LLRF Upgrades for Studying Transient Beam-Loading in RHIC 28 MHz Accelerator Cavity for the Electron-Ion Collider

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1. Abstract

The 28 MHz cavities, currently used in the Relativistic Heavy Ion Collider (RHIC), will be modified into 24.6 MHz cavities to be used in the Hadron Storage Ring (HSR) for the future Electron-Ion Collider (EIC). One major difference between the EIC and the current RHIC system is that the EIC HSR will host proton beams with 10 times shorter bunch length, 3 to 10 shorter bunch spacing, and up to 3 times higher beam current than those in RHIC. While this will allow for greater luminosity, it will also introduce challenges for the LLRF system in the form of stronger transient beam-loading. To counteract these effects, digital implementations of a feedfoward (FFWD) and One-Turn Delay Feedback (OTFB) have been developed for an FPGA. Furthermore, using a newly developed digital network analyzer, software has been created that allows for a straightforward method of tuning the LLRF systems for maximum cavity impedance reduction. These developments will be evaluated with beam in the 28 MHz cavities during the 2025 RHIC Run.

2. Implementation

OTFB

The comb filter is implemented in the biquad form [5] and is described by the general transfer function:

$$H(z)=\frac{b_0+b_1 z^{-D}+b_2 z^{-2D}}{1+a_0 z^{-D}+a_1 z^{-2D}}$$

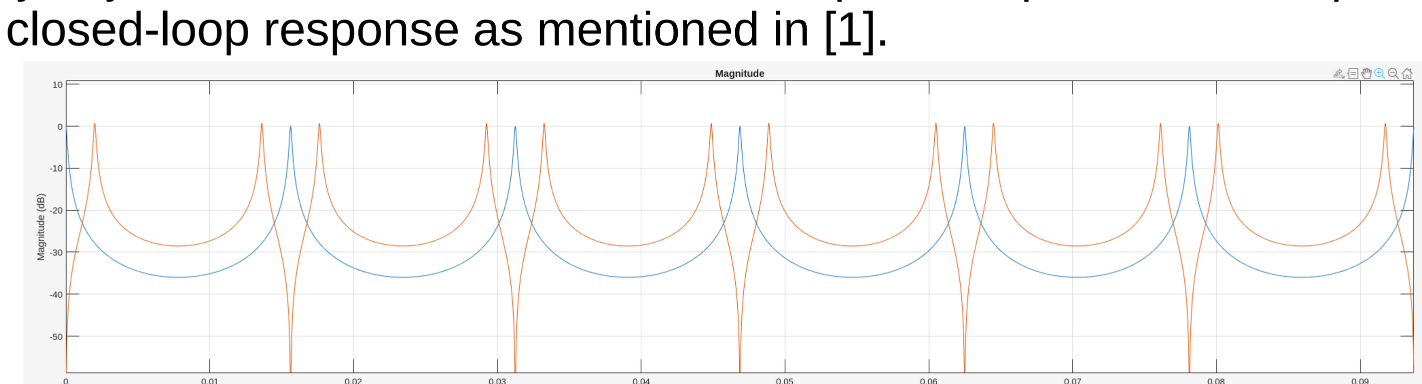
To switch between the normal comb response and the double-comb response, the following values must be set for the coefficients:

Normal Comb:	*Double Comb:*
$b_0 = 1 - a$	$b_0 = b_1 = 1 - a^2$
$b_1 = b_2 = 0$	$b_2 = 0$
$a_0 = a$	$a_0 = -2\cos(2\pi\phi)\, a$
$a_1 = 0$	$a_1 = a^2$

Here, "a" determines the bandwidth of the peaks. As "a" gets closer to 1, the peaks get more narrow.

And $\phi = f_{offset} / f_{rev}$

The OTFB implementation also features a variable delay line, fractional delay adjustment for the comb filter, and a phase equalizer to compensate for the closed-loop response as mentioned in [1].



Bunch-By-Bunch Measurement

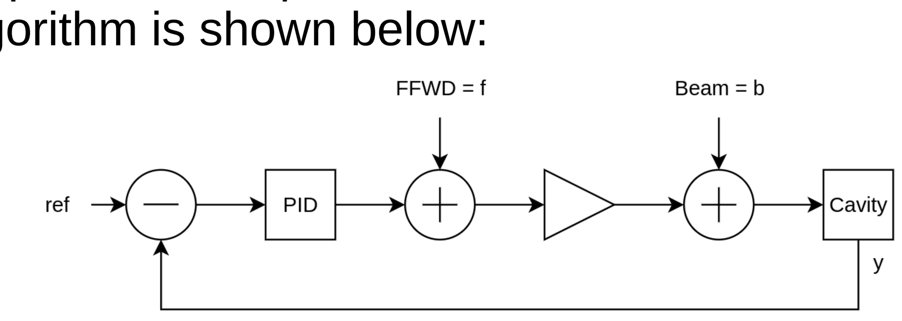
The bunch-by-bunch (BbyB) firmware is a FPGA design for the ADC. It is used to measure the amplitude and phase of the 120 buckets found in RHIC. This allows us to determine the amount of transient induced by the beam on both the cavity amplitude and phase and this result can be used to inform the settings of the feedforward.

The design is based on a NCO that is set to the RF frequency. Each roll-over of this NCO represents a new bucket. During each bucket, the IQ values are averaged over and, using a CORDIC, are converted to magnitude and phase.

FFWD

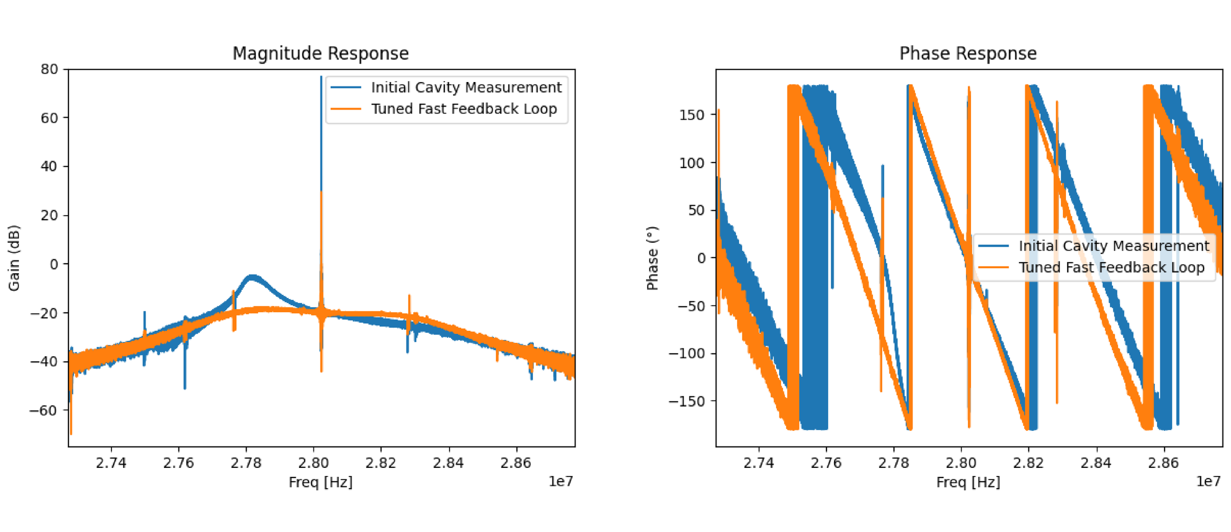
A simple ffwd consists of a NCO, like the BbyB, that counts RF buckets. The user can then set the ffwd to apply gain only during the abort gap (last 9 buckets), along with the exact amplitude and phase of the ffwd.

An adaptive ffwd implementation has also been developed that utilizes the measurement from the BbyB. Using this measurement, the inverse transfer function is applied to derive the ffwd term needed to cancel the transient. The calculation is done using a Python script which then controls the DAC amplitude and phase for each bucket. A simplistic, high-level, view of this algorithm is shown below:



$$H=\frac{y}{f} \rightarrow f_{correction} = -y * H^{-1}$$

Measuring The System Response



The measurements to the left show the response of one of the 28 MHz cavity systems in RHIC. The system is made up of two loops, a long delay digital loop and a short delay analog loop.

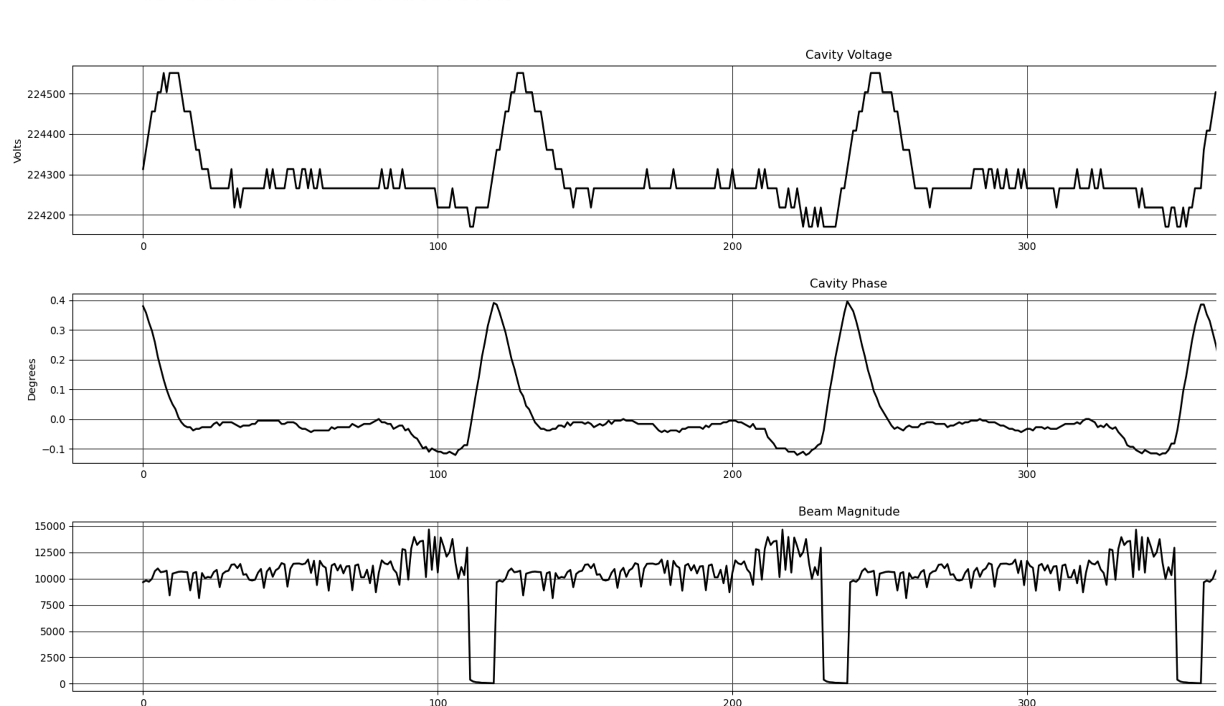
The blue response is the initial measurement and shows a badly tuned analog loop response. The lopsided magnitude response indicates that the loop delay is not properly configured resulting in lower stability margins.

The orange response is the system after adding a 2.5 ns cable to the analog loop, resulting in a more balanced and stable response.

These same measurements were used to determine the loop delay and to then configure the OTFB.

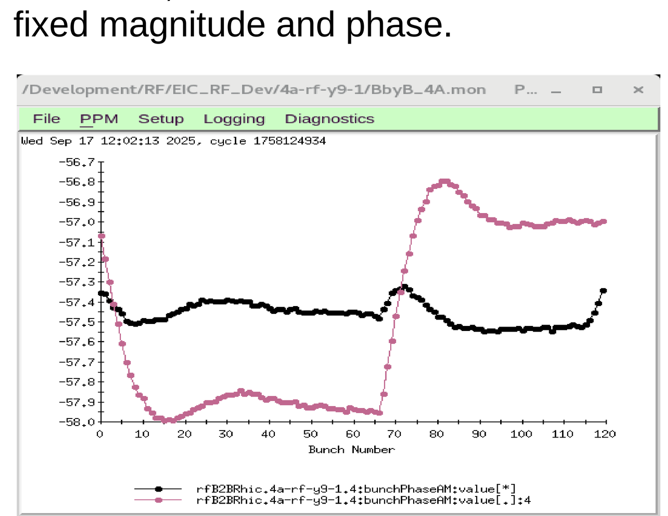
Measuring The Transient

The BbyB is able to measure the transient on the cavity voltage relative to the abort gap. From here, the ffwd term can be timed in to correct this transient.

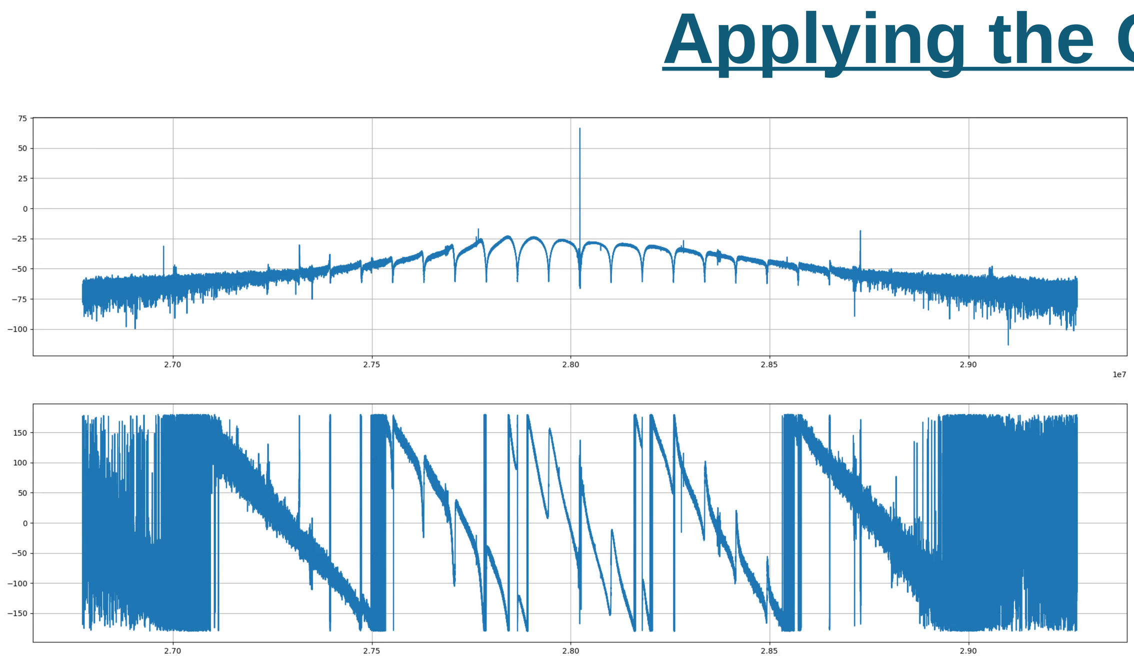


Applying the FFWD

The graph below shows the cavity phase before (pink) and after (black) applying the ffwd. The peak-to-peak transient drops from 1.2 degrees to 0.1 degrees. This is with the simple fffwd implementation, not the adaptive ffwd. This approach is limited in it's performance as it doesn't have any granularity to the ffwd term, either the ffwd is off or it is on with some fixed magnitude and phase.



Applying the OTFB



The graph on the left shows the closed-loop system response of the 28 MHz cavity with the PID, OTFB, and analog fast-feedback enabled.

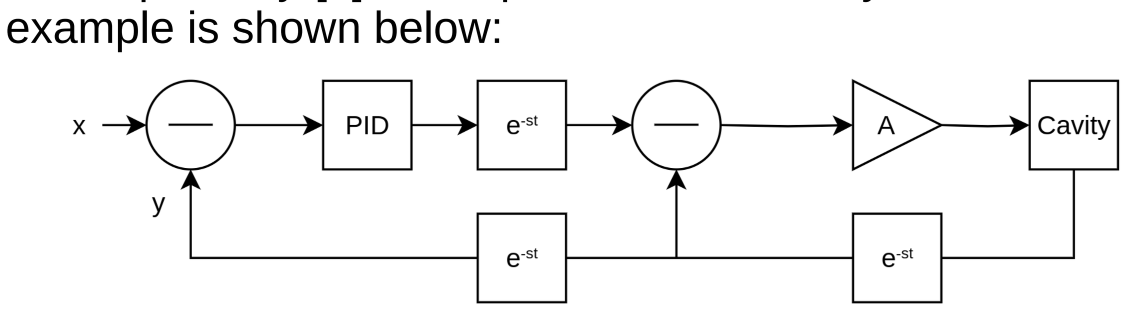
Ignoring the PID and fast-feedback, we see that the OTFB alone is providing ~30 dB of gain around the first few harmonics and additional gain up to 8 harmonics from the RF frequency.

This has the effect of lowering the effective cavity impedance seen by the beam and will significantly lower the transient induced by the beam. A test with beam has yet to take place.

Tuning The Loop Using The Digital Network Analyzer

A Digital Network Analyzer (DNA) has been developed at BNL [2] and it is used to tune the loop parameters to ideal values. First, the DNA is used to get a measurement of the closed loop response.

Then, inspired by [3], a simple model of the system is defined. One such example is shown below:



And H = y/x. As can be seen, the model accounts for cable delays, digital, and analog components. The parameters of each block can be altered, resulting in a slightly different loop response.

In an iterative process, measurements are taken and model parameters are altered until the model response fits the measurement. The fit process is a non-linear least-squares problem. Specifically, the following loss function is minimized:

$$L(\vec{\theta})=\sum_{\omega}\left|H_{meas}(j\omega)-H_{fit}(\vec{\theta},j\omega)\right|^2$$

From here, by looking at the new parameter values, we can derive information about the closed-loop system. This information, the loop delay in particular, is used to set the OTFB delay and gain values.

Conclusion and Future Work

So far, only the simple implementation of the ffwd has been tested with beam, the OTFB and adaptive ffwd algorithm have yet to be fully validated.

Besides fully validating the designs, there still remains some additional work. Firstly, the OTFB design described in this poster can only function so long as the revolution frequency is fixed. A final implementation of the design must be able to deal with acceleration conditions and potential solutions have been proposed by others, specifically in [4].

Furthermore, the adaptive ffwd is designed to work with a CW system. Work must be done to generalize this algorithm to work with a pulsed system.

References

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[4] F. Javier Galindo Guarch, Philippe Baudrenghien, J. Manuel Moreno Arostegui, "A new beam synchronous processing architecture with a fixed frequency processing clock. Application to transient beam loading compensation in the CERN SPS machine." 2021, https://doi.org/10.1016/j.nima.2020.164894.
[5] G. Hagmann, P. Baudrenghien, J. Betz, J. Egli, F. J. Galindo Guarch, G. Kotzian, M. Rizzi, L. Schmid, A. Spierer and T. Wlostowski, "The CERN SPS Low Level RF upgrade project," doi:10.18429/JACoW-IPAC2019-THPRB082

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