IF-MIXTURE PERFORMANCE DURING CAVITY CONDITIONING AT STF-KEK

Sigit Basuki Wibowo*, The Graduate School for Advanced Studies, Kanagawa 240-0193, Japan
Toshihiro Matsumoto, Shinichiro Michizono, Takako Miura, Feng Qiu,
KEK, 1-1 Oho, Tsukuba, Ibaraki 305-0801, Japan

Abstract

The Superconducting rf Test Facility (STF) at High Energy Accelerator Research Organization (KEK) was built for research and development of the International Linear Collider (ILC). In order to satisfy the stability requirement of the accelerating field, a digital low-level RF (LLRF) control system is employed. In this control system, signal from a cavity is down-converted into intermediate frequency (IF) signal before being digitized by analog-to-digital converter (ADC). In order to reduce the required number of ADCs, we proposed a technique that combines several IFs and to be read by a single ADC. Signal reconstruction of each IF is performed by digital signal processing. The performance of this technique, which is named IF-mixture, is reported in this paper.

INTRODUCTION

Superconducting rf Test Facility (STF) at High Energy Accelerator Research Organization (KEK) was built for the purpose of research and development related to International Linear Collider (ILC). The RF is 1.3 GHz with a pulse duration of 1.5 ms and a repetition rate of 5 Hz. An RF stability of 0.07 % (RMS) in amplitude and 0.24° (RMS) in phase are required for the ILC [1]. Because of such a long pulse duration, a digital low-level RF (LLRF) control system may be adopted.

In one RF station of ILC, a single klystron drives 39 cavities. In order to fulfill the accelerating field stability requirements, a digital LLRF control system based on a field programmable gate array (FPGA) board will be installed to control the RF field with vector-sum feedback (FB). Therefore, the amplitude and phase (or I and Q components) of all 39 cavities must be measured to calculate vector-sum. Furthermore, the RF waveform of drive power and reflection power from all the cavities must be monitored to ensure stable operation of the ILC RF station.

In the digital LLRF control system, RF signal from the cavity is down-converted into intermediate frequency (IF) signal by mixing with 1.31 GHz local oscillator (LO). After the down-conversion process, the amplitude and phase information of the signal are still preserved. This signal is then digitized by an analog-to-digital converter (ADC), as shown in Figure 1(a). The I and Q components of the RF signal are determined by digital signal processing (DSP). For a single ILC RF station, the digital LLRF control system requires approximately 120 ADCs.

* sigitbw@post.kek.jp

One possible way to reduce the number of ADCs is to combine several IF signals, to be read by a single ADC, and reconstruct each IF signal by DSP. This technique is named IF-mixture. In our research, we have combined up to four IF signals, thereby reducing the required number of ADCs by a factor of four. Fig. 1(b) shows the example of the technique with two IF signals.

The IF-mixture technique with vector-sum FB control applied to four cavities was successfully developed at STF-KEK [2–4]. Recently, the IF-mixture was developed to accommodate 16 inputs for one board. Vector-sum FB control with eight cavities will be evaluated during STF operation from October to November 2016.

IF-MIXTURE TECHNIQUE

In IF-mixture, several IFs are combined and read by one ADC. Given an input signal containing a number K of IF signals, the combined signal can be written as

$$X(t) = \sum_{i=1}^{K} \left\{ I_i(t) \cdot \cos\left(\omega_{\mathrm{IF}_i} t + \varphi_i\right) \right\} - \sum_{i=1}^{K} \left\{ Q_i(t) \cdot \sin\left(\omega_{\mathrm{IF}_i} t + \varphi_i\right) \right\} \quad (1)$$

where i is the index of the i^{th}-IF signal, $X(t)$ is the combined signal, $I_i(t)$ is the I-component of the i^{th}-IF, $Q_i(t)$ is the Q-component of the i^{th}-IF, φ_i is the phase offset of the i^{th}-IF, and $\omega_{\mathrm{IF}_i} = 2\pi \cdot \mathrm{IF}_i$. In IF-mixture technique, the sampling rate (SR) of the ADC and the frequency of i^{th}-IF must satisfy the condition $L \cdot \mathrm{IF}_i = N_i \cdot \mathrm{SR}$ (L is an integer greater than 3 and N_i is an integer). In IF-mixture, the selection of IF is

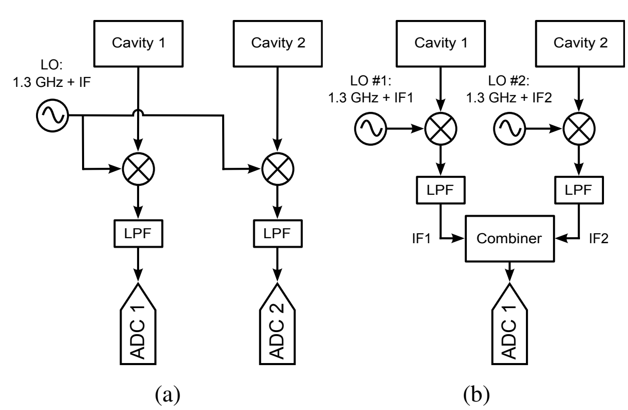


Figure 1: Digital LLRF system schematic: (a) Typical system with single IF and (b) IF-mixture with two IF signals.

ISBN 978-3-95450-169-4

crucial. The L and N must be selected properly so that the I and Q components of each IF signal can be estimated from the combined signal.

The I and Q components of each IF signal can be numerically calculated using the following formula [5]

$$I_i = \frac{2}{L} \sum_{n=0}^{L-1} X(n) \cos\left(\frac{2\pi \cdot N_i}{L} \cdot n\right) \tag{2}$$

$$Q_i = \frac{2}{L} \sum_{n=0}^{L-1} X(n) \sin\left(\frac{2\pi \cdot N_i}{L} \cdot n\right) \tag{3}$$

where $X(n)$ is the sampled data of the combined signal, I_i is the I-component of the i^{th}-IF, Q_i is the Q-component of i^{th}-IF, and N_i is the N value of i^{th}-IF.

IF SELECTION

To combine the IF signals, a passive power combiner is used. The practical power combiner has some level of non-linearity, which can produce intermodulation distortion. The frequency produced by intermodulation will interfere the IF signal of interest if both signals exist at the same frequency.

Our target is to use up to four IF signals. We use an ADC SR of 81.25 MHz. The IFs must be selected carefully to minimize the intermodulation distortion. We choose $L = 18$, so that the possible values of N are 1,2,3,4,5,6,7, and 8.

We evaluated the second-order intermodulation distortion by choosing the combination of $(L, N_1, N_2, N_3, N_4) = (18, 1, 2, 3, 4)$. Two-tone signals were input to the combiner (ZMSC-4-1 from Mini Circuits, Inc.) and the results are shown in the Table 1. IF_1 is the most affected by second-order intermodulation products when the inputs to combiner are IF_2&IF_3 and IF_3&IF_4. The difference between the IF signals used as input and those unused is approximately 40 dB.

Table 1: Magnitude at Combiner Output with Two-Tone Signal to Investigate Second-Order Intermodulation Products

Input	Magnitude at Output [dBFS]			
	IF_1	IF_2	IF_3	IF_4
IF_1 & IF_2	−20.92	−10.61	−82.32	−85.92
IF_1 & IF_3	−20.93	−80.00	−20.73	−82.44
IF_1 & IF_4	−20.95	−85.18	−76.84	−12.30
IF_2 & IF_3	−61.75	−10.63	−20.37	−87.21
IF_2 & IF_4	−83.74	−10.67	−84.47	−12.02
IF_3 & IF_4	−59.08	−80.90	−20.58	−11.79

In order to minimize the second-order intermodulation distortion, the use of subsequent IF signals must be avoided. Hence, we select the combination of $(L, N_1, N_3, N_5, N_7) = (18, 1, 3, 5, 7)$. The L value must be selected to avoid the second order intermodulation products that exist at the frequencies between (SR/2) and SR. The L value must

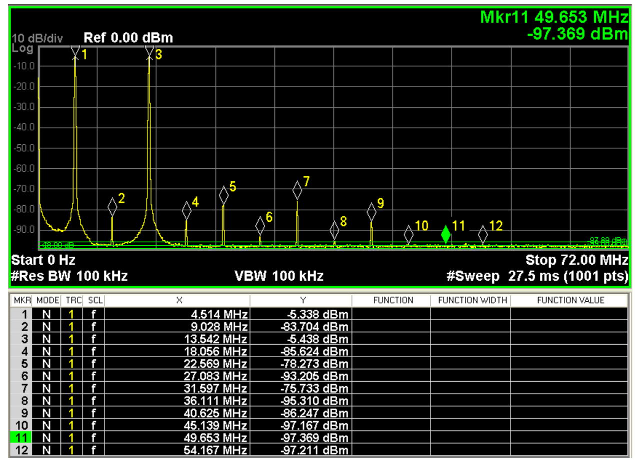


Figure 2: Example of the spectrum analyzer result from the combiner output when the inputs are IF_1 and IF_3

be chosen as even to avoid those intermodulation products folding back at the IFs of interest. Furthermore, the distance between IFs should be sufficiently wide and the filters for IFs should be commercially available. The selected $L = 18$ fulfilled the aforementioned considerations.

We evaluated the effect of third-order intermodulation products of the selected combination by giving two-tone to the combiner input. The power levels of all IFs are evaluated at the combiner output with a spectrum analyzer, the results of which are shown in the Table 2. We see that the difference between the IF signals used as input and those unused is approximately 70 dB for all combinations. One example of the frequency spectrum of the combiner output when the inputs are IF_1 and IF_3 is shown in Fig. 2.

Table 2: Power at Combiner Output with Two-Tone Signals to Investigate Third Order Intermodulation Products

Input	IFs Power Level at Output [dBm]			
	IF_1	IF_3	IF_5	IF_7
IF_1 & IF_3	−5.34	−5.44	−78.27	−75.73
IF_1 & IF_5	−5.47	−76.82	−5.56	−78.59
IF_1 & IF_7	−5.42	−89.48	−78.61	−5.76
IF_3 & IF_5	−73.47	−5.40	−5.45	−74.49
IF_3 & IF_7	−78.09	−5.72	−97.64	−5.89
IF_5 & IF_7	−87.60	−68.47	−5.13	−5.15

Based on the evaluation of second-and third-order of intermodulation products, we select the combination of four IFs as follows $IF_1 = 4.5$ MHz, $IF_3 = 13.5$ MHz, $IF_5 = 22.5$ MHz, and $IF_7 = 31.5$ MHz. This combination has less effect of intermodulation products, compared to the subsequent IFs combination.

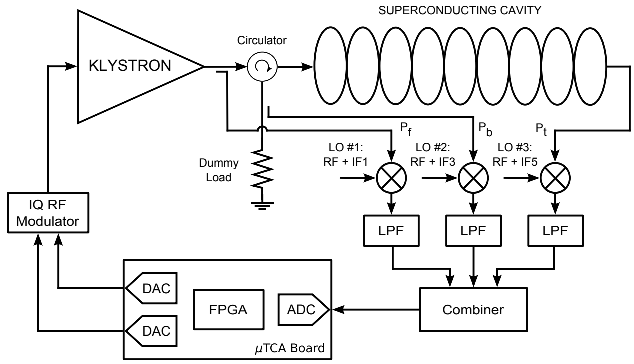
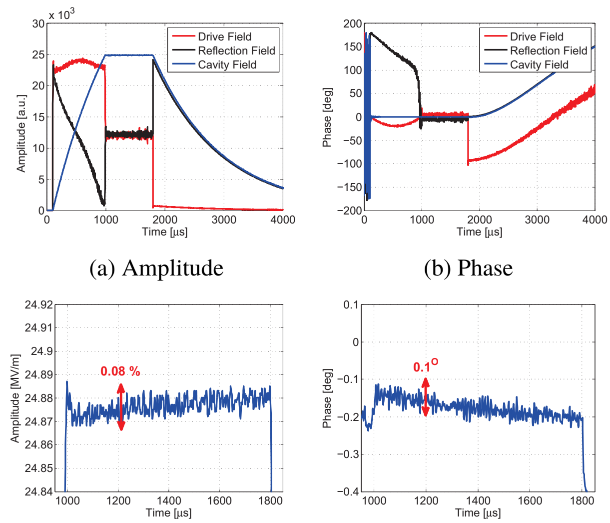


Figure 3: Simplified schematic of digital LLRF control system configuration. 600 kW klystron is used to drive the cavity with 5×10^6. The cavity gradient is 25 MV/m. The IF signals of the drive field (P_f), reflection field (P_b), and cavity field (P_t) are combined.



(a) Amplitude (b) Phase

(c) Amplitude (d) Phase

Figure 4: (a) and (b) show the waveform of amplitude and phase of IF-mixture technique, respectively. The results show that IF-mixture can retrieve the drive field (P_f), reflection field (P_b), and cavity field (P_t) from the combined signal as expected. (c) and (d) show the flattop of cavity field.

DIGITAL FEEDBACK SYSTEM

IF-mixture was implemented on µTCA hardware [6]. It consists of four 16-bit ADC LTC2208 (Linear Technology, Inc.), four 16-bit DAC AD9783 (Analog Devices, Inc.), a Virtex FPGA XC5FX70T (Xilinx, Inc.), and a Power PC with Linux installed. Four IFs are combined by a power splitter/combiner ZMSC-4-1 (Mini Circuits, Inc.). A total 16 IF signals can be read by this board. In order to distribute the ADC sampling clock and various frequencies for the LOs, a frequency divider AD9510 (Analog Devices, Inc.) is used.

IF-mixture evaluation was conducted during the cavity conditioning at STF-KEK between September and December of 2015. Each cavity was conditioned at the maximum gradient before quenching. The average accelerating gradient was 30 MV/m [7]. The cavities each have a loaded Q_L of 5×10^6 and are driven by a 600 kW klystron. The system configuration for employing the IF-mixture is shown in the Fig. 3. The IF signal of the drive field, reflection field, and cavity field are combined.

FEEDBACK PERFORMANCE

The waveform (amplitude and phase) of drive field, reflection field, and cavity field of IF-mixture are shown in the Figs. 4(a) and 4(b). The gradient was set to 25 MV/m. The IF-mixture technique can retrieve each signal from the combined signal as expected. The IF-mixture performed proportional feedback control. The proportional gain is approximately 200. This gain is calculated from the difference between the set point and the average of the measured flattop. To discard any overshoot at the leading edge of the flattop, only 1200 – 1700 µs of flattop is considered for the stabilities calculation. The stabilities including the tilt are 0.015 % (RMS) and 0.018° (RMS) in amplitude and phase, respectively. The amplitude and phase cavity field flattops are shown in Fig. 4(c) and 4(d), respectively.

The performance of IF-mixture technique was also compared to the typical system with single IF. For a fair comparison, both systems are treated as signal monitoring, as shown in Fig. 5. The feedback system was another board, namely a cPCI board [8,9]. The cPCI board features a Xilinx Virtex II pro FPGA, ten 16-bit ADC (LT2208), and two 14-bit DAC (AD9764).

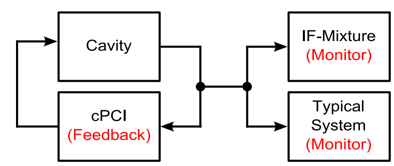


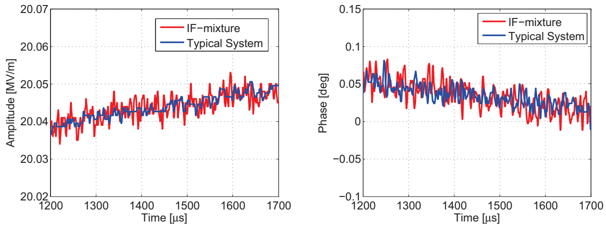
Figure 5: Measurement setup for comparison between IF-mixture and typical system with single IF. For a fair comparison, both systems are set to signal monitoring. Feedback with proportional control is performed by another board, namely a cPCI board [8, 9].

The flattop result is shown in the Fig. 6. The IF-mixture technique can achieve stability of 0.019 % (RMS) in amplitude and 0.018° (RMS) in phase. A typical system with a single IF can achieve stability of 0.015 % (RMS) in amplitude and 0.014° (RMS) in phase. The tilt is included in the stability calculation. These results show that the stability of IF-mixture is the same order as that of typical system with single IF, and therefore, the IF-mixture technique can fulfill the ILC stability requirements.

SUMMARY

The IF-mixture technique was developed at STF-KEK. Combined signal can be separated into their constituent IFs, as expected. Under feedback control operation, the ampli-

ISBN 978-3-95450-169-4



(a) Amplitude (b) Phase

Figure 6: Comparison of flattop of cavity field between IF-mixture and a typical system with single IF.

tude and phase stabilities are 0.015 % (RMS) and 0.018° (RMS), respectively. This stability results can fulfill the ILC requirement, and therefore the IF-mixture technique is can be applied in the ILC. In the next STF operation, eight cavities will be operated simultaneously, and vector-sum feedback control with IF-mixture technique will be evaluated.

REFERENCES

[1] "ILC Technical Design Report", http://www.linearcollider.org/ILC/?pid=1000895.

[2] T. Matsumoto *et al.*, "Development of Digital Low-Level RF Control System using Multi-Intermediate Frequencies", in *Proc. PAC'07*, New Mexico, USA, 2007.

[3] T. Matsumoto *et al.*, "Performance of Digital Low-Level RF Control System with Four Intermediate Frequencies", in *Proc. LINAC'08*, Victoria, Canada, 2008.

[4] T. Matsumoto *et al.*, "Digital Low-Level RF Control System with Four Intermediate Frequencies at STF", in *Proc. PAC'09*, Vancouver, Canada, 2009.

[5] M. Grecki *et al.*, "Estimation of IQ Vector Components of RF Field", in *Proc. 12th Int. Conf Mixed Design of Integrated Circuits and Systems*, 2005.

[6] T. Miura *et al.*, "Low-Level RF System for cERL", in *Proc. IPAC'10*, Kyoto, Japan, 2010.

[7] Y. Yamamoto *et al.*, "High Gradient Cavity Performance in STF-2 Cryomodule for the ILC at KEK", in *Proc. IPAC'16*, Busan, Korea, 2016.

[8] S. Michizono *et al.*, "Performance of Digital LLRF system for STF in KEK", in *Proc. LINAC'08*, Victoria, Canada, 2008.

[9] S. Michizono *et al.*, "Digital LLRF System for STF S1 Global", in *Proc. IPAC'10*, Kyoto, Japan, 2010.