Development and Construction Status of New LLRF Control System for SuperKEKB

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Abstract

In this report, the latest design and new progress of the LLRF control system for the SuperKEKB are summarized including the RF reference distribution system.

Beam commissioning of the SuperKEKB will be started in 2015. A new LLRF control system, which is an FPGA-based digital RF feedback control system on the MicroTCA platform, has been developed to satisfy the requirement for high current beam operation of the SuperKEKB. The good performance of the prototype was demonstrated in the high power test with an ARES cavity. Very good FB stability of 0.02% in amplitude and 0.02 deg. in phase was obtained. Auto tuner control also worked successfully.

As a new function, klystron phase lock loop was additionally implemented within the cavity feedback control loop in the FPGA, and it was successfully worked in the low-level operation test. Then the quantity production with some refinements is in progress.

Additionally another new LLRF control system is needed in a damping ring (DR) for the positron injection. In the DR-LLRF system, vector sum control of three cavities is required.

A new RF reference distribution system was also designed for the SuperKEKB. In this system the reference signal will be distributed by means of "Star" configuration into the RF control sections and transferred optically by using the phase-stabilized optical fiber. A new optical delay control system for multi-divided transfer lines was developed by applying the direct IQ sampling method, and the required stability of ±0.1 degrees was obtained.

Upgrade to SuperKEKB

Luminosity : x 40 !

Beam Current: x 2

β_y@IP: x 20 (Emittance: 1/5)

Commissioning Start in 2015!

New LLRF Developed

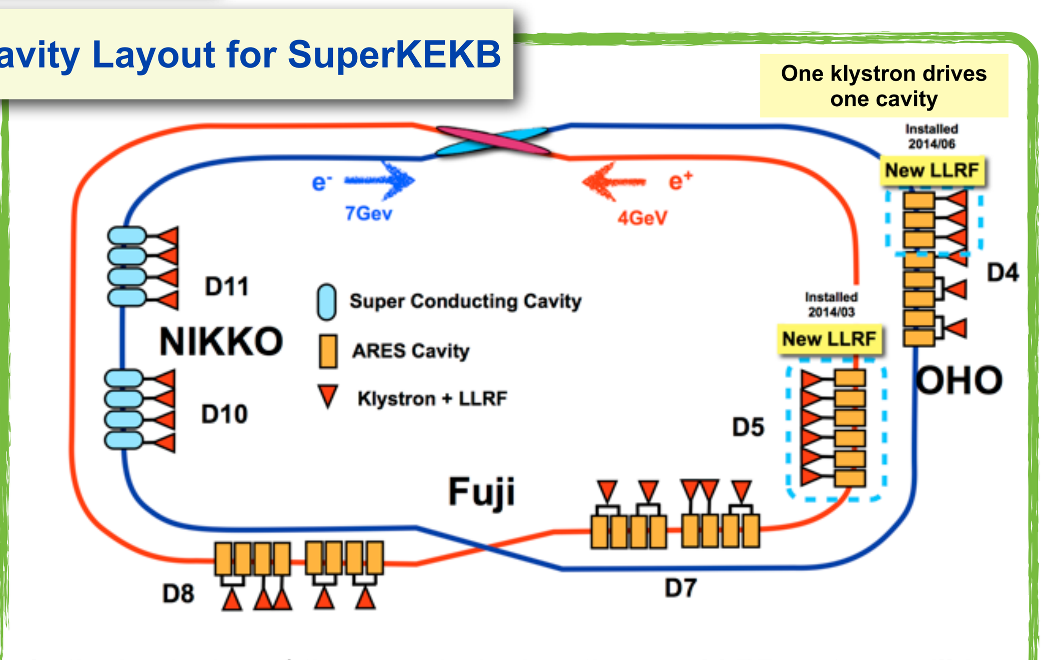
Existing analog systems will be replaced by new digital ones.

RF Stability Requirements

for acc. gradient	+/- 1% +/- 1 deg.
Our target value for LLRF System	+/- 0.1% in Amplitude +/- 0.1 deg. in Phase

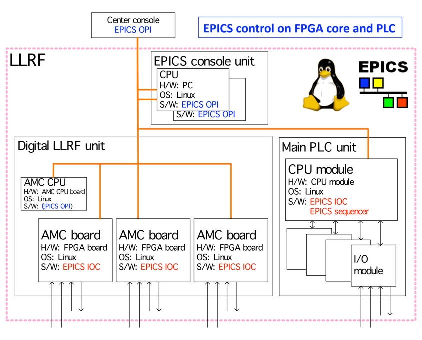
Existing Analog System for KEKB

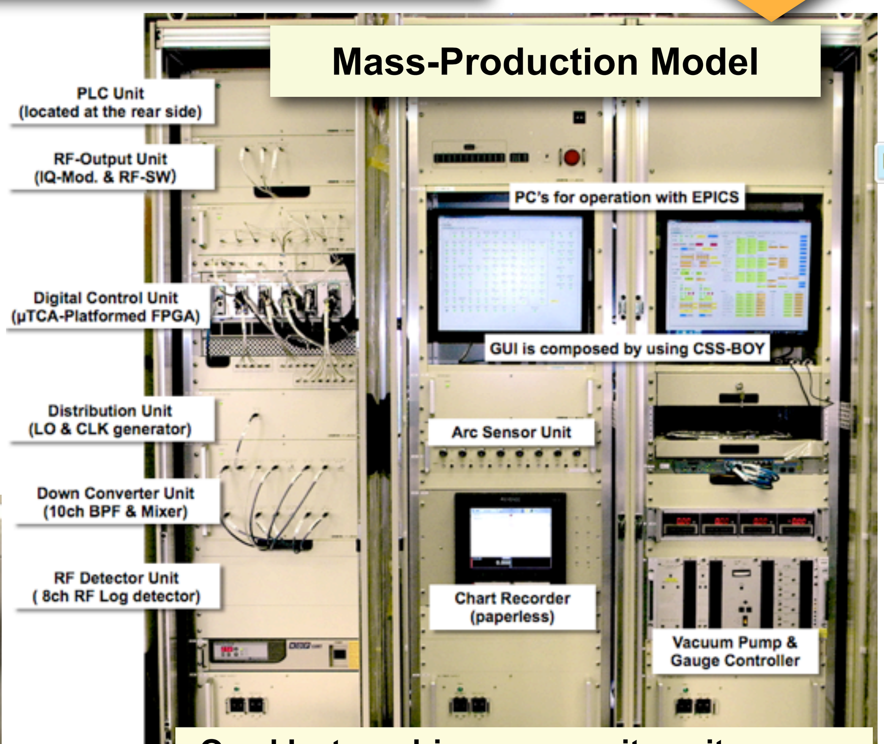
Cavity Layout for SuperKEKB



In the beginning of the commissioning, the new LLRF systems will be applied to nine stations for the ARES cavities at the OHO section

New LLRF System for SuperKEKB



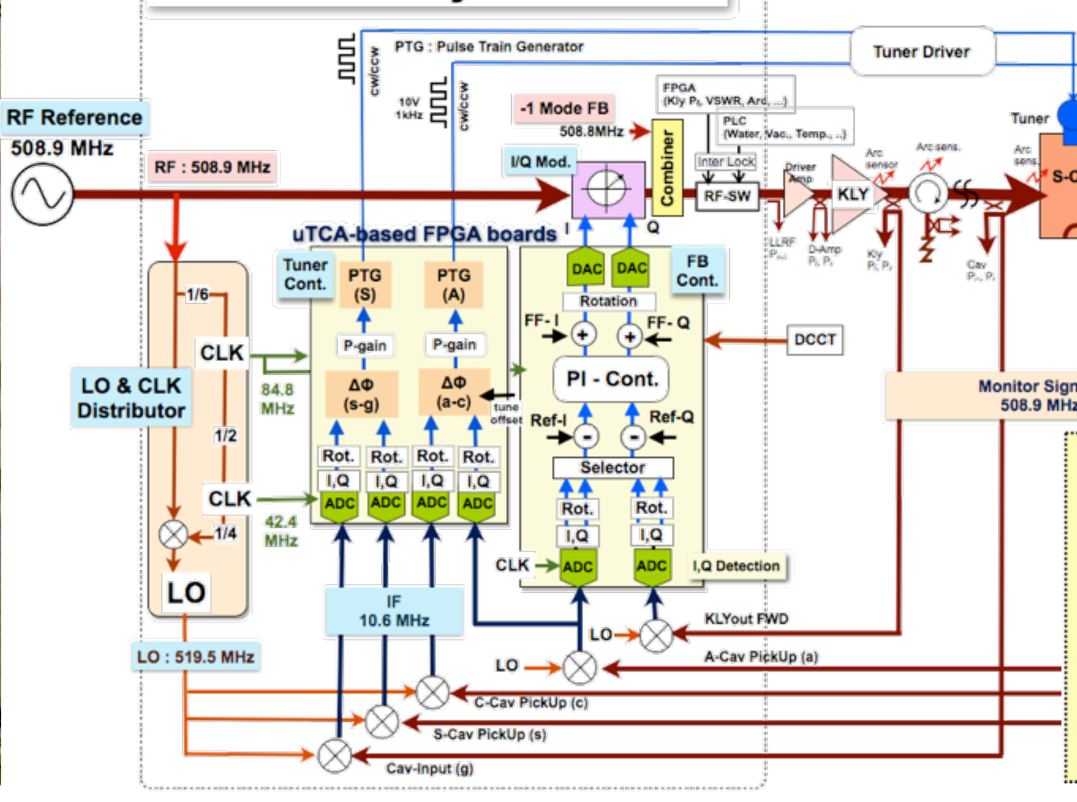


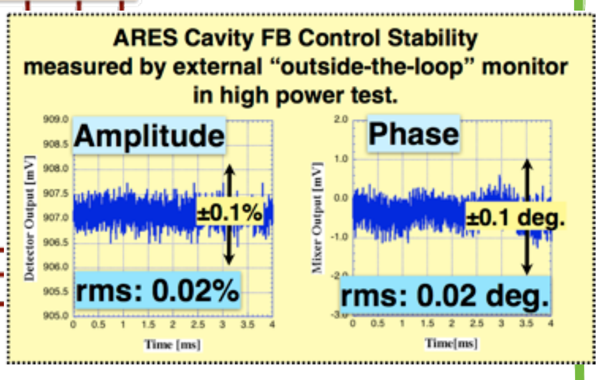
One klystron drives one cavity unit, one LLRF control system corresponds to one cavity-unit control.

MTCA-platform Digital Control Unit

- It consists of μTCA-based FPGA boards & PLC (EPICS-Sequencer).
- Linux-OS with EPICS-IOC is installed into each of them. They can be operated remotely via EPICS-Channel Access.
- Hardware is common for both of ARES & SC Cavity. (Also both softwares are much the same.)
- EPICS record names will be consistence with the present systems.
- Klystrons (LLRF) : Cavity unit = 1 : 1 (SuperKEKB)

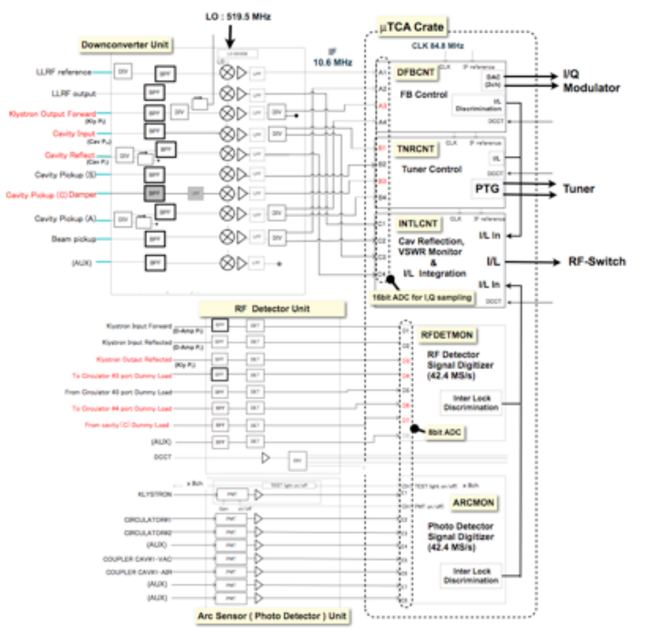
Block diagram for ARES Cavity





Monitoring RF signals are down-converted into 10-MHz IF signals, and then I/Q-sampled by ADCs at the FPGA boards. Proportional-integral (PI) FB control is applied to the vector modulation by the DFBCBT. The "? = -1 mode" control signal can be combined with driving-output for suppression of coupled bunch instability.

For ARES cavity, two tuners of S-cavity and A-cavity are controlled concurrently by the TNRCNT. Besides piezo tuner controller is implemented in the FPGA for SC cavity; it generates analog voltage output for the piezo tuner.



In the digital control unit, five FPGA boards function as MicroTCA-standard advanced mezzanine cards (AMCs) : Digital FB Controller (DFBCNT), Tuner Controller (TNRCNT), Inter-Lock Controller (INTLCNT), RF-Detector Monitor (RFDETMON) and Arc-discharge Monitor (ARCMON).
The DFBCNT, TNRCNT and INTLCNT have 4-channel 16-bit ADCs and DACs. RFDETMON and ARCMON have 8-channel 8-bit ADCs. 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.

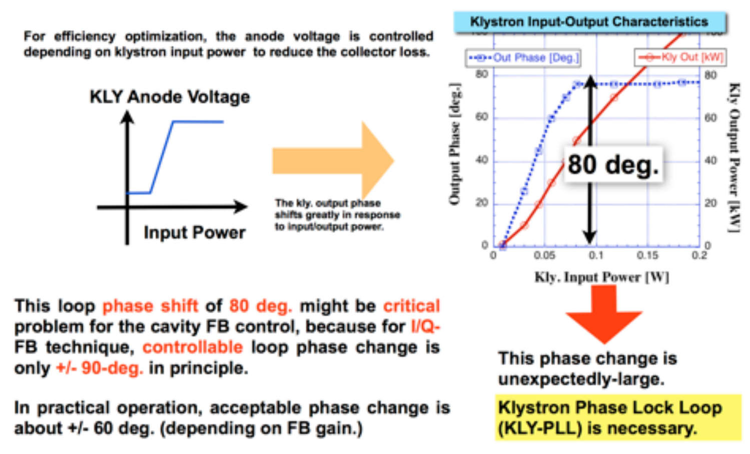
The INTLCNT monitors cavity reflection and the VSWR, and it also summarizes all of the other FPGA's interlock states to switch RF-off. The RFDETMON acquires waveforms of RF log detectors at 42.4 MSPS like an oscilloscope, which makes flexible filtering or discrimination possible for the interlock. External trigger is also available for the acquisition. Similarly, the ARCMON also acquires photo-signals detected by the arc-sensor unit which has 8-channel photo sensors to detect discharge in cavity input coupler, klystron window and circulator.

The photo sensor for the arc-detecton is a high-speed photomultiplier-tube (Hamamatsu Photonics H10720). Large-core optical fibers are used to transfer the discharging flashlight to the arc-sensor unit. The performance of the arc-sensor with the large-core fiber was evaluated, then sufficient sensitivity and responsive property were verified for the arc-detection.

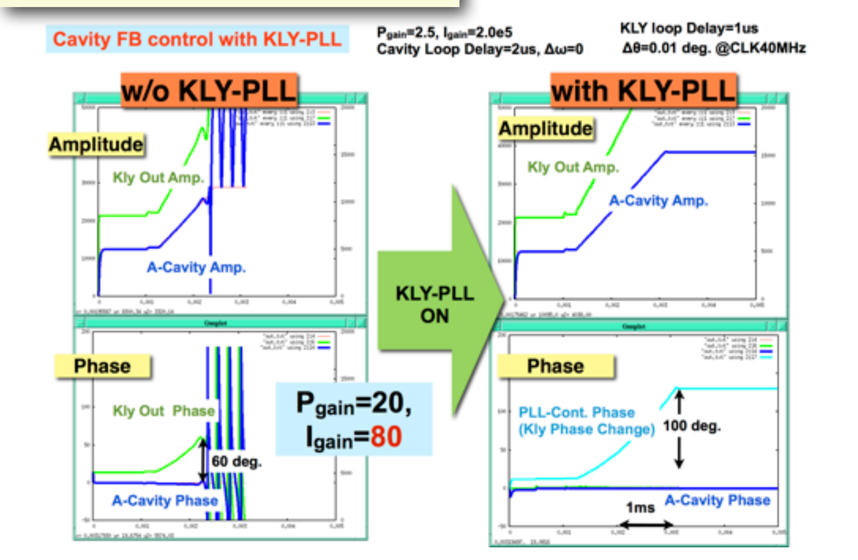
For the mass-production, several refinements from the prototype were applied to the FPGAs; for example, mini-size loose coaxial connectors on the front panel were changed to bundled type by a fixed connector, and also the clock distribution was improved to be lower jitter. Furthermore, the FPGA board was upgraded to be possible to remote-update the configuration program (firmware), so the FPGA firmware of all stations can be updated remotely concurrently.

Klystron Phase Lock Loop

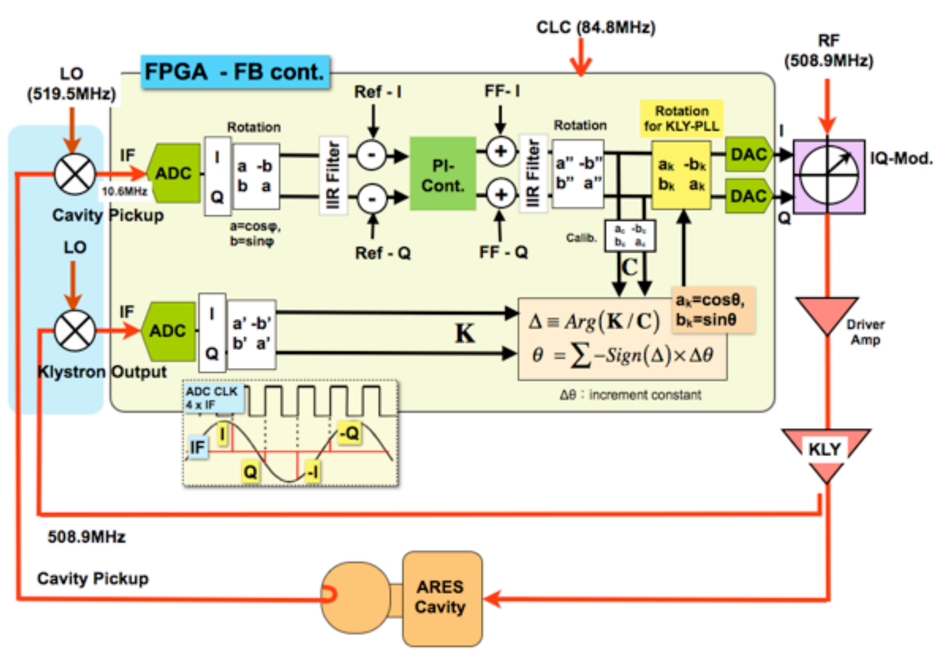
Klystron Phase Change due to Anode Voltage Control



Time Domain Simulation of FB-control with KLY-PLL



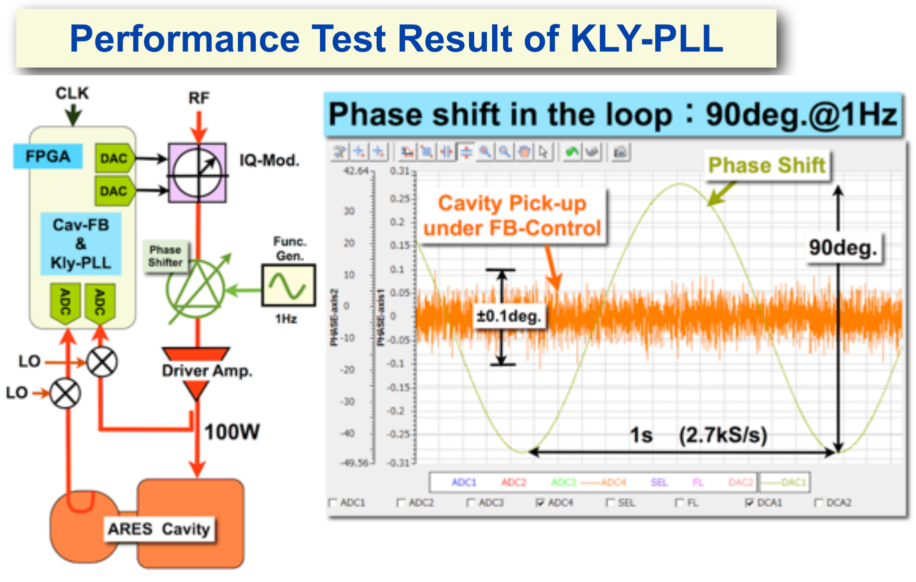
Klystron PLL was implemented in FPGA



Klystron anode voltage is controlled depending on driving RF power level to reduce collector loss for the efficiency. As the result, the 80-degree phase shift of klystron output was observed due to the anode voltage control in high power test. This phase change of 80 degrees is unexpectedly large. Large Phase shift (I-Q coupling) in closed loop might invalidate the I/Q-FB technique. According to our calculation and simulation, acceptable phase shift for the I/Q-FB control is approximately within ±50 degrees in our operation condition, and it was consistent with the high power test result.

For the left reason, klystron phase lock loop (KLY-PLL) is needed in cavity-FB loop. KLY-PLL is implemented in the DFBCNT. It works digitally in the FPGA with the cavity-FB control. For the KLY-PLL, additional phase-rotation function is inserted before the DAC outputs to the I/Q modulator. The klystron phase is detected on basis of FB-output phase as the reference. "θ" in the figure, which corresponds to total phase shift of the klystron, is accumulated by a increment constant to cancel the phase shift, and then the phase rotation parameters (cosθ and sinθ) are given dynamically. The "cos" and "sin" values are given by preset tables in 2-degree step with linear interpolation. The required loop band is supposed to be less than 1 kHz, because the anode voltage response is approximately 1 Hz.

Performance Test Result of KLY-PLL

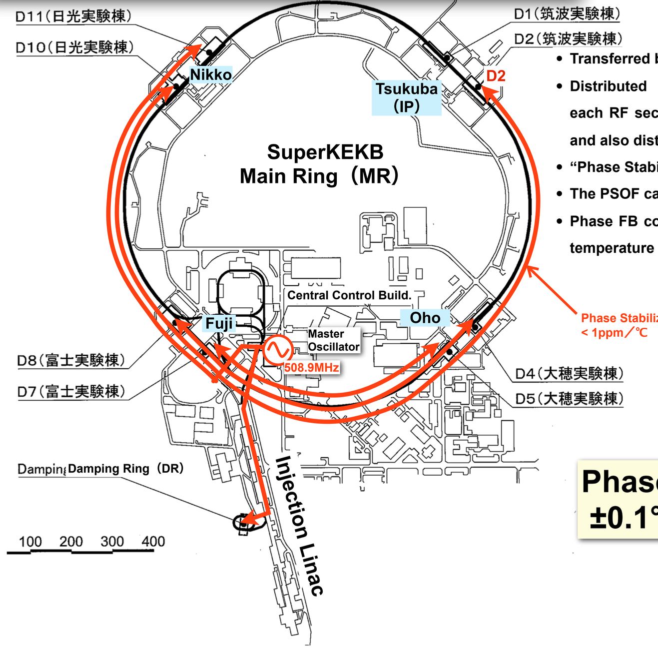


Cavity FB control is successfully working with KLY-PLL while loop phase is changing in 90-deg.

In this test, the ARES cavity was driven by a 100-W driver amplifier without klystron, so it is not high-power test. A voltage-controlled phase shifter was inserted in the loop, and it rotated the phase by 90 degrees at 1 Hz as shown in the figure; the green line indicates the phase shift, while the orange line is the cavity pick-up phase under cavity FB-control. As shown in the figure, the KLY-PLL worked well as expected, and consequently cavity FB control was still stable. If the KLY-PLL is open, the cavity FB control is broken with oscillation.

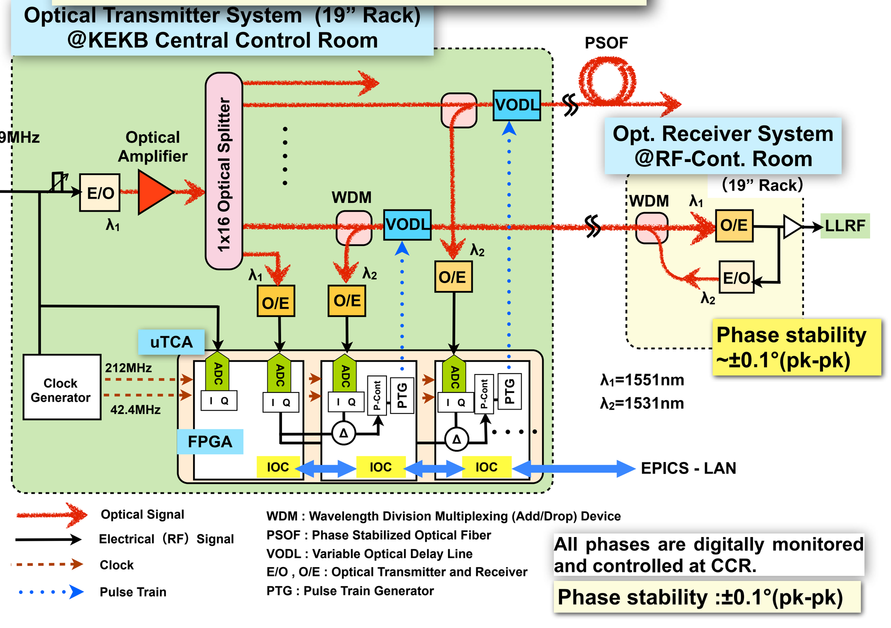
RF Reference Distribution

Distributed by means of star configuration through the phase stabilized optical fiber.

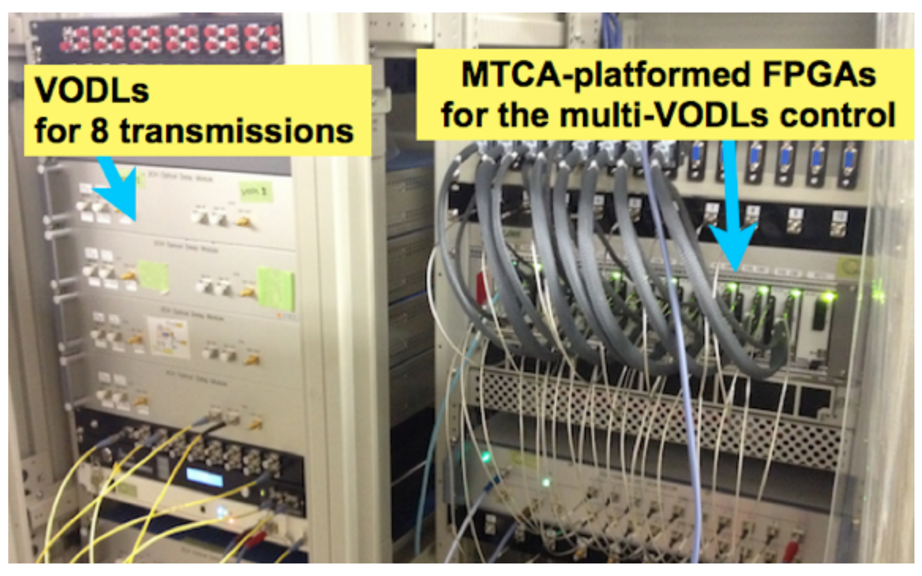


Phase stability : ±0.1°(pk-pk)@508.9MHz

Optical Transmitter and Receiver System with Phase Lock Loop.



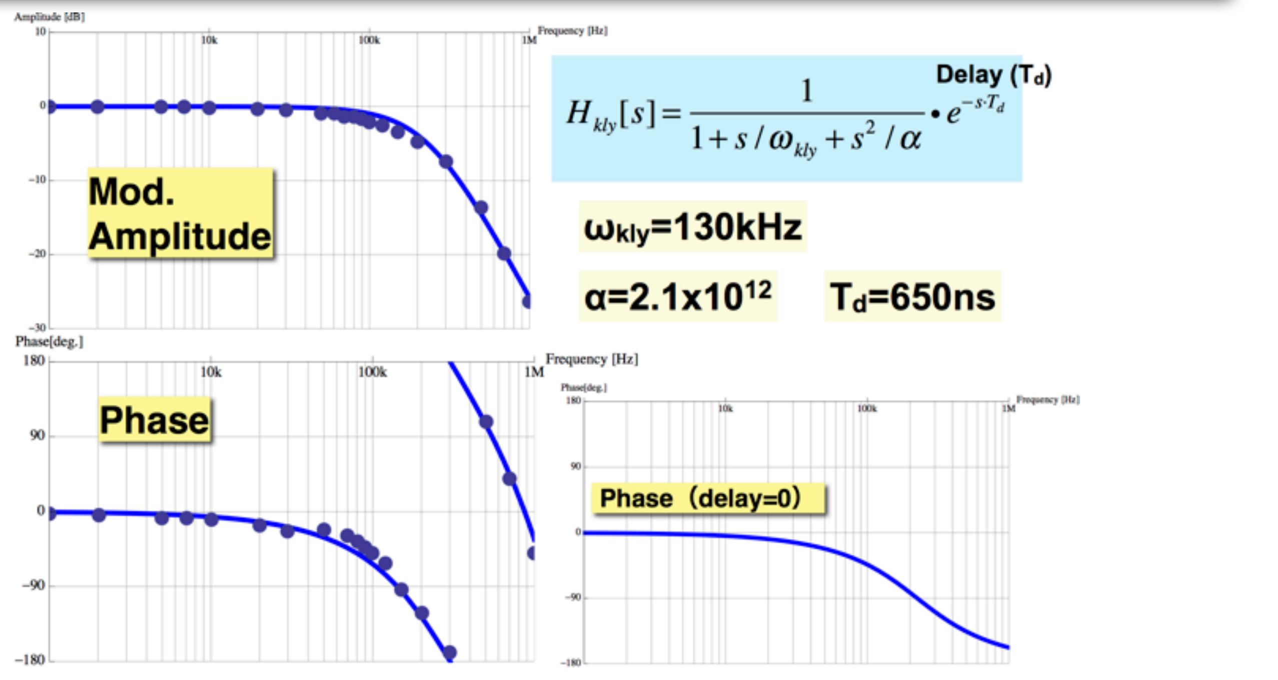
VODLs for eight distributions and the multiple VODL control system (MTCA-AMSs), which was already installed at the CCR.



RF reference distribution system was also newly designed for SuperKEKB. The require phase stability for the RF reference is ±0.1 degrees (pk-pk) during beam operation. The RF reference signal of 508.9 MHz is optically divided and distributed into six RF sections, the damping ring and the Belle-II detector from the central control room (CCR) by means of "Star"-topology configuration with the "Phase Stabilized Optical Fiber (PSOF)". The installation of the PSOF cables in the accelerator tunnel was already completed.

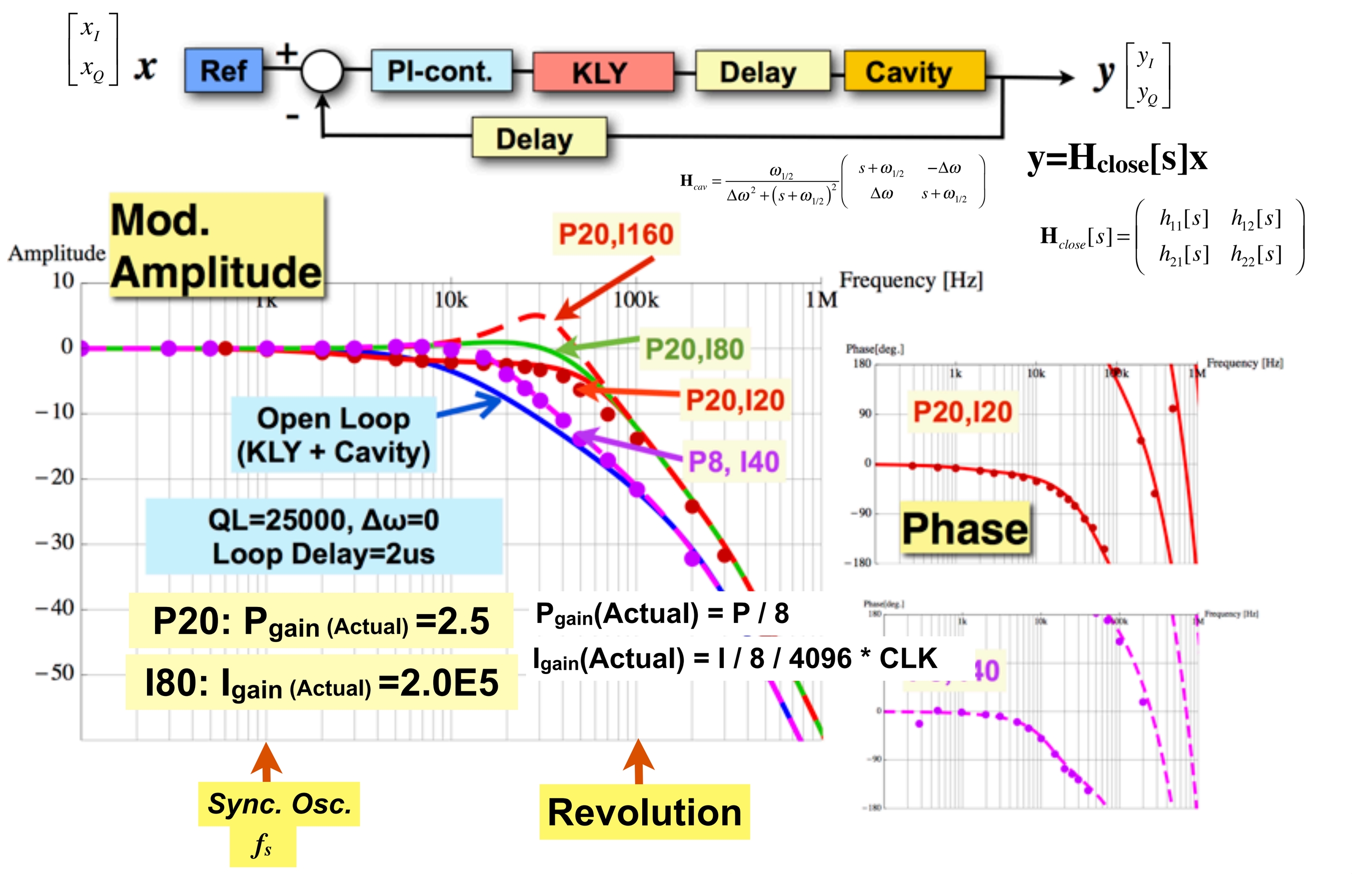
Furthermore, for the thermal drift compensation of the multi-divided optical transfer lines, a multiple optical delay control system was developed. MTCA-AMCs (FPGA boards) monitor the phases of respective round-trip signals by direct-sampling method, and they control respectively variable optical delay lines (VODLs) to cancel the phase change. With this VODL control system, the required phase stability of ±0.1 deg. was completely achieved.the picture of the VODLs for eight distributions and the multiple VODL control system (MTCA-AMSs), which was already installed at the CCR.
The E/O and O/E used in this system are the same as that for the J-PARC Linac, which are equipped with Pertier device for thermal stabilization. The transfer jitter with them is 110 fs (rms) as the measured result.

Measured Klystron Frequency Characteristics



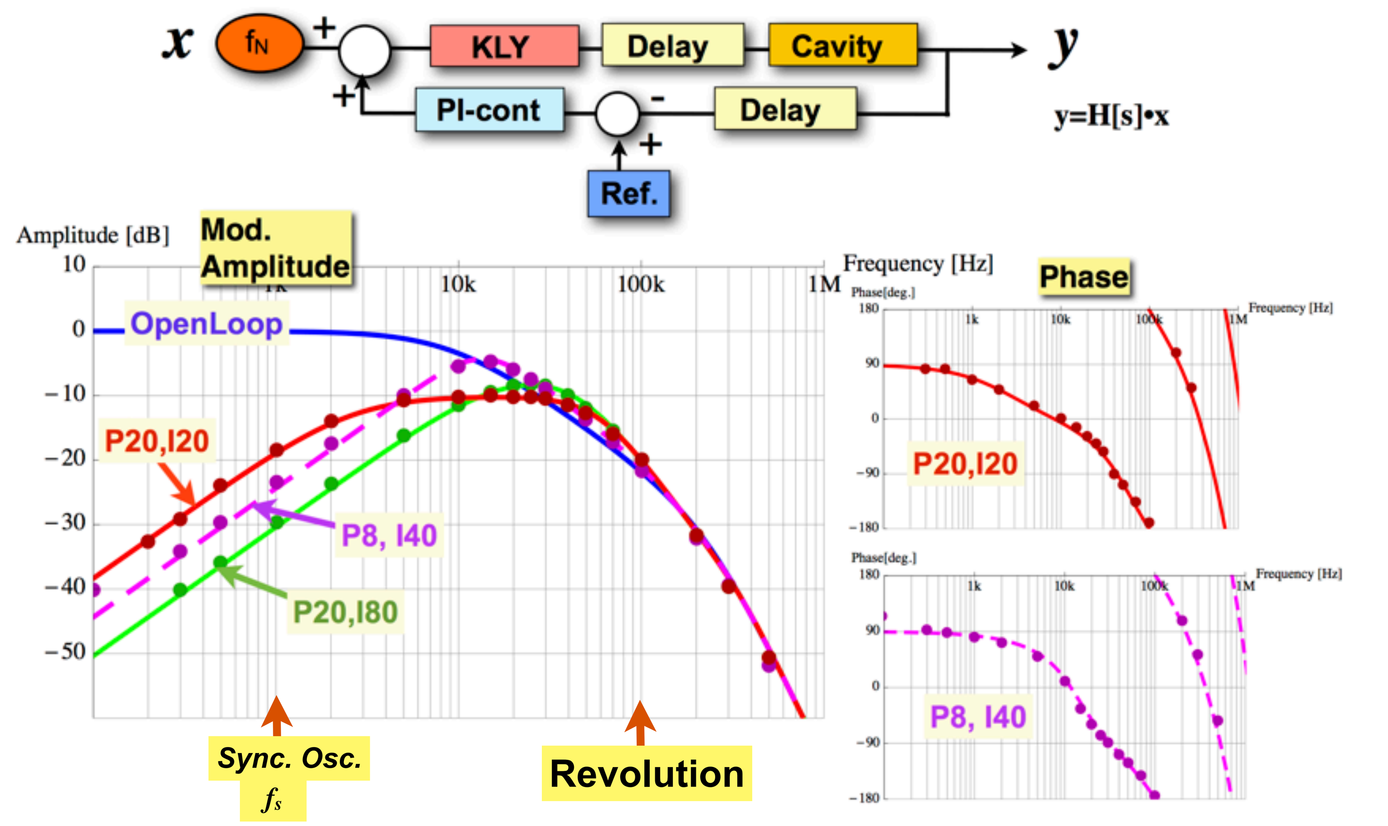
Bode Plot of FB-Control

Calculation of Trans. Func. & Measured Result in High Power Test



Disturbance Rejection Characteristic

Calculation & Measurement



Bunch Gap Transient Effect

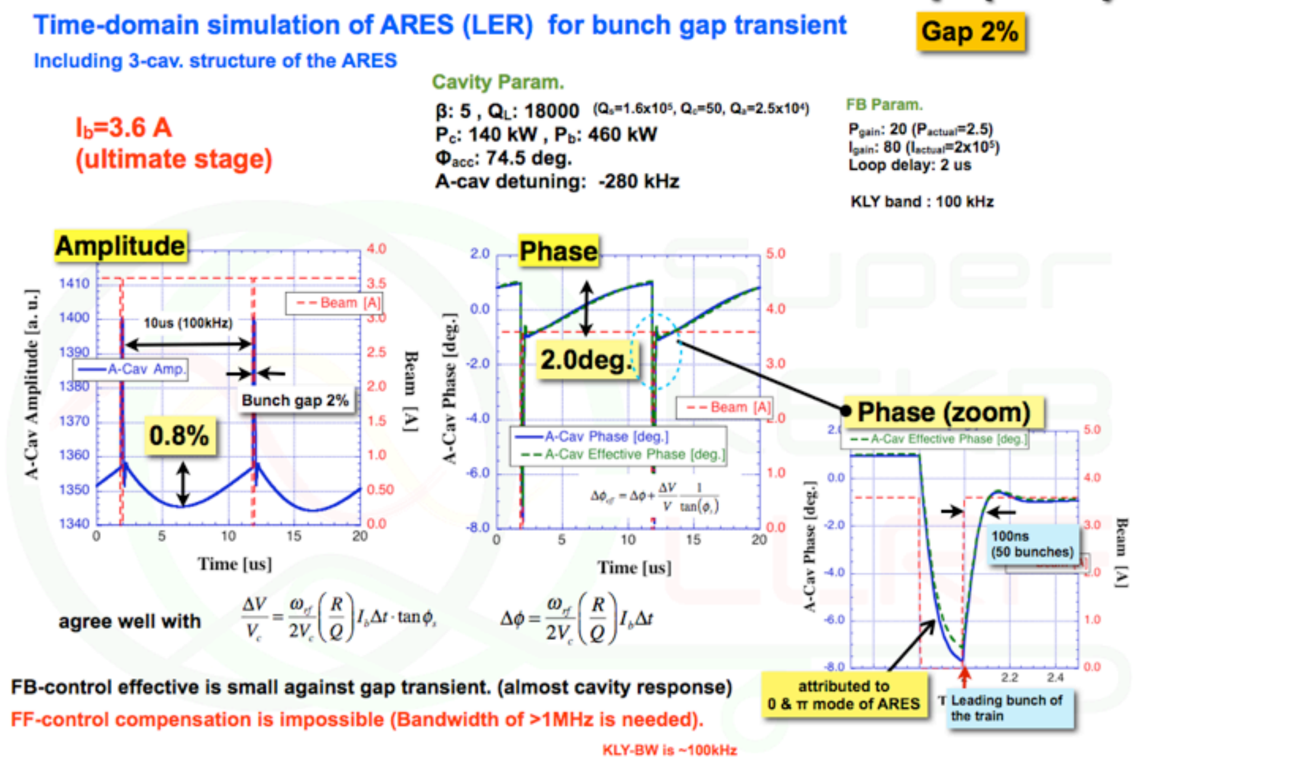
As one of the LLRF issues, transient effect caused by an abort gap of the bunch train also should be considered for the large current beam storage. Because the abort bunch gap modulates the accelerating field in the cavities and the synchronous phase of each bunch, then it makes unequally-spaced bunches. The synchronous phase modulation in the bunch train corresponds to a longitudinal bunch displacement between the both rings at the collision point, which might reduce the luminosity.

The phase modulation due to the bunch gap transient was estimated for the SuperKEKB. The length of the abort bunch gap will be reduced from 5% of the ring in KEKB to 2% of the ring in SuperKEKB by improving the rise time of the abort kicker. The full current beam storage is assumed in this estimation.

Simulation of Phase Modulation due to Bunch Gap (LER)

Time-domain simulation of ARES (LER) for bunch gap transient — Gap 2%

Including 3-cav. structure of the ARES

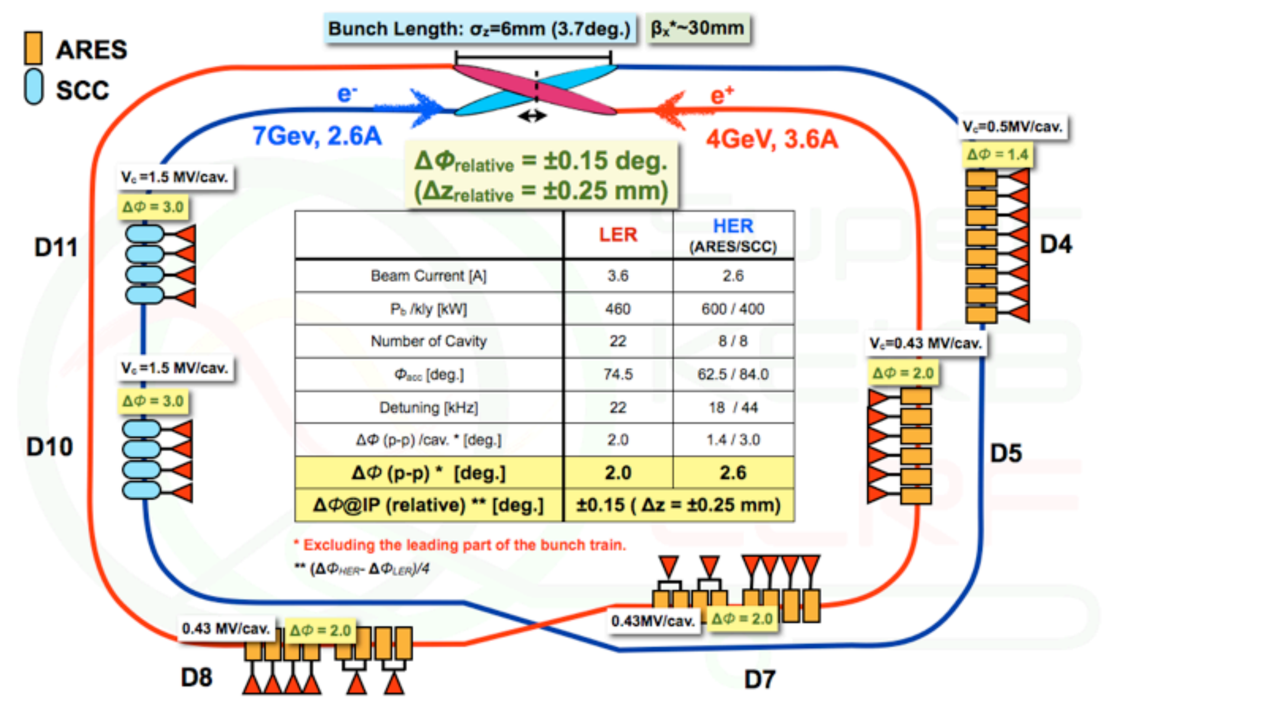


The time-domain simulation result of the amplitude and phase modulation in ARES cavity for the LER. This simulation is including three-cavity structure of ARES. In the figure, periodic interval of 10-μs corresponds to the revolution of 100 kHz, and dashed line in the phase plot indicates effective phase taking account of the amplitude shift. As the simulation result, 2-degree phase shift due to the bunch gap is found, and this result agrees well with analytical calculation.

Except, in the gap, a dip of large displacement appears. This large dip of phase change is attributed to the parasitic modes of ARES cavity which is 3-cavity system, that means 0 and pi-mode are excited. Accordingly, the leading part (about 100 ns) of bunch train will feel large phase change of 7 degrees. If cavity is just a single cell, no dip appears in the gap. The phase change effect due to the parasitic modes of ARES cavity was also observed in the KEKB operation.

FB-control is not effective for this gap transient effect as shown in Figure 7.xx,. It is almost cavity response. FF control also could not compensate this transient effect, because klystron bandwidth is about 100 kHz, while required bandwidth in the driving system is greater than 1 MHz for the compensation.

Estimation of Relative Phase Shift@IP between HER & LER due to 2%-bunch gap in the ultimate stage



	LER	HER (ARES/SCC)
Beam Current [A]	3.6	2.6
P_b /kly [kW]	460	600 / 400
Number of Cavity	22	8 / 8
Φ_{acc} [deg.]	74.5	62.5 / 84.0
Detuning [kHz]	22	18 / 44
ΔΦ (p-p) /cav. * [deg.]	2.0	1.4 / 3.0
ΔΦ (p-p) * [deg.]	2.0	2.6
ΔΦ@IP (relative) ** [deg.]	±0.15 (Δz = ±0.25 mm)	

* Excluding the leading part of the bunch train.
** ($\Delta\Phi_{HER}$- $\Delta\Phi_{LER}$)/4

This is summary of the synchronous phase modulation due to the bunch gap transient, excluding the large phase displacement at leading part of bunch train. For simplicity, the equal beam loading for all ARES cavities in the LER is assumed here. As shown in the table, relative phase shift ΔΦ at the interaction point (IP) between the LER and HER will be ±0.15 degrees, which corresponds to a longitudinal displacement of ± 0.04 σz, where a longitudinal bunch length (σz) is 6 mm (rms) while the beta function at IP (β*) is about 30 mm. Consequently the phase modulation due to the bunch gap is expected be acceptable small as compared with the beam size at IP except the leading part of bunch train. It is similar level as the KEKB operation. However, the large phase displacement of the leading bunches might not be negligible. As a future issue, it should be more investigated for detail that how the phase dip in the gap affects the luminosity in SuperKEKB operation.