PROTOTYPE PERFORMACE OF DIGITAL LLRF CONTROL SYSTEM FOR SUPERKEKB

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Abstract

For the SuperKEKB project, a new LLRF control system has been developed to realize high accuracy and flexibility. It is an FPGA-based digital RF feedback control system using 16-bit ADCs, which works on a μTCA platform. The performances of a prototype of the LLRF system were evaluated. The measured results of the feedback control stability, temperature characteristics and cavity-tuner control will be presented, and future issues will be discussed in this report.

Sufficient performance of feedback control was obtained. However, the temperature dependence was not small for the requirement. The countermeasures for the temperature drift were implemented in the FPGA.

INTRODUCTION

SuperKEKB is a new upgrade project to make the luminosity of the KEKB accelerator 40 times higher[1]. In order to obtain this high luminosity, the nano-beam scheme will be adopted at the interaction point; accordingly, low-emittance beam will be required. Furthermore, the stored beam current should be approximately twice as high as in KEKB. For high-current and high-quality beam acceleration without instability, accuracy and flexibility in accelerating field control are very significant. Therefore, a new digital low level RF (LLRF) control system was developed for SuperKEKB. It is planned that the existing LLRF systems used for KEKB operation will be replaced by new ones, step by step.

The accelerating frequency of the storage ring is about 508.9 MHz (CW operation). Required stability in accelerating fields is ±1% in amplitude and ±1° in phase. For the LLRF system, our target value of the stability is less than ±0.3% in amplitude and ±0.3° in phase.

For acceleration, both normal conducting (NC) cavities and superconducting (SC) cavities are used. In the final design, 26 NC cavities and 8 SC cavities will be installed. The NCC, which is called ARES [2], has a unique structure for KEKB in order to avoid the coupled-bunch instability [3][4]. ARES is a three-cavity system: the accelerating (A-) cavity is coupled with a storage (S-) cavity via a coupling (C-) cavity. For the LLRF system, concurrent auto tuner control of both the S- and the A-cavities is also a significant function.

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NEW LLRF SYSTEM FOR SUPERKEKB

Figure 1 shows a picture of a newly developed digital LLRF system for SuperKEKB. It has three 19-inch racks. The main components are placed in the left-side rack. The digital control is performed by μTCA-based FPGA boards and a PLC (EPICS-Sequencer) [5]. EPICS-IOC on Linux OS is embedded in each of them [6]. They can be operated remotely via EPICS-channel access. Hardware is common for both the ARES and SCC. (Also the software of both cavities is much the same.) EPICS record names will be consistent with the present systems. For SuperKEKB, one klystron drives one cavity unit, so one LLRF system controls one cavity unit.

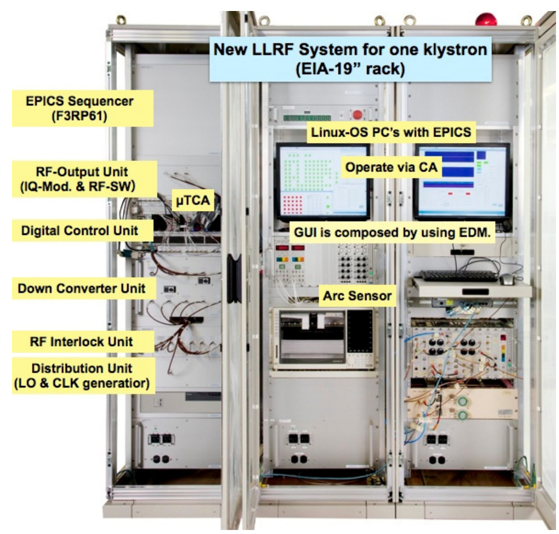

Figure 1: Prototype of the LLRF system for SuperKEKB.

Figure 2 shows the μTCA-platform digital control unit. It has 3 FPGA boards, designated A, B, and C. Board A performs cavity feedback (FB) control. The Board B controls the cavity tuner. Board C is the interlock controller; it also monitors RF level and cavity VSWR for the interlock. Each FPGA board has 4-channel 16-bit ADC and DAC.

A block diagram of the LLRF control (the digital feedback control and the tuner control) for the ARES cavity is shown in Figure 3. The RF amplitude and phase are modulated by an I/Q modulator. RF monitor signals are down-converted into 10-MHz IF signals with LO signal, then, the IF signals are sampled by ADC on the FPGA board at quadruple the frequency of the IF.

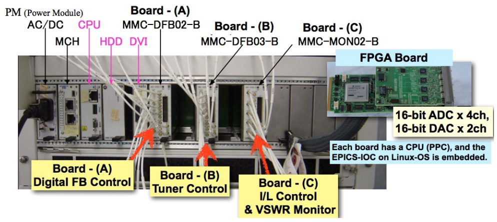

Figure 2: Picture of the µTCA crate and FPGA boards. Three FPGA boards are installed.

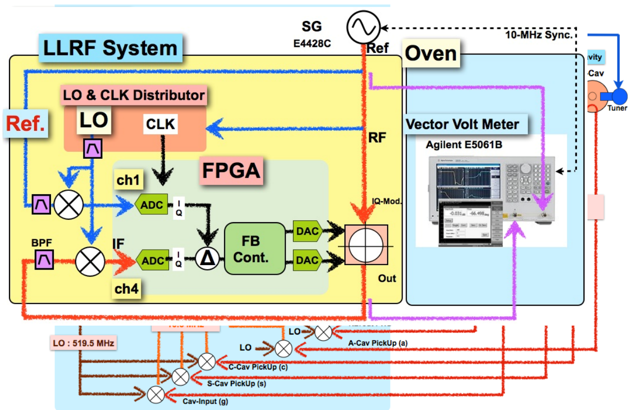

Figure 3: Block diagram for ARES cavity control.

I/Q components are directory obtained. Phases can be easily calibrated by calculation of I/Q rotation. Then proportional-integral FB control is applied to the I/Q modulation: this technique has become standard for digital RF control recently. In the FPGA, the selector chooses between the klystron output monitor and the A-cavity pickup signal; then just one of the two is stabilized. LO and CLK signals are generated from the reference signal by dividing and mixing in the distribution unit.

For ARES, two tuners, for the S- and A-cavities respectively, should be controlled concurrently. The tuner controller FPGA monitors 4 signals: cavity input, S-cavity pickup, C-cavity pickup and A-cavity pickup. The FPGA measures the tuning phase of the two cavities, and directly generates a pulse train to drive a tuner motor.

Also the beam signal from the DCCT is monitored, and I/Q offsets can be flexibly controlled for beam loading compensation. The "μ = -1 mode" control signal can be combined with output. However, direct FB control is not adopted in the new system. (For the μ = -1 mode and direct FB control, refer to [4].)

For the SCC LLRF control, the piezo tuner controller is also implemented in the FPGA; and it generates analog voltage output for the piezo control.

PERFORMACE EVALUATION

FB Control

The FB control performance was evaluated by using a simulant cavity. The simulant cavity is a coaxial resonator. Loaded Q is about 3000. For the ARES cavity of SuperKEKB, the loaded Q is about 20000 (input coupling is about 5). So, this evaluation condition is more demanding of stability than is real operation.

The results of FB control are shown in Figure 4. These plots show the monitored data by the ADC at FPGA under FB control. Amplitude (left) and phase (right) are plotted. Ten acquisitions' worth of data are superimposed. The sampling is about 1 MHz, and one acquisition has 4000 data points; thus the time duration of this plot is about 4 ms. The results show very good stability: in r.m.s, 0.03% in amplitude and 0.02º in phase.

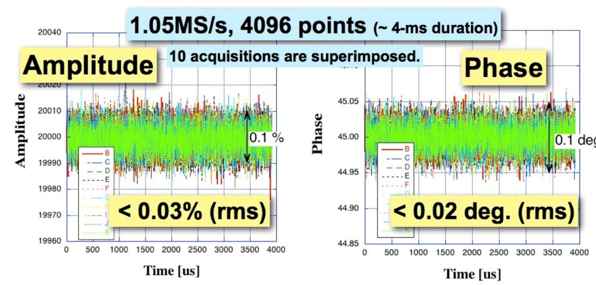

Figure 4: Measurement results of FB control stability using a simulant cavity. The amplitude and phase over a 4-ms duration are plotted.

These results show the internal stability of the loop. The effective system stability should be confirmed by external "outside the loop" measurements on the test system. This evaluation is now going on.

Temperature Dependence

Temperature characteristics are very important for long-term stability. For the LLRF system, our target stability is less than ±0.3% in amplitude and ±0.3º in phase. Therefore, acceptable temperature coefficient is about 0.1% per ºC in amplitude and 0.1 degree of phase angle per ºC in phase, since ambient temperature change is about ±2º C during operation with air conditioning. The temperature coefficient of this LLRF system was measured as 0.6%/ºC in amplitude and 0.25º / ºC in phase, so it does not satisfy the requirements. The bandpass filter (BPF) property is a main factor in the temperature dependence, nonetheless, BPF is essential in LO generation and pick-up RF monitoring.

To improve the temperature dependence, we implemented the compensation technique with the reference signal in the FPGA. That is, the reference signal is directly monitored together with the other channel on the FPGA, and the FB control values will be calibrated with the reference change as shown in Figure 5; thus the BPF's dependence will be cancelled. In the original design, the reference signal was not used for the FB-control, thus the stability directly depends on the BPF of each channel.

The validity of the compensation with the reference was evaluated. The measurement setup is shown in Fig. 5: output signal under FB control was monitored by the Agilent E5061B which works as a Vector Volt Meter (VVM). Figure 6 shows the measurement results. Trend

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graph of the amplitude and phase measured by the VVM during 2 days is plotted with the room temperature in the figure. From this results the temperature coefficient is 0.05%/ ºC in amplitude and 0.07º / ºC in phase; consequently the required stability was satisfied successfully.

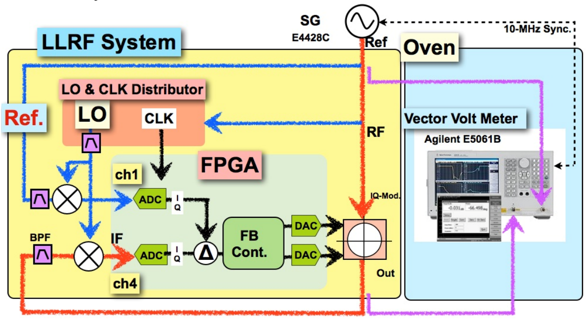

Figure 5: Schematic of setup for temperature dependence evaluation.

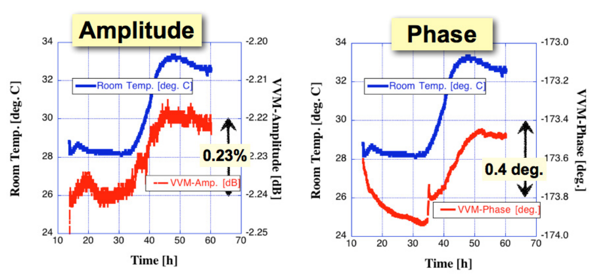

Figure 6: Measured temperature dependence of amplitude (*left*) and phase (*right*) with room temperature change over the course of about two days.

ARES Tuner Control

We tested FB control and auto tuner control by using a real ARES cavity and driver amplifier. This test was driven with just 100 W; the klystron was not used.

Figure 7 shows the running test result of auto tuner control with FB control. This is a trend graph for 2 days. In the figure, cavity tuning phases and the tuner positions of the two cavities (S-cavity and A-cavity) are plotted. ("Tuning phase" means the phase between the input and pickup.) Dashed lines (green and orange) indicate the tuner positions of the S- and A-cavities respectively. The tuners moved slightly to keep tuning. This tuner position change corresponds to about 15º of the storage cavity. Accordingly, tuning phases were controlled to be constant. The concurrent auto tuner control given by the FPGA board for both cavities worked successfully.

SUMMARY

Prototype of a digital LLRF system for the SuperKEKB was developed, and its performance was evaluated. Very good FB performance (stability of 0.03% in amplitude and 0.02º in phase) was obtained; however, the effective system stability should be evaluated by external "outside the loop" measurements on the test system.

The temperature dependence was not negligible with respect to the requirement. By directly compensating FB-control values with a reference signal monitored together with the other channel, the temperature dependence could be cancelled successfully.

Auto tuner control by the FPGA worked successfully for both S- and A-cavities of ARES. Piezo tuner control is not yet tested.

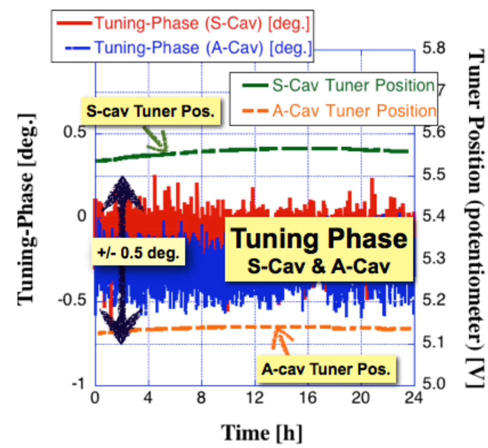

Figure 7: Running test result of auto tuner control of the real ARES cavity under FB control with 100-W driving. The cavity tuning phases and the tuner positions of the S- and A-cavities are plotted.

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