ISBN: 978-3-95450-168-7 doi:10.18429/JACoW-IPAC2015-MOPHA056

STATUS OF LLRF CONTROL SYSTEM FOR SUPERKEKB COMMISSIONING

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Abstract

Beam commissioning of the SuperKEKB will be started in JFY2015. A new LLRF control system, which is an FPGA-based digital RF feedback control system on the MicroTCA platform, has been developed for high current beam operation of the SuperKEKB. The mass production and installation of the new systems has been completed as scheduled. The new LLRF control systems are applied to nine RF stations (klystron driving units) among existing thirty stations.

As a new function, klystron phase lock loop was digitally implemented within the cavity FB control loop in the FPGA, and in the high power test it worked successfully to compensate for the klystron phase change. Beam loading was also simulated in the high power test by using an ARES cavity simulator, and then good performance in the cavity-voltage feedback control and the cavity tuning control was demonstrated to compensate the large beam loading for the SuperKEKB parameters.

INTRODUCTION

SuperKEKB is a new upgrade project, which is aiming at 40-times higher luminosity than the KEKB [1], accordingly it requires much lower-emittance and higher-current beam storage. The first commissioning of SuperKEKB (Phase-1) will start in JFY2015.

Accuracy and flexibility in accelerating field control are very essential for storage of high-current and high-quality beam without instability. Therefore, new low level RF (LLRF) control system, which is based on recent digital architecture, was developed for the SuperKEKB, and the good performance of the prototype was demonstrated in the high power test as reported in Ref. [2]. The existing analogue LLRF systems used for KEKB operation will be replaced by new ones, step by step. In the first commissioning of SuperKEKB, the new LLRF control systems are applied to nine LLRF stations among about thirty stations.

The accelerating frequency of the storage ring is about 508.9 MHz (CW operation). The regulation stability of 0.02% and 0.02º (rms) in the cavity amplitude and phase, respectively, were obtained in the high power test of the LLRF control system [2]; that sufficiently satisfies the requirements.

For the beam acceleration of the main ring (MR), both normal conducting cavities (NCC) and superconducting cavities (SCC) are used. The NCC, which is called ARES

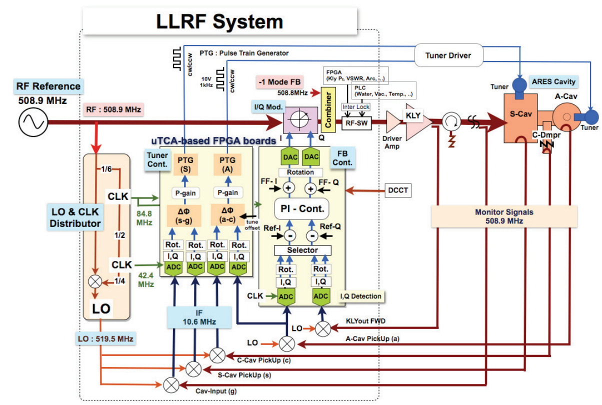

Figure 1: Block diagram for ARES cavity control.

[3], has a unique structure for the KEKB in order to avoid the coupled-bunch instability caused by the accelerating mod [4]. ARES is a three-cavity system: the accelerating (A-) cavity is coupled with a storage (S-) cavity via a coupling cavity.

A damping ring (DR) is newly being constructed at the injection linac for the positron emittance reduction. In the DR, the RF-frequency is the same as that of the main ring (MR), and three cavities, each of which is a HOM-damped single cell cavity (not an ARES type), are driven by one klystron for the acceleration. Thus another LLRF control system for the DR was also designed. It is almost the same as that of the MR, except the three-cavity vector sum control is required.

NEW LLRF SYSTEM FOR SUPERKEKB

Figure 1 shows a block diagram of cavity-voltage (Vc) feedback (FB) control and auto tuner control for the ARES cavity driving for the SuperKEKB. One klystron drives one cavity unit, so one LLRF control system corresponds to one cavity-unit control. The principal functions of this system are performed by five FPGA boards which work on MicroTCA platform as advanced

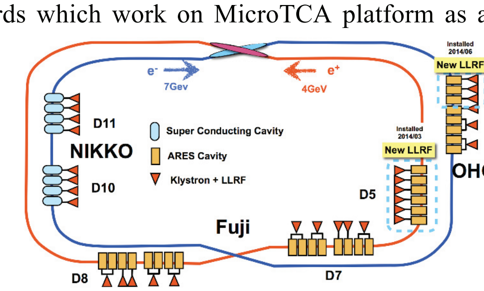

Figure 2: RF system layout for the Phase-1. Nine LLRF stations were replaced with the new ones.

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mezzanine cards [5]: Vc-FB controller (FBCNT), cavity-tuner controller (TNRCNT), inter-lock handler (INTLCNT), RF-level detector for the interlock and arc-discharge photo-signal detector. For slow interlocks (e.g. vacuum, cooling water) and sequence control, a PLC is utilized. EPICS-IOC on Linux -OS is embedded in each of the FPGA boards and the PLC [6]. As shown in Fig. 1, the new LLRF control system handles I/Q components of controlling signals in the FPGAs. Good regulation performance was demonstrated. For detail, refer [2][7].

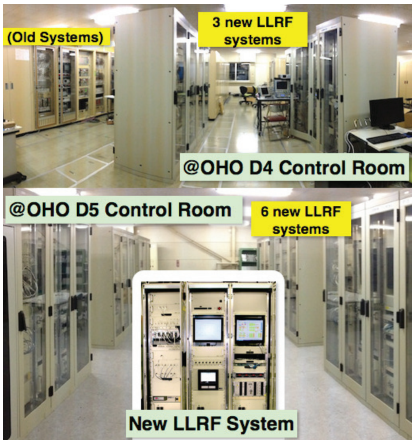

Figure 3: Installation appearance of the new LLRF control systems in the RF control rooms at D4 (upper) and D5 (lower) section.

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Figure 2 shows the arrangement of the RF systems of the MR. As shown in the figure, the new LLRF control systems were installed into nine stations at the control rooms of Oho-D4 and D5 RF sections for the SuperKEKB commissioning. The other stations will be operated by existing systems in the Phase-1. Figure 3 shows the installation appearance of the new LLRF control systems in D4 and D5 control rooms. The cabling was almost completed. The RF cable loss measurement and the overhaul of the old systems were also finished for all stations. Before the Phase-1 start, RF conditioning for all cavities will be started in December 2015.

The new operation interfaces (GUI) for the accelerator operators, which integrate both the new and old systems, should be prepared before the commissioning starts.

The DR-LLRF control system will be produced and installed in JFY2015.

HIGH POWER TEST OF KLY-PLL AND LARGE-BEAM LOADING TEST

As reported in the previous IPAC, 80-deg. phase shift in a klystron output was observed in the high power test [2]. This phase shift is the result of the anode voltage control depending on input power to optimize the collector loss for the efficiency, and it is unexpectedly large. The phase shift (or I-Q coupling) inside the closed loop makes cavity I/Q-FB control unstable.

For the above reason, additional function of klystron phase lock loop (KLY-PLL) was implemented into the FPGA of the FBCNT [7]. It works digitally in the FPGA with the cavity-FB control. Additional phase-rotation function is inserted before the DAC outputs to the I/Q modulator to cancel the phase shift as shown in Fig. 4. The responsivity of the KLY-PLL is designed to be enough slower than the Vc-FB control, because the anode voltage control responsivity is approximately 1 sec.

High power test of the KLY-PLL was performed. Figure 4 shows the setup of the high power test. The klystron output was loaded to the 1.2-MW dummy load. Since according to the SuperKEKB design parameters, required driving power for ARES cavity will be up to 750 kW to provide the beam power at the full-current storage in the electron ring [8], the maximum output power was assumed to be up to 850 kW for the optimization of this test condition, however it is not the saturation power of the klystron. As shown in Fig. 4, the Vc-FB control was also tested by using an ARES cavity simulator [9]; the klystron-output monitor signal was divided into the cavity simulator, then the cavity response signals were simulated by the simulator in real time to be output and monitored by the LLRF control system. This simulator consists of FPGA with an ADC for I/Q-sampling and four I/Q-modulators for the outputs of the three-cavity response of ARES and the cavity reflection. The simulator has nearly 800-ns latency, then, totally the FB loop delay is about 2 μs, which is consistent with the real ARES cavity operation. This cavity simulator can also simulate the beam loading effect and the cavity tuner control.

KLY-PLL Test

Figure 5 shows the klystron input-output characteristics measured under closed loop of the KLY I/Q-FB control and the KLY-PLL control. Red line indicates klystron output power. The 850-kW output power was successfully achieved. The linearity and gain is enough good over the operation range.

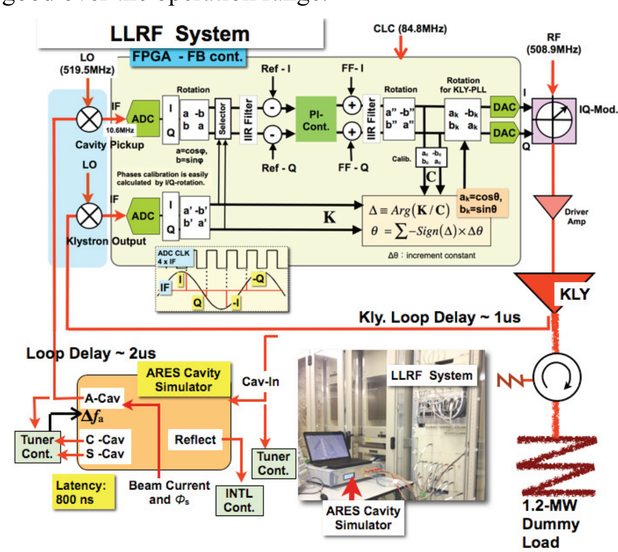

Figure 4: Setup of high power test of KLY-PLL and beam loading test using ARES cavity simulator.

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Blue line indicates the compensated phase by the KLY-PLL; it corresponds to the phase change of the klystron due to the anode control. As the result, KLY-PLL worked successfully over 800-kW range, and 80-degree phase change was compensated completely by the KLY-PLL. Consequently the cavity FB control was quite stable without problem.

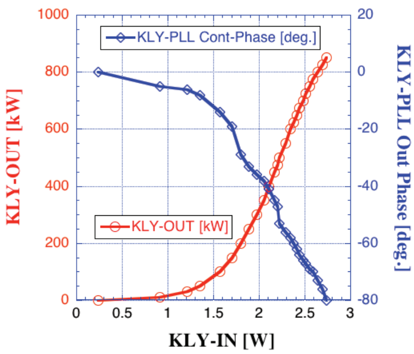

Figure 5: Klystron input-output characteristics measured under closed loop of the I/Q-FB control with the KLY-PLL control.

Beam Loading Simulation Test

According to the design parameters, the coupling factor (β) of ARES cavity is set to be five for the optimum condition: the cavity wall loss is about 150 kW at 0.5-MV acceleration voltage, and the beam power will be about 600 kW at the full-current beam storage [8]. Under such operation condition, the optimum cavity detuning of the A-cavity will be about -180 kHz (-18 kHz for the π/2-mode of ARES) to compensate for the reactive component of the heavy beam loading.

In the high power test for the cavity regulation control test, the beam loading of the full-current storage in the electron ring was assumed in the cavity simulator. The result of the beam loading simulation test under the cavity FB control is shown in Fig. 6. The chart log is plotted as increasing the beam current. As shown in the figure, since the cavity amplitude (blue) and phase (green) were regulated by the FB control appropriately, the klystron output power (red) was increased adequately as the beam current was increased to compensate the beam loading, and then 750-kW output was reached at the maximum

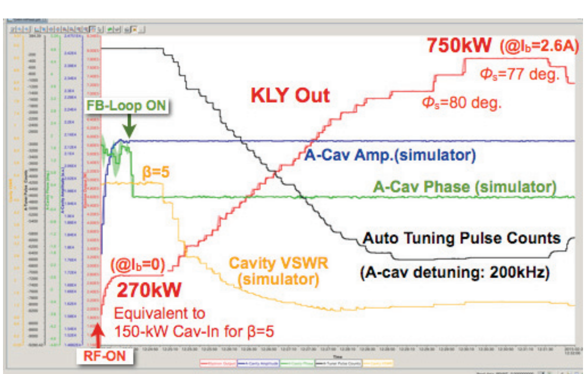

Figure 6: The chart of beam loading simulation test by using ARES cavity simulator under the closed loop for the cavity-voltage regulation control with KLY-PLL.

beam loading successfully. On the other hand the cavity reflection (VSWR, yellow) was decreased as expected. These cavity responses in the plot were made by the cavity simulator in real time. The black line indicates number of output-pulse counts to shift the cavity tuning, which was the result of the automatic tuning control to cancel the reactive component of the beam loading. This tuning change corresponds to nearly -200-kHz detuning of the A-cavity as predicted. At the 750-kW klystron output with the full-current beam loading, the I/Q-FB control for the Vc regulation was very stable even under the large-cavity detuning. From these results, good performance of the Vc regulation control, cavity-tuning control and KLY-PLL was confirmed in the high power test using the cavity simulator with the beam loading simulation for the SuperKEKB operation.

SUMMARY

The beam commissioning of SuperKEKB will be started in JFY2015. The new LLRF control systems developed for SuperKEKB were installed at nine RF stations among about thirty stations, and the cabling was almost completed; they are ready for the operation. The other stations will be operated with existing old systems.

High power test of the KLY-PLL control and the full-current beam loading simulated FB control test was performed over 850-kW RF power range by using the ARES cavity simulator, and they were successfully worked.

Fabrication of another new LLRF control system for DR is scheduled in JFY2015.

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