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BPM FEEDBACK FOR LLRF ENERGY AND PHASE REGULATION IN CHARGE STRIPPING BEAMLINES*

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Abstract

Charge stripping is inherent for high power ion heavy accelerators such as the FRIB linac. However, at high power, strippers require motion to prolong the operational life of the stripping media, or by flowing a liquid lithium film. The charge stripping process introduces energy losses that vary with the lithium film thickness, which can result in observable beam losses along the tuned beamline at high on-target beam power, above ~100 kW, if not adequately mitigated. BPM phase feedback is used to compensate for these effects in real-time, adjusting upstream RF cavities in order to maintain a constant beam energy and phase post-stripper, which significantly reduces beam energy fluctuations.

INTRODUCTION

The Facility for Rare Isotopes Beams (FRIB) started beam operation in May 2022 [1]. So far about 40 scientific experiments have been conducted at FRIB. Initially the beam power started at 1 kW and has been increased steadily for the past two years toward the ultimate goal of 400 kW. The focus of the FRIB has shifted from technical construction to reliable and efficient operation [2, 3], and power ramp up [4, 5]. Table 1 shows the beam power ramp up trajectory since the commencement of user operation and plans in the coming epochs [5].

Table 1: FRIB Power Ramp-up Trajectory and Plan

Beam Power	Species	# of User Experiment	Start Date
1 kW	^{48}Ca, ^{70}Zn, ^{82}Se	3	05/2022
3 kW	^{36}Ar, ^{124}Xe, ^{198}Pt	5	11/2022
5 kW	^{36}Ar, ^{40}Ar, ^{48}Ca, ^{64}Zn, ^{124}Xe	15	02/2023
10 kW	^{18}O, ^{40}Ar, ^{22}Ni, ^{28}Si, ^{48}Ca, ^{82}Se, ^{124}Xe, ^{238}U	17	10/2023
20 kW			Epoch 2
50 kW			Epoch 3

Charge stripping is necessary for high power heavy ion accelerators. At FRIB, for low beam power regime, a carbon foil stripper is used; for higher beam power regime, a liquid lithium stripper is used [6]. Neither the carbon foil nor the liquid lithium film has perfect uniformity. Variations in the stripping media introduce spread in the energy loss, which in turn result in significant beam loss alone pretuned beamline especially at high beam power. The temporal variation of the liquid lithium film thickness result is variation of the mean energy of the stripped beam, which can cause beam losses in the same way. Finding a solution that can mitigate the effect of energy loss variation in the stripper is critical for the success of the FRIB power ramp up.

This paper will discuss the selection of devices for measurement and energy and phase regulation, the technical feasibility study, and some initial test results at low beam power level. A simple user interface has already been created for operators to activate the feedback during normal high power (~10 kW at the moment) operation. Although not yet required, this early experience will verify the effectiveness of the solution and prepare operators for further power ramp up.

ENERGY AND PHASE REGULATION

To achieve stable energy and arrival phase at the entrance of the first multi-gap buncher (MGB01) in the folding segment 1 (FS1), a feedback control scheme is considered. It is important to identify which devices are best suited to provide the beam energy and arrival phase measurement, and which devices will be used to correct them. Figure 1 shows various beam line devices near FS1 area, including beam position monitors (BPMs), charge stripper, MGB01 and superconducting radio frequency (SRF) cavities inside the cryomodules (CB11 and CH01).

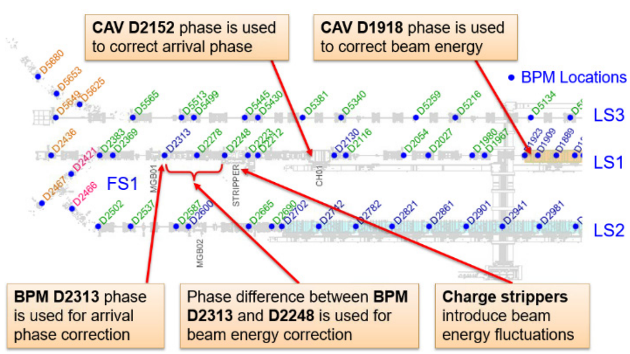

Figure 1: Beam line devices near FS1.

Measuring Devices

The energy will be measured by the phase difference between two BPMs after the charge stripper and before the MGB01. To achieve the best measurement accuracy, the distance between the two BPMs should be maximized, hence BPM D2248 and BPM D2313 are chosen for the energy measurement, see Figure 1. For stable beam transport

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downstream, not only the beam energy that reaches the MGB has to be constant, but also the beam arrival phase at the MGB should be constant as well. The arrival phase is measured by BPM D2313 alone.

Controlling Devices

To correct the beam energy and arrival phase variations, the SRF cavities upstream of the charge stripper will be used. To minimize the number of cavity whose setting needs to be adjusted, it is preferred to have the cavity close to the charge stripper. Based on such consideration, the last cavity in the accelerating cryomodule (CB11) before the charge stripper is chosen to correct the energy variation and the last cavity in the bunching cryomodule (CH01) is chosen to correct the arrival phase variation.

TECHNICAL FEASIBILITY STUDY

To change the energy gain of the beam from a cavity, one can either change the amplitude (i.e. field) set-point of the cavity or the phase set-point of the cavity. Changing the amplitude of the cavity though could cause Lorenz force induced detuning and further contribute to instability. It is preferred to change the phase set-point instead.

Fast Phase Ramp Rate

For the typical linac phasing process, the cavity phase ramp rate is set to 20 °/s. For the effective feedback control of the energy and arrival phase, the low level radio frequency (LLRF) controller must be able to adjust the cavity phase much faster. It was not clear at the beginning how fast the phase of an SRF cavity can change. To find out the limit, the cavity phase ramp rate was increased gradually from a few hundred degrees per second up to 1000 °/s (or 1 °/ms). When it was increased further, the cavity started to trip. Figure 2 is the fast waveform captured by the LLRF controller [7] that shows the result of a test where the cavity phase set-point was increased by 2 ° every 10 ms. The peak phase error was less than 0.2 °, which satisfied the RF control requirement of 1 °.

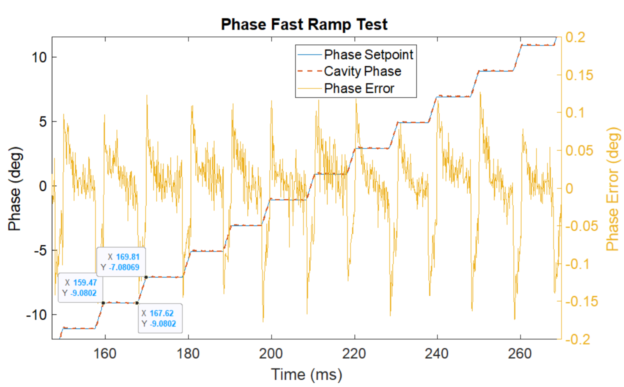

Figure 2: Cavity phase control performance under fast phase ramp rate of 1000 °/s.

Ethernet Based Feedback

Another design consideration is how the BPM phase information will be sent to the LLRF controllers. A hardwired connection between the BPM and the LLRF carrying an analog or digital signal is one option. But such a connection does not yet exist and new cables would have to be pulled. There is also firmware development that would be required on both the BPM and LLRF side for this interface to work.

An alternative to the hardwire connection solution is to send the BPM phase information through Ethernet. This way there is no added noise and the BPM phase is readily available in the digital form in the input-output controller (IOC). Other benefits of this solution include flexibility to send the BPM phase information to any LLRF controllers without the hassle of wiring and the minimum firmware/software work involved. The most significant concern for this approach is the network latency, which would delay the response time.

Due to the limited distance between the two chosen BPMs, the uncertainty in the beam energy measurement could be high. To have a more precise measurement of the beam energy, some averaging is necessary. It was decided that the BPM IOC will send the phase information to the LLRF controller every 10 ms (i.e. at 100 Hz rate). A test shows the network delay is around 1 ~ 2 ms, which is not significant relative to the the 10 ms integration time.

INITIAL TEST RESULT

An initial test was done in May 2023 to validate the proposed solution. The test was done without any charge stripper. Instead, a controlled beam energy change was introduced by changing the amplitude set-point of an upstream cavity (CAV D1906). In this test, only the beam energy feedback loop is enabled. Figure 3 shows the test result. One can see that the beam energy deviation (green trace) is corrected in about 0.2 s by changing the phase of the cavity D1918 (red trace) by around 20 °. The arrival phase (blue trace) has a steady state offset because the arrival phase correction was not activated.

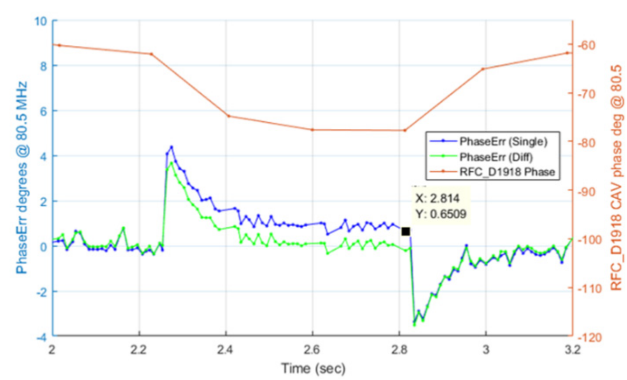

Figure 3: Initial test result of a single feedback loop (energy correction only) with cavity D1918.

Later in December 2023, a similar test was conducted with some improvements. First, a better filtering technique was implemented to allow better precision at steady state and faster response during transients. Second, both energy and arrival phase regulation were activated. Lastly, the regulation response time was improved to around 0.1 s.

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USER INTERFACE

A compact, easy to use interface as shown in Figure 4 has been developed for the operators to interact with the tool developed for the energy and phase regulation. The "ON" and "OFF" buttons allow operators to enable or disable LLRF feedback. Before enabling the LLRF feedback, the operator needs to click the "BPM Set Nominal" button to establish a baseline which the LLRF feedback considers as the set-point.

The "ENABLED" status of the LLRF feedback does not necessarily mean the feedback is "ACTIVE". For the feedback to be active, certain conditions have to be met. First, the beam chopper repetition rate must be set to 100 Hz, meaning that there is some beam present in the linac for every 10 msec period. Second, there should be sufficient beam intensity for the BPMs to have reliable readings. Lastly, the nominal phase must be kept up-to-date. If the required correction becomes too large, the tool will automatically switch to an inactive state until new nominal phase set-points are set. Once the above conditions are met, if the feedback is enabled, the feedback state will automatically become "ACTIVE".

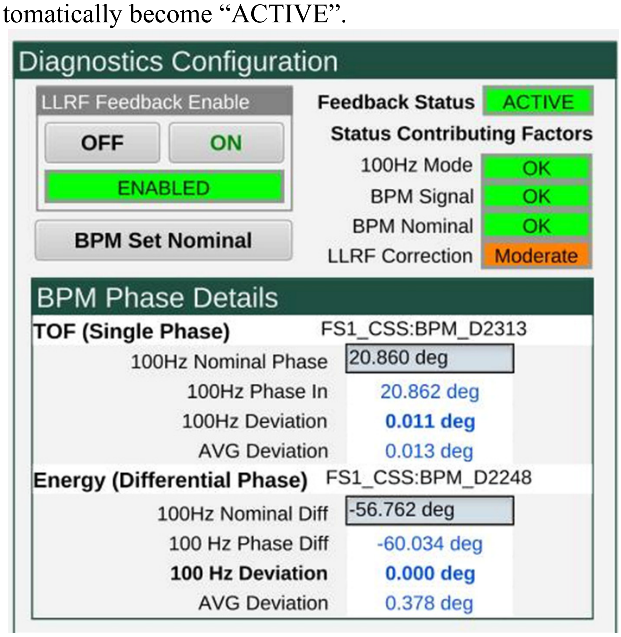

Figure 4: Beam energy and arrival phase regulation user interface.

FUTURE DEVELOPMENT

The next step for this effort is to train the operators to use the provided user interface. Once operators become familiar with the tool, the feedback will be activated during experiments. The beam energy and phase stability will be closely monitored to evaluate the effectiveness of the feedback control. We plan to monitor beam losses in the linac with feedback enabled, and we expect to see measureable improvements in beam energy stability and reduced beam losses.

SUMMARY

FRIB started running user experiments two years ago and has been increasing the beam power steadily. As the beam power gets higher, beam loss has to be well controlled. The imperfection in the uniformity and stability of the charge stripping media is a source of energy variation that can cause significant beam loss through the FS1 and downstream pre-tuned linac. To address this issue, a beam phase monitoring feedback solution was developed. Two BPMs between the charge stripper and the MGB01 are used to provide beam energy and arrival phase information and the phases of two SRF cavities are used to correct any variation. The feedback is done through Ethernet communication and software, minimizing the development effort by not requiring extensive FPGA firmware updates. Initial test results show the proposed solution works well, with a response time of about 0.1 s. A user interface has been developed and we look forward to enabling this energy stabilization feedback for all high power beam operation in the near future.

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