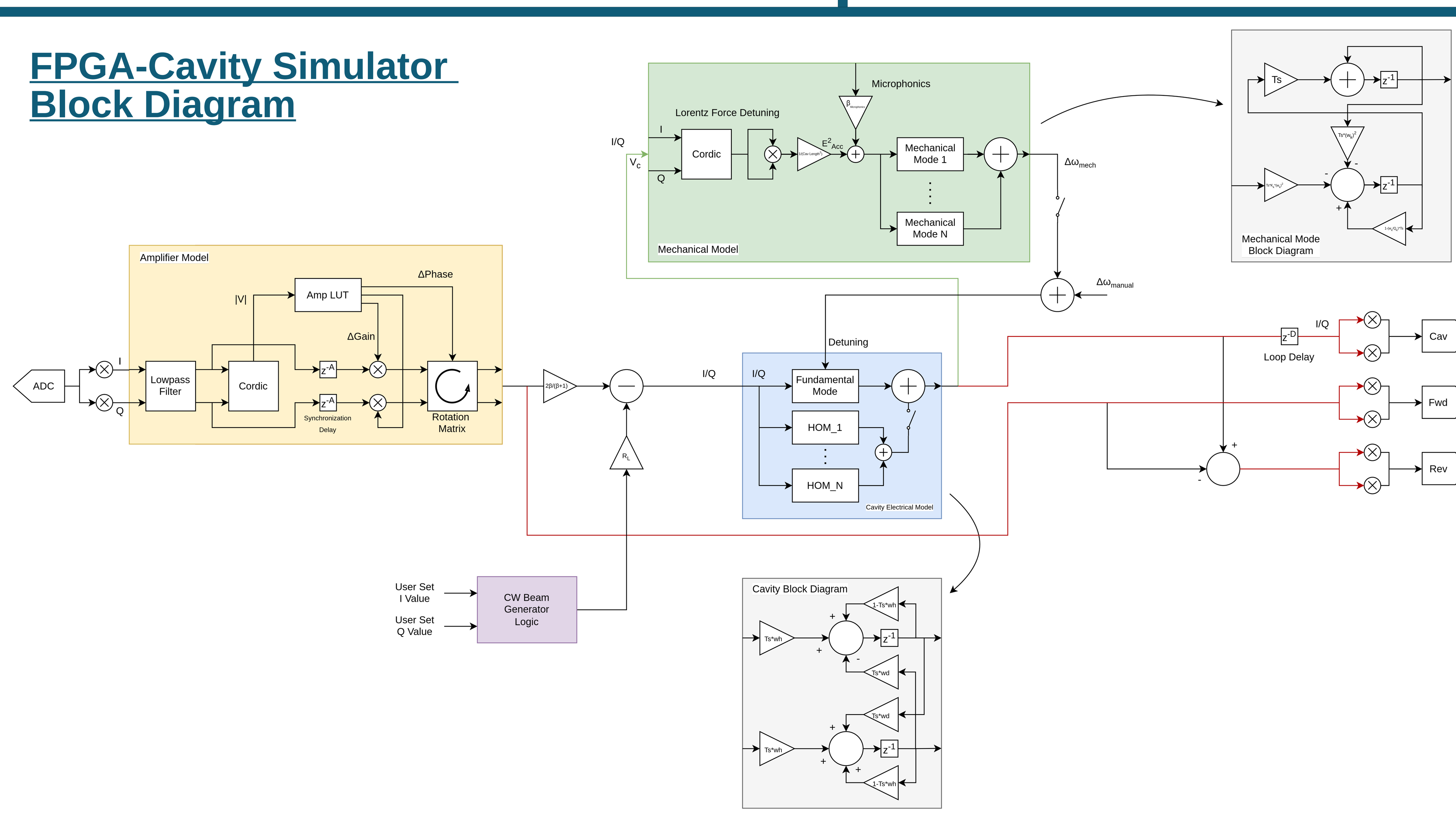
Beam Model

Ideally, the beam would be implemented as discrete Gaussian pulses (that are ~5ns wide for RHIC). However, this would require a very high sampling rate.

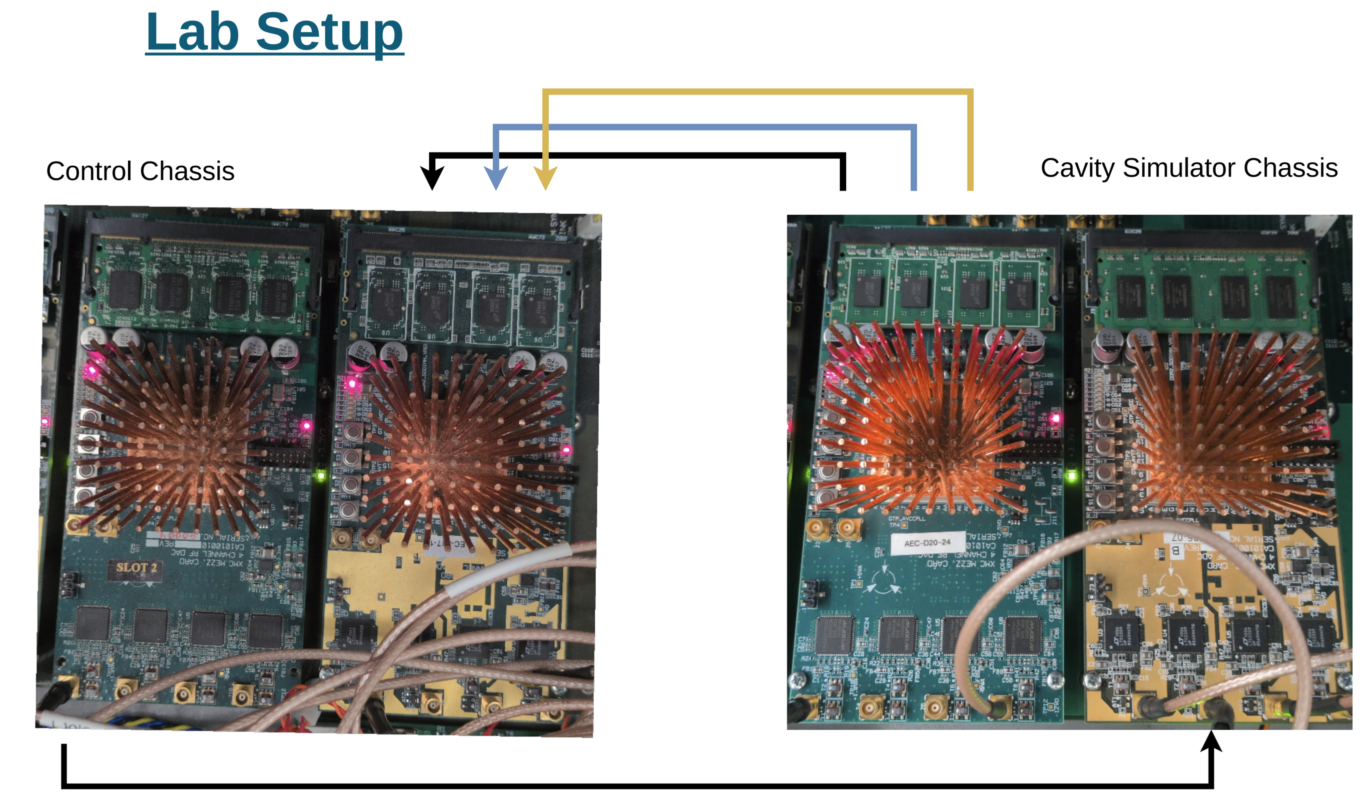
Instead, the beam is implemented as DC pulses with a period determined by the revolution frequency and a duty cycle determined by the number of buckets occupied. The user can adjust the amplitude (beam current) and phase of the beam.



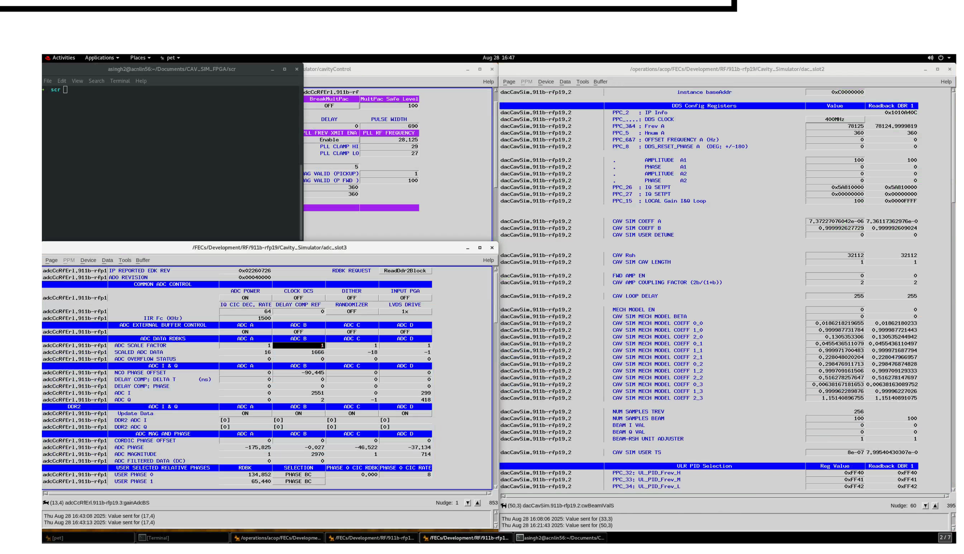
FPGA-Cavity Simulator Block Diagram



Lab Setup

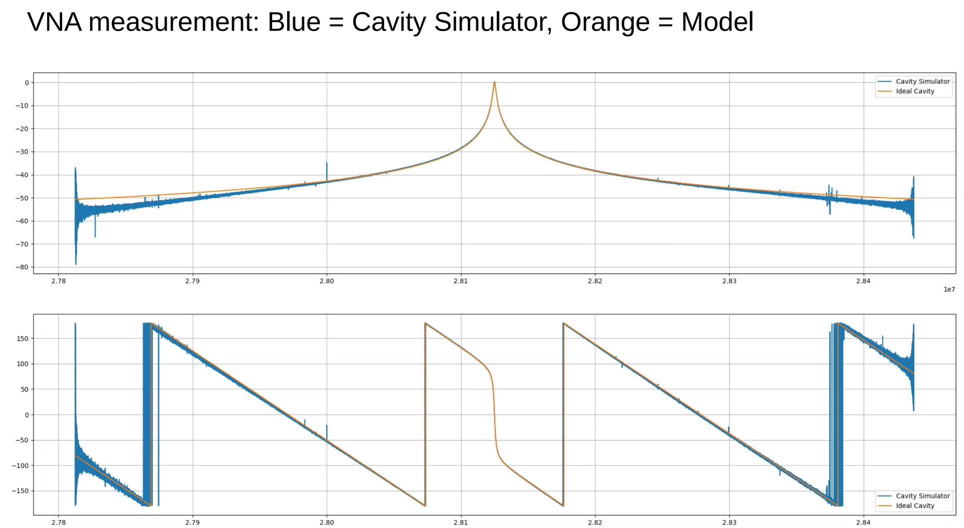


One can then interact with the cavity simulator using the already existing controls software (Pet Pages, GPMs, etc.)

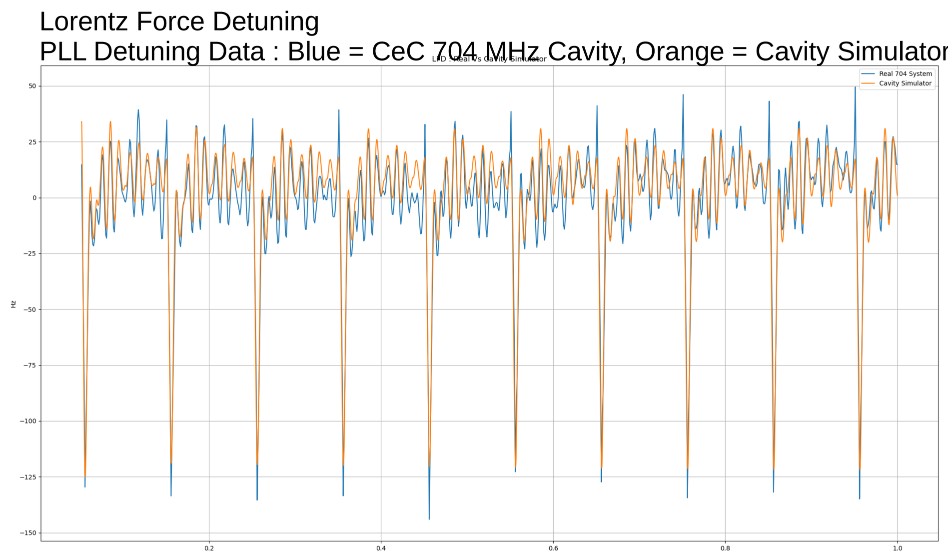


Results And Validation

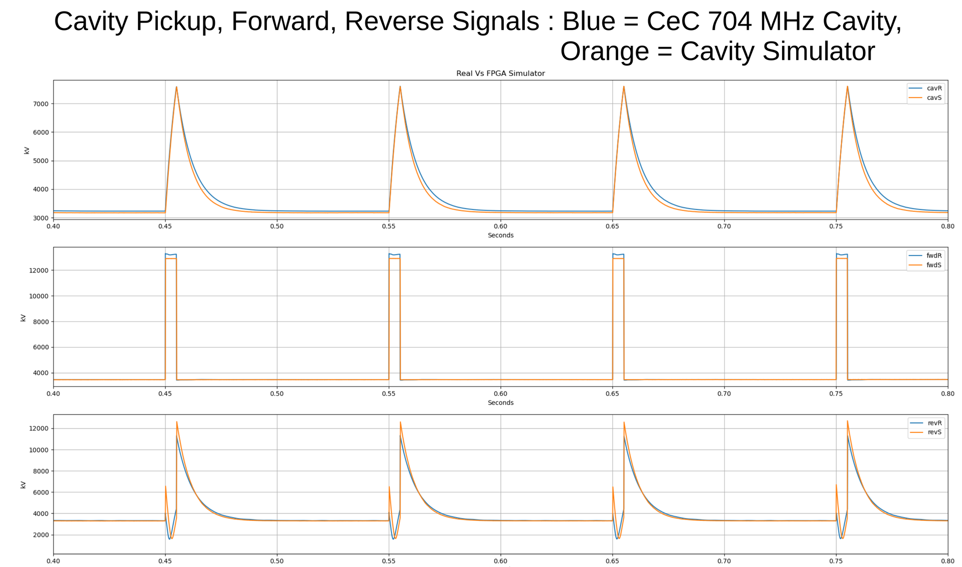
VNA measurement: Blue = Cavity Simulator, Orange = Model



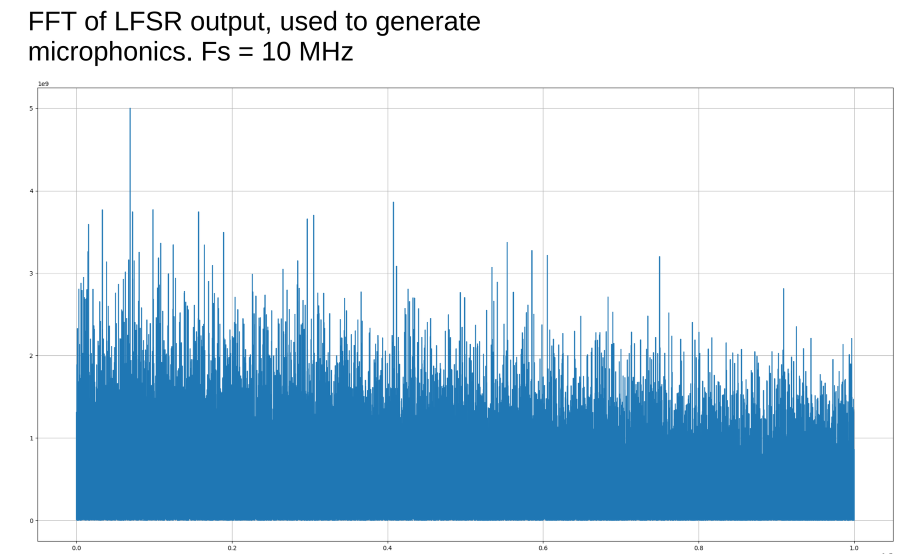
Lorentz Force Detuning
PLL Detuning Data : Blue = CeC 704 MHz Cavity, Orange = Cavity Simulator



Cavity Pickup, Forward, Reverse Signals : Blue = CeC 704 MHz Cavity, Orange = Cavity Simulator



FFT of LFSR output, used to generate microphonics. Fs = 10 MHz



Conclusion and Future Work

The cavity simulator is already proving to be useful for testing RF controls algorithms, specifically for SRF cavity field control. However, there still remains work related to the simulator.

The microphonics implementation using the LFSR does not seem to work on HW, this is still a work in progress.

Also, the loop delay through the simulator is rather excessive (~3.4 us). A majority of the delay is due to data transmission from the ADC to the DAC, but the VHDL code can also be optimized to lower the delay. In some sense though, this is not the worst issue as a longer loop delay only complicates the control problem more.

The simulator would also greatly benefit from resonance control capabilities in the form of a stepper or ferrite tuner model. Lastly, a high-gain, low-delay feedback model must be added.

References

[1] Qiu, Feng, Michizono, Shinichiro, Miura, Takako, Matsumoto, Toshihiro, Liu, Na, and Wibowo, Sigit Basuki. "Real-time cavity simulator-based low-level radio-frequency test bench and applications for accelerators." Phys. Rev. Accel. Beams, vol. 21, Mar 2018, pp. 032003.

[2] T. Schilcher, "Vector Sum Control of Pulsed Accelerating Fields in Lorentz Force Detuned Superconducting Cavities", Ph. D. thesis, Hamburg, 1998.

[3] C. Serrano, et al. "Cryomodule-on-chip Simulation Engine" ICALEPCS 2017

[4] J.R. Delayen. "Ponderomotive instabilities and microphonics—a tutorial." Physica C: Superconductivity, vol. 441, no. 1, 2006, pp. 1-6.

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