EVALUATION OF DIGITAL LLRF CONTROL SYSTEM PERFORMANCE AT STF IN KEK

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Abstract

The Superconducting RF Test Facility (STF) at the High Energy Accelerator Research Organization (KEK) was built for research and development of the International Linear Collider (ILC). Several digital low-level radio frequency (LLRF) control systems were developed at the STF. The purposes of these developments are to construct a minimal configuration of the ILC LLRF system and achieve the amplitude and phase stability of the accelerating field in the superconducting accelerator. Evaluations of digital LLRF control systems were conducted during the conditioning of eight superconducting cavities performed between October and November 2016. The digital LLRF control system configured for ILC was demonstrated and the performance fulfilled the required stability criteria of the accelerating field in the ILC. These evaluations are reported in this paper.

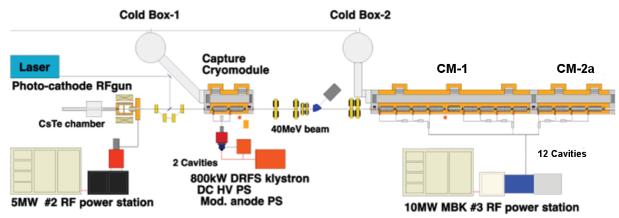

Figure 1: STF layout consists of normal conducting photocathode RF gun, two superconducting 9-cell cavities in the capture cryomodule driven by 800 kW klystron, eight superconducting 9-cell cavities (cavity number 1 ~ 8) in the CM-1 cryomodule, four superconducting 9-cell cavities in the CM-2a cryomodules (cavity number 9 ~ 12). Both CM-1 and CM-2a cryomodules are driven by one 10 MW multi-beam klystron.

INTRODUCTION

A field programmable gate array (FPGA)-based digital low-level radio frequency (LLRF) control system will be employed in the International Linear Collider (ILC) to achieve the radio frequency (RF) stability requirements. The amplitude and phase stabilities of 0.07 %(RMS) and 0.35 °(RMS), respectively, are required for ILC [1]. For the acceleration, the ILC utilizes 1.3 GHz superconducting RF cavities, operating at an average gradient of 31.5 MV/m. The RF system will be organized in approximately 400 RF stations. Each RF station is composed of one 10 MW multi-beam klystron driving 39 superconducting cavities. The feedback control is implemented to compensate the non-repetitive disturbance and measurement noise. As only a single klystron is used to drive 39 cavities, the digital LLRF control system has to control the vector sum of the accelerating field of those cavities. The vector sum is the sum of the complex vectors representing the accelerating fields of all cavities.

The size of one RF station in the ILC is approximately 60 m in length, which may add a delay to the signal transmission from cavity to digital LLRF control system. One possible solution to reduce this problem is to distribute the LLRF control system into several sub-systems, in a master–slave configuration. The slave LLRF control systems calculate partial vector sums from the corresponding cavities and are placed near the cavities to shorten the signal transmission lines. The partial vector sums from all slave LLRF control systems are sent to the master LLRF control system via an optical communication link. One issue in this connection is the additional delay to the control loop caused by optical communication link, which may lead to system instability.

This paper presents an evaluation of the digital LLRF control system with a master–slave configuration and an investigation to confirm the effect of the optical communication link delay on the RF stabilities. The demonstration of the minimum setup of digital LLRF control system with the master–slave configuration for the ILC was conducted at Superconducting RF Test Facility (STF)-High Energy Accelerator Research Organization (KEK) during the cavity conditioning in the autumn of 2016. The layout of the STF is illustrated in Figure 1. A total of twelve cavities in two cryomodules, CM-1 and CM-2a, were installed as the STF-2 project [2].

DIGITAL LLRF CONTROL SYSTEM WITH MASTER–SLAVE

The LLRF control system with master–slave configuration will be adopted in ILC. Figure 2 shows the proposed system for one RF station. As a slave, the LLRF front-end controller calculates a partial vector sum from the corresponding cavities and the result is sent to the central LLRF controller as a master, where the total vector sums are calculated and the klystron output are controlled. In order to accommodate large data transfer from the front-end to the central system, an optical communication link is used.

The minimum setup of the digital LLRF control system with master–slave configuration for ILC was built at STF-

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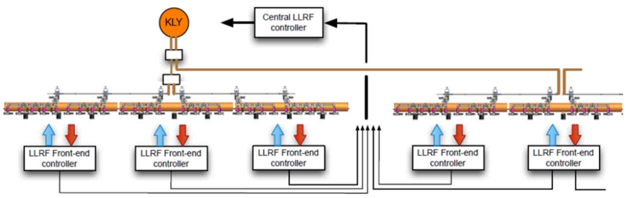

Figure 2: Digital LLRF control system with master–salve configuration for the ILC. As a slave, the LLRF front-end controllers directly measure the signals from corresponding cavities and send the result to central LLRF controller as a master [1].

KEK, which is illustrated in Figure 3. The 1300 MHz signals from the cavities are down-converted by mixing with 1310 MHz local oscillator (LO) to get a 10 MHz intermediate frequency (IF). After being digitized by the analog-to-digital converter (ADC), the IF signal is converted into an *in-phase* component (I) and *quadrature-phase* component (Q) [3]. In the slave digital LLRF board, the partial vector sum of VS2 from corresponding cavities are calculated and sent to the master digital LLRF board through an optical communication link with an approximate length of 20 m. In the master digital LLRF board, the total vector sum from partial vector sum of VS1 and VS2 is calculated. The delay introduced by the optical communication link can be compensated by introducing an additional delay in the partial vector sum of VS1 through the DLY module. To suppress the parasitic modes in the multi-cell cavities, a fourth-order conjugate poles digital infinite impulse response (IIR) filter [4] with a bandwidth of 250 kHz was implemented after the total vector sum calculation. The feedback and feedforward control algorithms are also performed in the master LLRF board. The digital signal is then converted into analog by a digital-to-analog converter (DAC) and is fed to the I/Q modulator to modulate the 1.3 GHz RF signal from the master oscillator (MO). This signal is then used to drive the klystron, which drives the cavities.

Both master and slave board are MTCA.4 standard hardware with 14-ch 16-bit AD9650 ADC (Analog Device, Inc.), 2-ch 16-bit AD9783 DAC (Analog Device, Inc.), and two FPGAs, Zynq-7000 and Spartan 6 (Xilinx Inc.). These boards employ 162.5 MHz for FPGA clock and 81.25 MHz for ADC/DAC clock.

MEASUREMENT SETUP

The motivation for the following measurement is to estimate the delay caused by the optical communication link. Because only the partial vector sum VS2 is subjected to the delay caused by the optical communication link, it must be compensated by giving an additional delay to partial vector sum VS1. The delay is added through the DLY module, to a similar extent as the optical communication link delay. To estimate the length of this delay, the measurement setup in Figure 4 was used. The forward signal (P_f) is fed to the

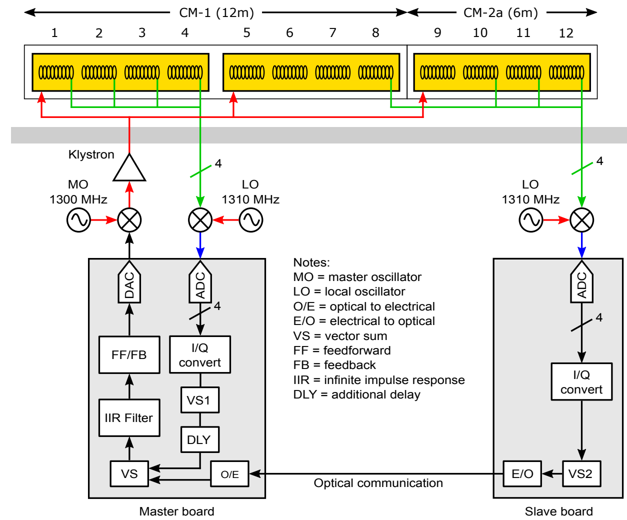

Figure 3: Simplified diagram of minimum setup of digital LLRF control system with master–slave configuration at STF-KEK. VS1 is the partial vector sum from the cavities connected to the master board. VS2 is the partial vector sum from the cavities connected to the slave board.

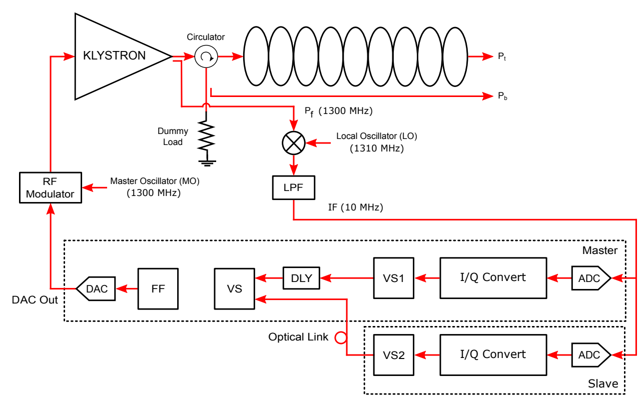

Figure 4: Measurement setup for estimating optical link communication delay.

master and slave boards. The DLY value is changed from 50–115 clocks with an interval of 5 clocks. The squared area from 4–8 μs shown in Figure 5(a) was calculated for every value of DLY and the normalized value is shown in Figure 5(b). The estimated delay is defined as a minimum value, which is 88.3 clocks. Therefore, the delay of 88 clocks was added to the DLY module. As the system clock frequency is 162.5 MHz, the delay corresponds to approximately 540 ns.

The motivation for the following measurement is to compare the RF stability between systems with and without the optical communication link delay. During the cavity conditioning, only eight cavities of number 1,2,3,4, and 8 in CM-1 cryomodule and number 10,11, and 12 in CM-2a cryomodule were utilized because the other cavities (number 5,6,7, and 9) had performance degradation [5]. Two kinds of setup

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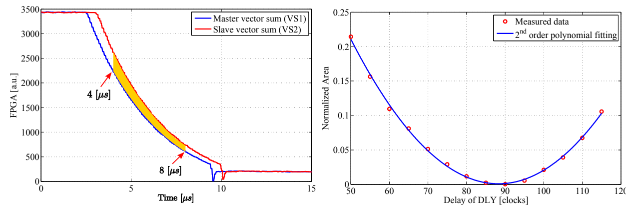
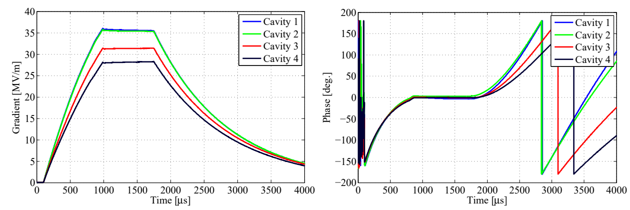


(a) Forward signal (b) Normalized squared area

Figure 5: Optical communication link delay estimation.



(a) Amplitude (b) Phase

Figure 6: Amplitude and phase of cavity no. 1,2,3, and 4. The mean flattop gradients of each cavity are Cavity 1 = 35.8 MV/m, Cavity 2 = 35.6 MV/m, Cavity 3 = 31.3 MV/m, and Cavity 4 = 28.0 MV/m.

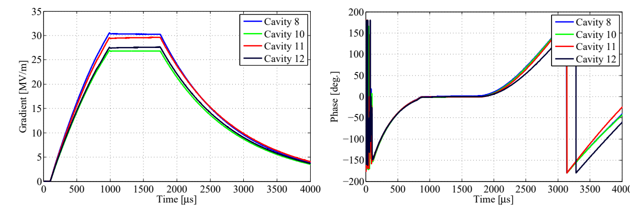
were constructed. In the first setup in which the optical link communication delay was involved, the signals from cavity number 1,2,3, and 4 were connected to the master board and the signals from cavity number 8,10,11, and 12 were connected to the slave board. In the second setup, in which the optical link communication delay was not involved, all cavity signals were connected to the master board.

PERFORMANCE EVALUATION

For setup 1, Figures 6, 7, and 8 show the waveform of the amplitude and phase, of the master partial vector sum, slave partial vector sum, and total vector sum, respectively. The amplitude and phase flattop of the total vector sum are shown in Figures 9(a) and 9(b), respectively.

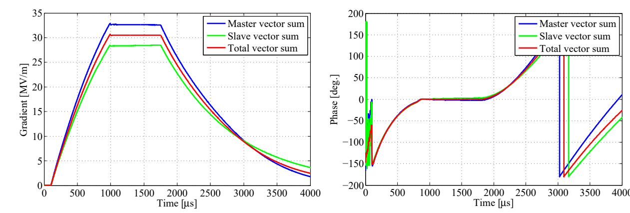
In order to discard any overshoot at the leading edge of the flattop, only 1000–1600 μs were considered for the stability calculation. The stabilities were calculated from 20 data. The amplitude and phase stabilities are 0.006%(RMS) and 0.027 °(RMS), respectively. The 30.5 MV/m cavity gradient can be achieved. Both the feedback and feedforward control were implemented. The feedback gain is approximately 150. A fourth-order conjugate poles digital IIR filter with the bandwidth of 250 kHz was implemented.

In setup 2, all cavity signals were fed to the master board inputs. This implies that, in the control loop, there is no additional delay caused by optical communication link in this setup. Table 1 lists the results of the two setups. Both setups could achieve similar stabilities. It can be concluded that the additional loop delay caused by the optical communication link does not affect the stability in the case of no beam.



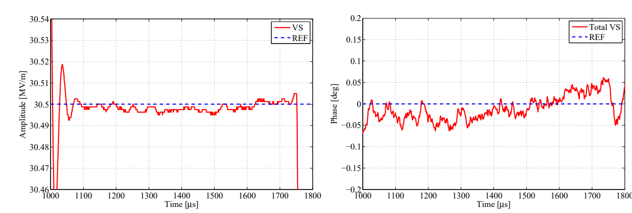
(a) Amplitude (b) Phase

Figure 7: Amplitude and phase of cavity no. 8,10,11, and 12. The average flattop gradients of each cavity are Cavity 8 = 30.3 MV/m, Cavity 10 = 26.8 MV/m, Cavity 11 = 29.5 MV/m, and Cavity 12 = 27.5 MV/m.



(a) Amplitude (b) Phase

Figure 8: Amplitude and phase of partial vector sum from slave and master and total vector sum. The average flattop gradient are *Master vector sum* (VS1) = 32.6 MV/m, *Slave vector sum* (VS2) = 28.4 MV/m, and *Total vector sum* = 30.5 MV/m



(a) Amplitude (b) Phase

Figure 9: Flattop of vector sum with filter bandwidth of 250 kHz.

Table 1: RF Stability Result of Two Kinds of Setup

Setup	Connected Cavity Master	Connected Cavity Slave	Stability Amp [%(RMS)]	Stability Pha [°(RMS)]
1	1,2,3,4	8,10,11,12	0.006	0.027
2	1,2,3,4,8,10,11,12	-	0.008	0.027

SUMMARY

We demonstrated at STF-KEK the minimum setup of the digital LLRF control system with a master–slave configuration for the ILC. The achieved stabilities were 0.006 %(RMS) and 0.027 °(RMS) in amplitude and phase, respectively, which can fulfill the ILC requirements. The experiments show that the delay introduced by optical communication link in the master–slave configuration does not have any effect on the RF stabilities in the case of no beam.

The master–slave configuration may be implemented for digital LLRF control system in the ILC.

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