OPERATION OF LLRF CONTROL SYSTEMS IN SuperKEKB PHASE-1 COMMISSIONING

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Abstract

First beam commissioning of SuperKEKB (Phase-1), which had started in February 2016 and continued until the end of June, has been successfully accomplished. Target beam current for Phase-1 needed for sufficient vacuum scrubbing was achieved in both 7-GeV electron and 4-GeV positron rings. This paper summarizes the operation results related to low level RF (LLRF) control issues during the Phase-1 commissioning, including the system tuning, the coupled bunch instability and the bunch gap transient effect.

RF system of SuperKEKB consists of about thirty klystron stations in both rings. Newly developed LLRF control system, which is composed of recent digital technique, is applied to the nine stations among the thirty for Phase-1. The RF reference signal distribution system has been also upgraded for SuperKEKB. These new systems and the existing old systems worked well without serious problem and they contributed to smooth progress of the commissioning.

INTRODUCTION

As reported in previous conferences, new digital LLRF control systems have been developed to realize high accuracy and flexibility in accelerating field control without instability for SuperKEKB [1, 2]. SuperKEKB is an upgrade project, which is aiming at 40-times higher luminosity than that of KEKB [3]. It is asymmetric energy collier consisting of a 7 GeV electron ring (high-energy ring, HER) and a 4 GeV positron ring (low-energy ring, LER). As the deign values, the stored beam current of 3.6 A in LER is about there times higher than that of KEKB achieved, and then the beam power will be triple. Many components of RF high-power system also have been reinforced to handle such high power beam.

RF system of SuperKEKB consists of about thirty klystron stations in both rings (See Fig. 1). The accelerating frequency of the storage ring is about 508.9 MHz (CW operation). Both normal conducting cavities (NCC) and superconducting cavities (SCC) are used. The NCC, which is called ARES [4], has a unique structure for the KEKB in order to avoid the coupled-bunch instability caused by the accelerating mode [5]. ARES is a three-cavity system: the accelerating (A-) cavity is coupled with a storage (S-) cavity via a coupling cavity.

The first beam commissioning of SuperKEKB (Phase-1) was accomplished in 2016. The RF systems and the new LLRF control systems worked well without serious trouble during the operation. This paper summarizes operation issues related to LLRF control in Phase1. Phase-2 will be started from January 2018.

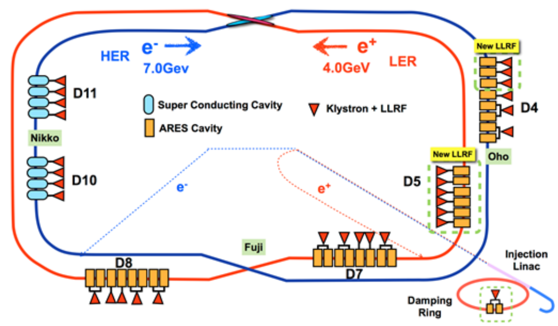

Figure 1: RF system arrangement for Phase-1.

LLRF CONTROL SYSTEM

Figure 1 shows the RF system layout for Phase-1 commissioning. The newly developed LLRF control systems are applied at nine stations at D4 and D5 of Oho section. Figure 2 shows a block diagram of ARES cavity driving system with the new LLRF control system for SuperKEKB. The principal functions of this system are performed by five FPGA boards which work on MicroTCA platform as advanced mezzanine cards (AMCs) [6]: Vc-FB controller (FBCNT), cavity-tuner controller (TNRCNT), inter-lock handler (INTLCNT), RF-level detector for the interlock and arc-discharge photo-signal detector. As shown in Fig. 2, I/Q components of controlling signals are handled in the FPGAs. 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 [7].

On the other hands, the other stations were still operated with existing (old analogue) LLRF control systems,

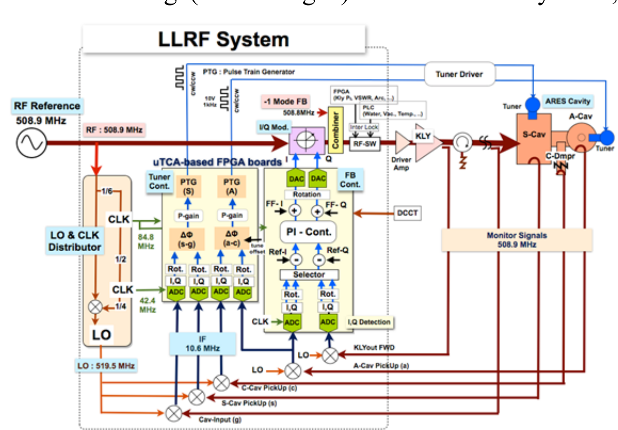

Figure 2: Block diagram for ARES cavity control.

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which had been used in the KEKB operation. These systems are composed of combination of NIM standard analogue modules. They are controlled remotely via CAMAC system. Many old defective modules found in the maintenance works were replaced with spares before the commissioning start.

RF reference distribution system was also upgraded for SuperKEKB [8]. RF reference signal is optically distributed into all RF sections by means of "Star" topology configuration from the central control room (CCR). "Phase Stabilized Optical Fiber", which has quite small thermal coefficient, is adapted. For the thermal phase drift compensation, optical delay line is controlled digitally at CCR for all transfer lines. The short term stability (time jitter) is about 0.1 ps (rms), and the long term stability (pk-pk) is ±0.1° = ±0.55 ps at 508.9MHz (expected by the optical delay control).

OPERATION STATUS OF LLRF CONTROLS IN PHASE-1

Figure 3 shows history of the stored beam current with beam dose (upper side) and the total acceleration voltage called total-Vc (lower side) for the both ring during Phase-1. It had started from 1st February 2016 and continued for five months. After the tuning of the injection-linac and beam transport line optics, on 10th February the first revolution beam was successfully observed in LER as accelerating cavities powered and the RF phases were adjusted. Subsequently the MR commissioning was performed smoothly. Target beam current of ~1A for Phase-1 was successfully achieved in both ring and vacuum scrubbing has been progressed as expected.

All new and old RF systems including RF reference distribution system worked well without serious trouble and provided sufficient accelerating voltage during Phase-1. Some software bugs in LLRF controls found during the operation were fixed.

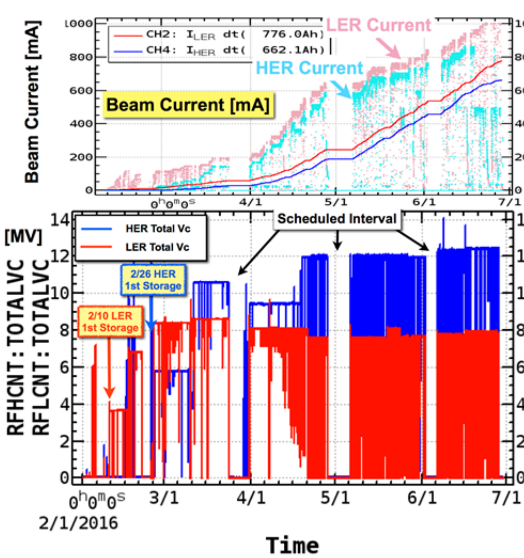

Figure 3: History of the stored beam current, the beam dose (upper side), and the total acceleration voltage called Total-Vc (lower side) for the both ring.

The cavity voltage operated in Phase-1 was 80~90% of the nominal voltage. Mutual phases between RF stations are optimized to obtain higher synchrotron frequency and to make the beam loading of each cavity balanced.

Coupled Bunch Instability

In HER, the μ=-1 mode instability due to the detuned cavities (parked with some reasons) was excited since the stored beam current became over 400-mA. Consequently, the μ=-1 mode damper system, which had been used in KEKB operation [9], was applied to the D4 station. It worked well to suppress the μ=-1 mode successfully as shown in Fig. 4, and the beam current could be increased.

The threshold current of the μ=-1 is about 1.7 A for LER and 1.2 A for HER [10]. In Phase-1, at an earlier stage than expected, the μ=-1 mode damper became needed due to the parked cavities with detuning, the stations of which had some troubles in the RF system.

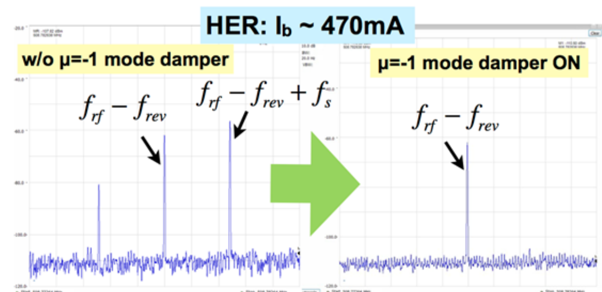

Figure 4: HER beam spectrum at the μ=-1 mode. By applying the μ=-1 mode damper, the couple bunch instability was successfully suppressed.

Bunch Gap Transient Effect

In generally, for a high-current multi-bunch storage ring, a bunch train has a gap of empty buckets in order to allow for the rise time of a beam abort kicker. The empty gap is also effective in clearing ions in electron storage rings. However, the gap modulates the amplitude and phase of the accelerating cavity field. Consequently, the longitudinal synchronous position is shifted bunch-by-bunch along the train, which shifts the collision point of each bunch.

The observed phase-shift due to the bunch gap effect, which was measured along the train in KEKB operation, agreed well with a simulation and a simple analytical formula in most part of the train. However, a rapid phase change was also observed at the leading part of the train, which was not predicted by the simulation or by the analytical form [5]. In order to understand the cause of this observation, we have developed an advanced simulation, which treats the transient loading in each of the three cavities of ARES [11]. The new simulation can reproduce well the observed rapid phase change. Accordingly, it was clarified that the rapid phase change at the leading part of the train is caused by a transient loading in the three-cavity system of ARES: the rapid phase change is attributed to the parasitic (0 & π) modes of ARES.

Figure 5 shows RF-phase transient of the accelerating

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cavity of ARES. It was measured by the new digital LLRF control system in the Phase-1 commissioning. The time interval of 10 microseconds is the revolution period. As shown in the figure, the phase modulation due to the bunch gap transient effect was clearly observed by the new LLRF system, and the rapid phase change caused by the parasitic mode of ARES can be also found at the leading part of the train. The simulation result (dashed red line) agrees well with the measurement. In the simulation, function of feedback control for cavity voltage regulation by LLRF control system is also included. From these results, validity of the new simulation code can evidently confirmed.

From the new simulation study, it is predicted that the rapid phase change caused by bunch gap will be about 6 degrees in cavity field at the design beam current of SuperKEKB. The collision point shift (relative phase difference between the two rings) due to such large phase change could make significant reduction of the luminosity in future collision experiment. The measures to avoid the luminosity reduction have been also proposed by the simulation study [11].

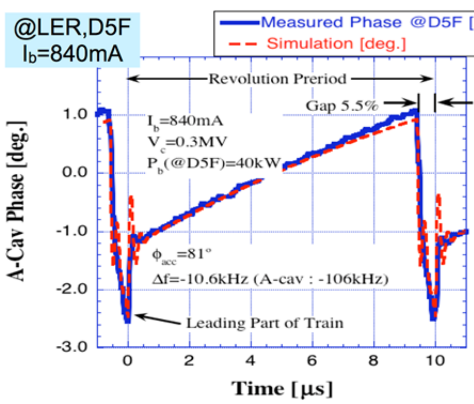

Figure 5: RF phase modulation in the accelerating cavity of ARES (blue line), which was measured by new LLRF control system in Phase-1, and the simulation result are plotted together during the revolution period (dashed line).

CONCERNED ISSUES FOR PHASE-2

We have still some concerned issues for the future operation, because the desired beam current for SuperKEKB will be much higher than achieved in KEKB.

One of the issues is the cavity detuning. At the design beam current, the accelerating cavity detuning of ARES will be about 270 kHz for the optimum tuning. This detuning corresponds to 70-degree phase shift in the cavity transmission (In the KEKB operation, maximum detuning is 170 kHz). Such large phase shift may deteriorate the stability in the cavity-field FB control by I/Q components. In order to mitigate the issue, implementation of additional function in the FB control is under consideration now.

Another issue is coupled bunch instability. The μ=-2 mode instability, which was negligible in KEKB, is predicted to be excited at the design current. Therefore, the μ=-2 mode damper system is additionally required for SuperKEKB. New damper system with new digital filters was developed for Phase-2 [10]. It will be available for μ=-1, -2 and -3 modes in parallel.

SUMMARY

Phase-1 beam commissioning of SuperKEKB was successfully accomplished. Desired beam current in the two rings was achieved and sufficient vacuum scrubbing was progressed. Phase-2 is scheduled in the last quarter of JFY 2017.

Newly developed digital LLRF control systems are applied to 9 stations at OHO section, and successfully worked in Phase-1. For Phase-2, some improvements against heavy beam loading will be implemented in the new LLRF control system.

The μ=-1 mode damper is applied to HER, and the coupled bunch instability due to detuned cavities is suppressed successfully. The μ=-2 and -3 mode damper system is now under development for Phase-2.

The phase modulation due to the bunch gap transient was clearly observed by the new LLRF control system, and validity of the new simulation code for the evaluation of bunch gap transient effect was confirmed. Accordingly, the proposed measures to cancel the large bunch gap transient effect are expected to be effective.

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