Brookhaven National Laboratory

BNL-229314-2026-TECH

EIC-ADD-TN-158

APEX STUDY : COMPENSATING TRANSIENT BEAM LOADING IN THE RHIC 28 MHZ

A. Singh

January 2026

Electron-Ion Collider

Brookhaven National Laboratory

U.S. Department of Energy

USDOE Office of Science (SC), Nuclear Physics (NP)

DISCLAIMER

APEX STUDY : COMPENSATING TRANSIENT BEAM LOADING IN THE RHIC 28 MHZ

A. Singh*, S. Mai, K. Mernick, F. Severino

*asingh2@bnl.gov

Abstract

With the EIC on the way, it is important that developments and strategies are in place to deal with the very high beam currents that the machine will feature. Specifically, the EIC will collide beams of up to 2.5 A, three times the beam current in RHIC. This higher beam current will cause significant voltage transients in the cavity fields which can lead to longitudinal instabilities and beam loss. In anticipation of these negative effects, studies were carried out on the RHIC 28 MHz cavities using newly developed firmware and software to diagnose and combat beam loading. Diagnostic tools such as the bunch-by-bunch (BbyB) ADC firmware and digital network analyzer (DNA) were used to characterize the closed loop system and transient on the cavity voltage magnitude and phase. Then, a one-turn delay feedback (OTFB) and adaptive feed-forward (aFFWD) were used to minimize the transient beam loading. The studies were carried out with beam during 2 accelerator physics experiements (APEXs) using one of the 28 MHz accelerating cavities here at RHIC.

INTRODUCTION

Many aspects of the RHIC complex (including the ring itself) will be repurposed for the EIC, this includes the 28 MHz accelerating cavities which will become 24.6 MHz accelerating cavities. This makes the 28 MHz cavities a good testing ground for new RF Controls algorithms. This paper will first describe the newly developed firmware and software, which includes the BbyB ADC firmware, the DNA, the OTFB, and the aFFWD algorithm. The paper will then discuss the offline work done prior to the experiment, including taking measurements of the beam loading, characterizing the closed loop system, and configuring the LLRF system. Then, the paper will showcase the results from the experiment. Lastly, the paper will conclude with a discussion of remaining work and some closing remarks.

LLRF FIRMWARE AND SOFTWARE DEVELOPMENTS

BbyB ADC FIRMWARE

The BbyB ADC firmware was designed to monitor the amplitude and phase for each of the 120 RF buckets in RHIC. It is a DSP technique that uses a NCO, tuned to the RF frequency, to count each bucket. During the bucket period, the baseband IQ data from the cavity probe is integrated and averaged to get the corresponding amplitude and phase. These values are then read back on the controls software.

THE DNA AND MODEL BASED TUNER

To characterize the closed-loop response of the LLRF system, including the cavity, a digital, FPGA-based, network analyzer has been developed. While a normal VNA could also be used, the DNA has the added benefit that it does not require any hardware changes to function. The DNA functions by creating a complex (IQ) chirp at baseband which then gets upconverted and outputted through the DAC. At the same time, the IQ data corresponding to the chirp (X) as well as the IQ data corresponding to the pickup signal (Y) is saved in BRAM. This data is then exported from the control system and saved in CSV files. From here, the processing is fairly straightforward and the transfer function from X to Y is defined as:

$$H(\omega) = \frac{\mathrm{F}(Y) \cdot \mathrm{F}(X)^*}{\mathrm{F}(X) \cdot \mathrm{F}(X)^*}$$

Where $\mathrm{F}(\cdot)$ is the Fast-Fourier Transform.

Along with the DNA, a model-based tuner has been developed. Inspired by [1], the idea is to create a linear model of the closed loop system that can be used to approximate the measurement taken by the DNA. An example of a linear model is shown below:

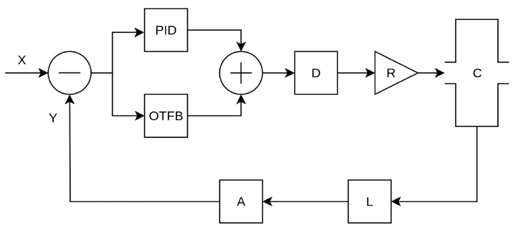


Figure 1: Linear Model of LLRF System

The theoretical transfer function Y/X can be defined based on the linear model. From here, a fit can be preformed between the model and the real data. Specifically, the following loss function is minimized:

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

By performing this fit, the values for the real loop parameters can be extracted, for example, the loop delay. More details on the implementation can be found in [2].

THE OTFB

The performance of direct feedback is limited by the loop delay of the closed loop system. In RHIC, a loop delay of at least 1 μs is typical for the LLRF systems. This is a significant delay considering the abort gap is similarly about

1 μs long and it results in the transient beam loading that we observe. An alternative form of feedback that can be used in conjunction with the direct feedback is the OTFB.

The OTFB is based on two principles. Firstly, the beam spectrum is made up of harmonics of the revolution frequency ± the synchrotron sidebands. Therefore, we should apply gain specifically at these frequencies, which can be done using a digital comb filter. Secondly, we note that, turn-by-turn, the beam spectrum does not vary significantly. Therefore, we don't need to apply the correction right away, instead we can wait exactly one revolution period before applying the gain. By combining these two principles, we get the OTFB.

By using the OTFB, we can further reduce the effective cavity impedance around the revolution lines by an additional 30 dB (typical value) for up to 8 harmonics (depends on the revolution frequency).

For more details about the OTFB implementation, refer to [3].

THE aFFWD ALGORITHM

The aFFWD utilizes a BbyB DAC firmware that has been developed here at BNL. The firmware allows the user to apply specific amplitude and phase values for each of the 120 buckets present in RHIC, making it a powerful tool for feedforward control. The aFFWD algorithm works on the following principle: First we notice that the beam causes some periodic disturbance on the cavity field and by applying a specific correction, we should be able to completely cancel this periodic disturbance. We find the transfer function from the output of the aFFWD DAC to the output of the cavity, call the transfer function H. If we call the disturbance on the cavity y, we can find the exact aFFWD correction by multiplying the inverse transfer function H^{-1} by -y, giving us $u = -y \cdot H^{-1}$. Special care has to be taken in applying the inverse transfer function as it can potentially amplify noise far from the cavity resonance, resulting in a poor feedforward correction.

The algorithm also integrates the error over the 120 buckets, and if this error excedes some threshold, the feedforward correction is recalculated. Thus making the algorithm adaptive.

OFFLINE PREPARATION

Prior to the experiment, much preparation was done during beam downtime and on maintenance days.

For one, the BbyB ADC firmware was installed in a development chassis and was connected to the cavity probe, forward power, reverse power, and wall current monitor signals. This allowed us to observe transient beam loading over varying machine operating conditions. An example of such a measurement for magnitude and phase of the cavity, and a wall current monitor is shown below:

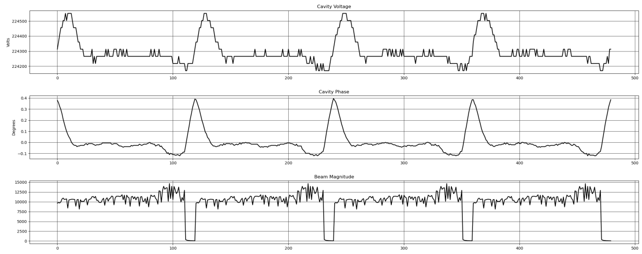


Figure 2: BbyB Cavity Magnitude and Phase Measurement

The OTFB requires precise knowledge of the loop delay to function effectively. Using the DNA and the model based tuner, we were able to find the loop delay with a high degree of accuracy. Specifically, we found the loop delay around the OTFB DAC to be about 2.1 μs.

Lastly, the aFFWD algorithm requires a system response measurement and calibration to work properly. With regard to calibration, basically we needed to calibrate the DAC drive settings to the voltage induced in the cavity. To take the system response measurement, we applied gain to one of the 120 buckets then measured the response using the BbyB ADC. The system response was then calculated using these two signals and the final system response was the average of 100 of such measurements. The measurement of the system response for the aFFWD is shown below:

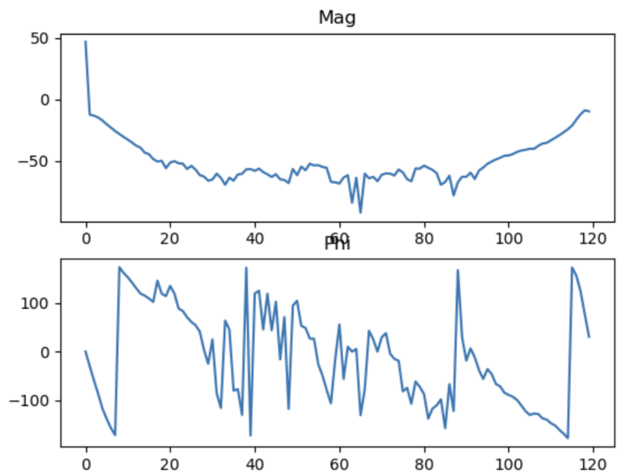


Figure 3: aFFWD System Response Measurement

Compare this to the same sort of measurement taken in the lab:

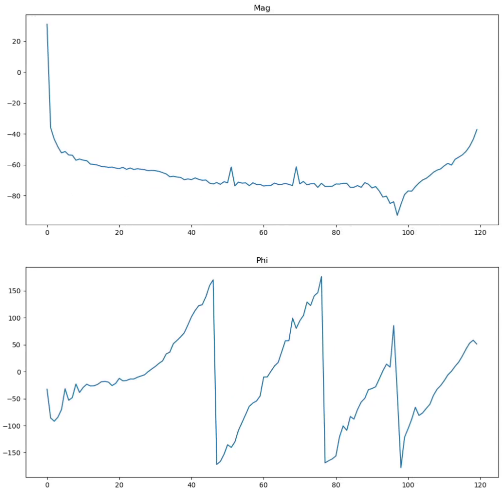


Figure 4: aFFWD System Response Measurement In Lab

We notice the top measurement is more noisy than the one taken in the lab. This would end up having an impact on the performance of the algorithm

SIMULATION AND EXPERIMENT RESULTS

The new developments were tested with with gold beam at injection with one of the 28 MHz accelerating cavities in RHIC.

First, the DNA was used to measure the system response. It was noticed that the phase margin of the system below the cavity resonance frequency was lower than the margin above. This was due to the delay through the direct analog fast-feedback being incorrect. By adding addtional cable delay in the tunnel, we were able to correct this response, resulting in a more stable system. The before and after DNA measurements are shown below:

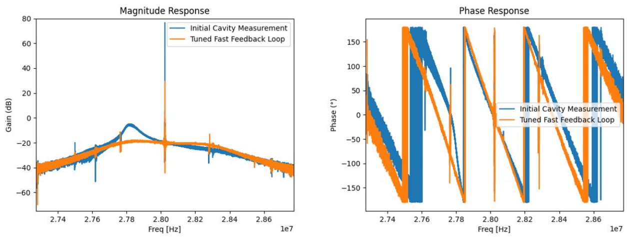


Figure 5: DNA measurement before and after correcting the loop phase

Then, using the predetermined loop delay of 2.1 μs we were able to configure the OTFB for 30 dB impedance reduction. A measurement of the total closed loop response is seen below:

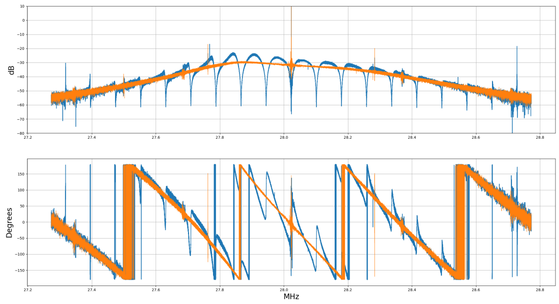
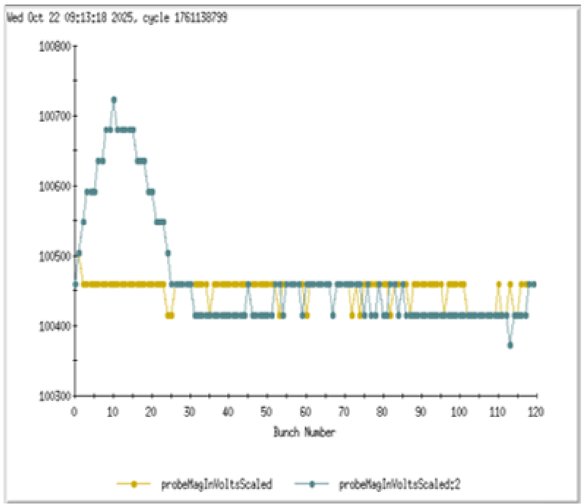
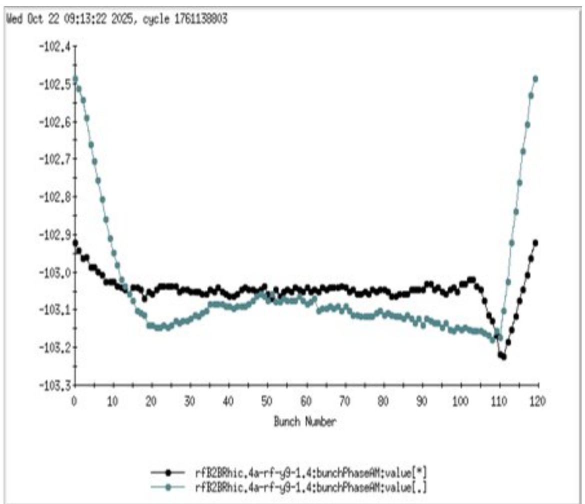


Figure 6: Total closed-loop system response

Following the initial setup, 111 bunches were injected into the yellow tunnel in RHIC. Below we can see a BbyB measurement which shows the transient beam loading before and after enabling the OTFB:





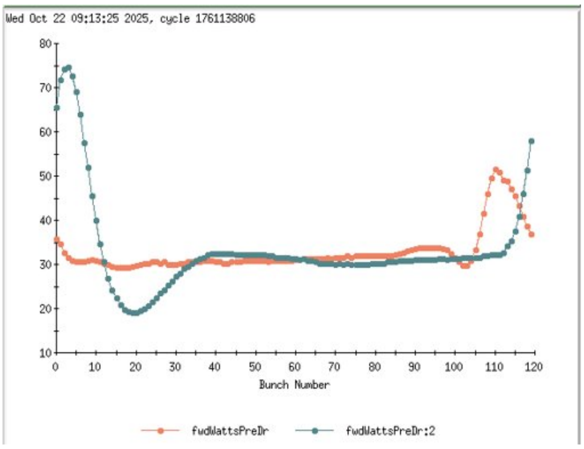


Figure 7: Bbyb measurement of transient beam loading with and without the OTFB (Blue is without the OTFB). Top shows the cavity magnitude, middle shows the cavity phase, and the bottom shows the forward power.

The magnitude transient drops from approximately 300 V to a completely flat response. The phase transient drops from 0.7 degrees to 0.3 degrees. The forward power transient drops from 55 W to 20 W. We see that in all but the cavity magnitude measurement, there remains a residual transient. Simulations indicate there remains a residual transient on the magnitude as well, meaning the current BbyB ADC is limited in its resolution.

Following the testing of the OTFB, the aFFWD algorithm was tested. Using the offline measurement of the system response and the BbyB ADC measurement, the feedforward correction was calculated. The BbyB DAC was then enabled, resulting in a correction of the transient as seen below:

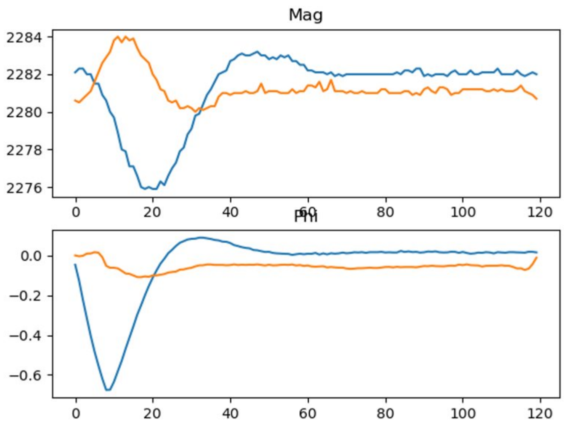


Figure 8: Transient before (blue) and after (orange) applying aFFWD correction. Magnitude is in FPGA counts.

The measurements show a residual transient in both the amplitude and phase which is due to the noisy offline system response measurement.

REMAINING WORK

Both the OTFB and the aFFWD algorithm were successfully demonstrated with beam during an APEX study in RHIC, resulting in a significant reduction of the transient beam loading. However, both algorithms require additional modifications to be considered complete. Firstly, the OTFB is designed to operate at a fixed revolution frequency. Currently a fractional delay is used only to tune the operating frequency. It may be possible to use the fractional delays in an active manner to tune the OTFB as the revolution frequency ramps up, but this approach may suffer from numerical errors from the fractional delay filter. Others have proposed possible solutions in the form a resampling scheme for beam-synchronous processes [4]. Regarding the aFFWD, a better method for measuring the loop response needs to be used, the DNA could be used. Furthermore, the current algorithm works on a computer external to the LLRF controls hardware and communication between the two happens over the network. In the future, the aFFWD algorithm should be implemented in the software code for the Common Platform hardware that will be featured in the EIC.

REFERENCES

[1] Teytelman, Dmitry. "A Non-invasive Technique for Configuring Low Level RF Feedback Loops in PEP-II." , no. 2005.

[2] S. Mai, et al., Baseband Digital Network Analyzer Upgrade For LLRF Controllers. BNL-229011-2025-TECHEIC-ADD-TN-146

[3] A. Singh, et al., One-Turn Delay Feedback (OTFB) Implementation for the EIC. BNL-229013-2025-TECH EIC-ADD-TN-147

[4] F.J.G. Guarch, et al., COMPENSATION OF TRANSIENT BEAM LOADING IN RAMPING SYNCHROTRONS USING A FIXED FREQUENCY PROCESSING CLOCK.