A LOW-LEVEL RF CONTROL SYSTEM FOR A QUARTER-WAVE RESONATOR*

J. W. Kim, D. G. Kim Institute for Basic Science, Daejeon, Korea
C. K. Hwang, Korea Atomic Energy Research Institute, Daejeon, Korea

Abstract

A low-level rf control system was designed and built for an rf deflector, which is a quarter wave resonator with a resonance frequency near 88 MHz. Its required phase stability is approximately ±1° and amplitude stability less than ±1%. The control system consists of analog input and output components, and a digital system based on an FPGA for signal processing. It is a cost effective system, while meeting the stability requirements. Some basic properties of the control system were measured. Then the capability of the rf control has been tested using a mechanical vibrator made of a dielectric rod attached to an audio speaker system, which induced regulated perturbation in the electric fields of the resonator. The control system is flexible such that its parameters can be easily configured to compensate for disturbance induced in the resonator.

INTRODUCTION

The low-level rf (LLRF) system is a control device to stabilize electromagnetic fields of the rf resonators used for electron and ion beam applications. A quarter-wave resonator was built to deflect a secondary electron beam to measure the longitudinal beam emittance of a low-energy ion beam [1, 2]. Stability required for the resonator in measuring the charge distribution of a beam bunch is around ±1° in rf phase and ±1% in amplitude, respectively.

The LLRF system is composed of analogue components in the front ends and a digital signal processing board using a field programmable gate array (FPGA), which is controlled by software based on Windows OS. The feedback loop in the FPGA needs a large phase margin to avoid loop instabilities. This kind of approach utilizing both analog and digital devices have successfully been applied to different accelerator systems [3], which often asks for more strict rf stabilities. A major merit of this system is that the rf components are readily available as commercial products employing a simple architecture, and thus curtails its cost. The properties of the LLRF system were first measured with signals generated using an attenuator to replace the pick-up signal of the cavity.

The test of the LLRF was performed using the vibrator and a model rf deflector which has a fundamental resonance frequency at 87.9 MHz in the deflection mode. The frequency of disturbance induced for testing is less than a hundred Hz because this low frequency range corresponds to resonance bandwidth for the mechanical structure similar to that of the rf deflector [4].

Numerical simulations have been performed using MATLAT tools [5] to test control methods such as one using ESO (extended state observer) and simple PID. We plan to adapt this LLRF system to use for superconducting cavities operating around at 80 MHz with further works on simulation and testing.

CHARACTERISTICS OF LLRF SYSTEM

Figure 1 shows a schematic circuit diagram of the LLRF system designed and constructed, and a photo of the components connected. The method that we chose utilizes both digital and analogue components. An analogue IQ demodulator (Analog Device model 8348) is used to convert the pick-up signal into I (in phase) and Q (quadrature phase) signals.

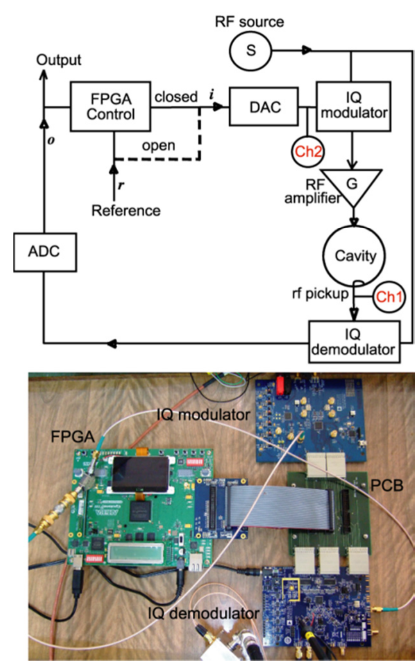

Figure 1: Upper: Schematic diagram of the LLRF system, Lower: Photo of the LLRF system showing major components. A printed circuit board (PCB) used for cable connections is also shown on the photo.

A detailed connection scheme describing the actual components used in the circuit is shown in Fig. 2. The

*Work supported by National Research Foundation Grant No. 20110018946 and by the Rare Isotope Science Project.
jwkim@ibs.re.kr

input signals are digitized by using AD 9204 analog to digital converter (ADC), and fed into the FPGA of CYCLONE III evaluation board (Altera Corp.) for signal processing. The processed signal is converted by using a digital to analog converter (DAC) AD9743, and is fed into IQ modulator (Analog Device ADL5385) to generate the control signal for the rf amplifier. The reference signal is provided by the rf source that is used to accelerate an ion beam for its longitudinal emittance to be measured. The maximum IQ gain and phase imbalances of the demodulator in use are ±0.25 dB and ±0.5∘, respectively, while the imbalances for the IQ modulator are lower.

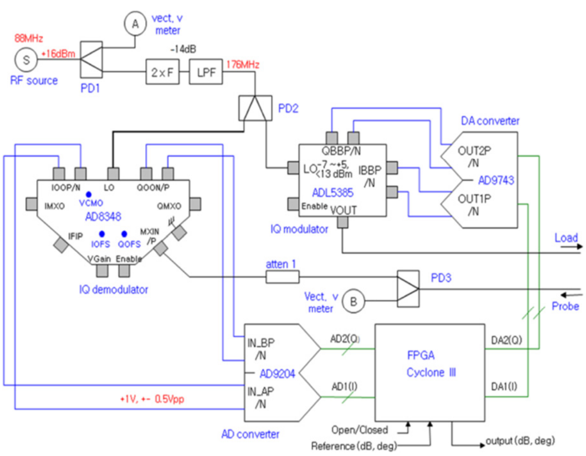

Figure 2: A detailed circuit diagram of the LLRF system.

The response of the LLRF system from the onset of disturbance, which was a change in amplitude, was checked as shown in Fig. 3. The clock of the FPGA is set as 50 MHz, and the time is counted as the number of clock cycle. The total delay for the test unit was roughly 30 cycles, *i.e.*, 0.6 μs. In this delay, about 0.5 μs came from hardware and 0.1 μs from software processing. Also, an additional delay can occur if signal processing is not performed at every clock cycle. The control loop of the amplitude induced some fluctuation at the beginning of the test, which later decayed. This result shows the transient behavior of the resonator at the disturbance. Both the amplitude and the phase change in the transient state even when the amplitude alone is disturbed. The control in steady state kept the phase variation to less than ±1∘. The phase control is independent of the amplitude control. Stabilization of the phase disturbance was also confirmed by inducing a pure phase disturbance. The reponse became smoother with averaging during software processing.

The properties of the LLRF system were first measured using the rf signals obtained with an attenuator to replace the signal from the cavity pick-up. Figure 4 shows the signals on the oscilloscope for the two modes of the loop circuit. The control signal matching the disturbance signal, which is produced by a signal generator, is shown when the loop is closed. Ch. 1 measures the error signal, and the signal shown on the open-loop disappears when the loop is closed. Ch. 2 gives the signal to control the error, which has the same frequency as that of the error signal. Noise shown on Ch. 1 in the closed-loop, which induced fluctuations in the control signal initially, was mainly generated by the mixers in the IQ demodulator. This noise was later reduced when the resonator was connected and can be reduced by installing a low-pass filter on the IQ demodulator.

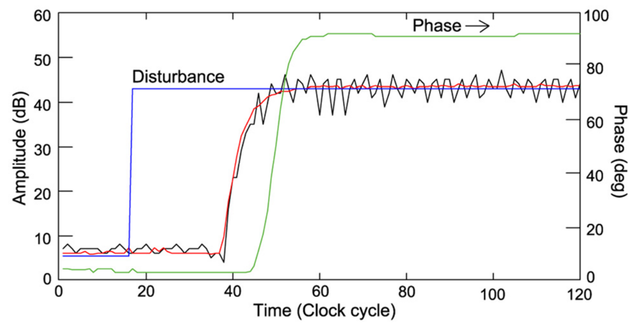

Figure 3: Controls of the amplitude and the phase by the LLRF system against a disturbance versus the time measured as clock cycle of the FPGA.

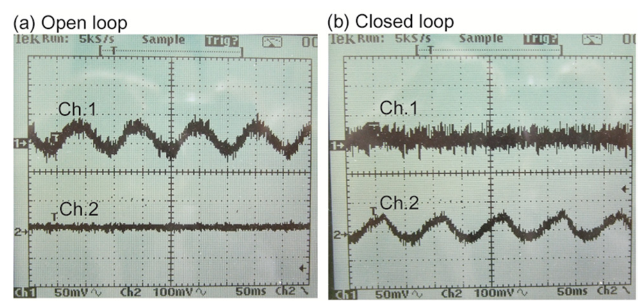

Figure 4: (a) Signals on the oscilloscope measured at two channels denoted in Fig. 1 when the loop is open, (b) when the loop is closed.

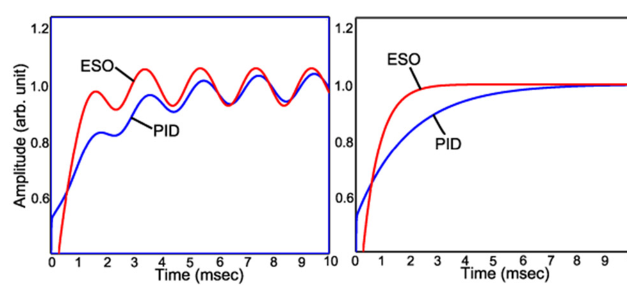

Figure 5: Comparison between ESO and PID methods. (Left) when the resonance frequency is adjusted to see variation on circuit parameters, (Right) when circuit parameters are fixed.

Different control methods have been tested by numerical simulations using MATLAB tools for the ESO and PID methods. Figure 5 shows the responses for the two kinds of disturbances, (1) when the circuit parameters

ISBN 978-3-95450-122-9

are fixed, and (2) when the resonance frequency is adjusted. It was observed that the response is slower for the PID when disturbance is a step function, but faster with small slow variation on the circuit parameters.

TEST OF THE LLRF USING A VIBRATION DEVICE

The LLRF system was tested using a full-scale model of the rf deflector, which was built prior to constructing the actual unit [1]. The resonance frequency of the lowest out-of-phase mode is 87.9 MHz, and the quality factor (Q value) measured is around 970. For the mechanical structures of the cavity having resonance frequency of around 90 MHz, major part of perturbation energy spectrum lies in the frequency range of less than 100 Hz [4]. In addition, main vibrational frequency of the support system is also expected to be less than 100 Hz. To perturb the system in the range of tens of Hz up to several hundred Hz, we devised a vibrating system driven by an audio speaker and amplifier system. The amplifier system was fed by a frequency generator.

The vibration test has been carried out at different frequencies, which were induced by a dielectric rod with a diameter of 3.0 mm firmly attached to the speaker system. The end of the rod is located between two plates of the deflector. The bead-pull method [6] was used to map the electric fields along the beam path inside the rf deflector. The shift of the frequency measured by using a Network Analyzer was 0.02 MHz when a bead made of Acetal with a diameter of 3.6 mm was inserted to the region between the two deflection plates, where the electric field is nearly uniform and its strength higher than in other region.

The control signals of the phase and amplitude when the purturbing frequencies are 20 Hz, 60 Hz and 100 Hz, are shown in Fig. 6. Noise is greatly reduced as the cavity is connected to the rf circuit as 50-MHz noise of the clock is filtered out by the cavity since its lowest resonance frequency is around 88 MHz. The steps shown in the amplitude signal corresponds to single bit of the DAC, meaning the error is controled to the hardware limit. A larger number of bits is needed for the control with a higher resolution. Also, a lowpass filter can be installed on the IQ demodulator at the cost of signal amplitude. A loss of signal intensity by 10 dB is usual, and thus an addiationl rf amplifier is needed.

The deflector system was well stabilized for the induced disturbances by the LLRF. The tests were performed againt much larger disturbances than usually occuring in the rf deflector system firmly fabricated and supported. There are some spikes appearing in the control signals in continous run, which will be addressed for further stable operation.

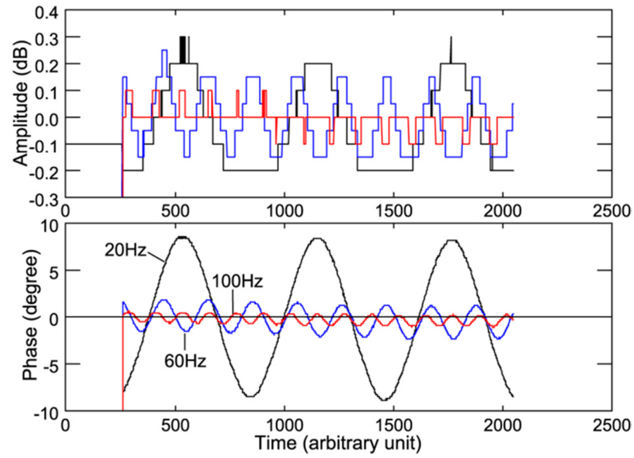

Figure 6: Upper: Amplitude signals needed for the corrections at three different frequencies of disturbance generated by a vibrating rod. Lower: Phase signals for the corrections. The same colors correspond to the same disturbance frequencies.

SUMMARY

An LLRF system has been designed based on analogue front ends and a digital processing board utilizing an FPGA. The system meets stability requirements for the rf deflector constructed for the bunch-length measurement of a low-energy ion beam. The system has been tested using a model rf-deflector cavity and by inducing controlled perturbation using an audio speaker system with a dielectric rod attached in the resonant frequency range of the cavity mechanical structure. Software to adjust the delay time and so forth can be easily configured to effectively control the perturbation, which varies the electric fields inside the cavity. It is a low cost system that can be used to control the rf fields of resonators operating in the frequency range of around 90 MHz.

REFERENCES

[1] J.-Y. Kim, D. Kim, H. Bhang and J. Kim, “A detector system for measurement of the longitudinal bunch shape of a CW ion beam”, J. Korean Phys. Soc. 58, 234 (2011).

[2] J.-Y. Kim et al., “Development of a bunch length detector”, Proc. of the Linac Conf., Tsukuba, Japan, Sep. 12-17, 2010, p. 617 (2010).

[3] H. Hassanzadega et al., “Low level rf system for the European spallation source’s Bilbao linac”, Phys. Rev. ST, 14, 052803 (2011).

[4] A. Facco, ”Mechanical mode damping in superconducting low β resonators” Proc. of 1997 Workshop on RF Superconductivity, Padova, Italy, Oct. 6-10, p. 685 (1997).

[5] MATLAB is a product of MathWorks, Inc.

[6] T. Wangler, Principles of RF Linear Accelerators, John Wiley & Sons, Inc., New York, 1998.