RF REFERENCE PHASE CONTROL SYSTEM IN THE SuperKEKB INJECTOR LINAC

T. Miura†[1], H. Katagiri, T. Kobayashi[1], T. Matsumoto[1], KEK, Tsukuba, Japan
[1]also at The Graduate University for Advanced Studies (SOKENDAI), Hayama, Japan

Abstract

The radio-frequency (RF) reference phase in the SuperKEKB injector linac has been specially controlled for stable beam injection into the main rings (HER/LER). The phase control system contains three parts: MOFB, MOPS, and SECT35PS. MOFB is the phase feedback system for drift compensation between the linac master oscillator (LMO) of 571.2 MHz and ring MO (RMO) of 508.9 MHz which has a frequency ratio of 49/55 to the LMO. The MOPS is an MO phase shifter for injection phase control. The LMO phase must smoothly shift to the injection phase for the HER or LER rings at a repetition rate of 50 Hz. However, the laser system of a photocathode RF gun for the HER beam does not accept such rapid phase changes. Therefore, MOPS was developed to satisfy the requirements of the laser system and injection phase control. SECT35PS is the phase shifter of the 2856 MHz RF reference downstream of the positron damping ring (DR) located in the middle of the linac. The DR is operated at the same frequency as the main rings, 508.9 MHz. The linac RF reference phase at the downstream of the DR is changed from pulse to pulse by the bucket selection system to increase the synchronization probability for the bucket selection of LER ring. In this paper, we describe an RF reference phase control system in the SuperKEKB injector linac.

INTRODUCTION

The KEK injector linac [1] is a facility that delivers low emittance and high bunch-charge electron/positron beams to the SuperKEKB HER/LER rings. Figure 1 illustrates the layout of the radio-frequency (RF) reference control and distribution system [2]. The linac master oscillator (LMO) (Keysight E8663D) is 571.2 MHz, and the main ring master oscillator (RMO) is 508.9 MHz. The frequency ratio between LMO and RMO is 55:49, and the common frequency is 10.385 MHz. Both the LMO and RMO are generated by inputting 10 MHz, which is 510 MHz of the main master oscillator (MMO) divided by 51, as the signal generator synchronization signal. For the SuperKEKB, a photocathode RF gun with a laser system was introduced to produce the low-emittance electron beams for HER, and a positron damping ring (DR) was constructed in the middle of the linac for the low-emittance positron beams for the LER. To accommodate these upgrades and ensure stable beam injection into the rings, three new phase control systems are introduced for the RF reference in the injector.

The first is an MO phase feedback module (MOFB), introduced for drift compensation between the LMO and RMO. If the phase drifts, the beam injection phase changes and the injection efficiency worsens. The MOFB is required for stable injection and is placed immediately after the LMO.

The second is an MO phase shifter (MOPS) for injection phase control. The LMO phase must shift smoothly to the injection phase for the HER or LER rings every 20 ms which corresponds to a linac repetition rate of 50 Hz. However, the laser system of the photocathode RF gun does not accept such rapid phase changes. Therefore, MOPS has been developed to satisfy the requirements of the laser system and injection phase switching. The MOPS has two

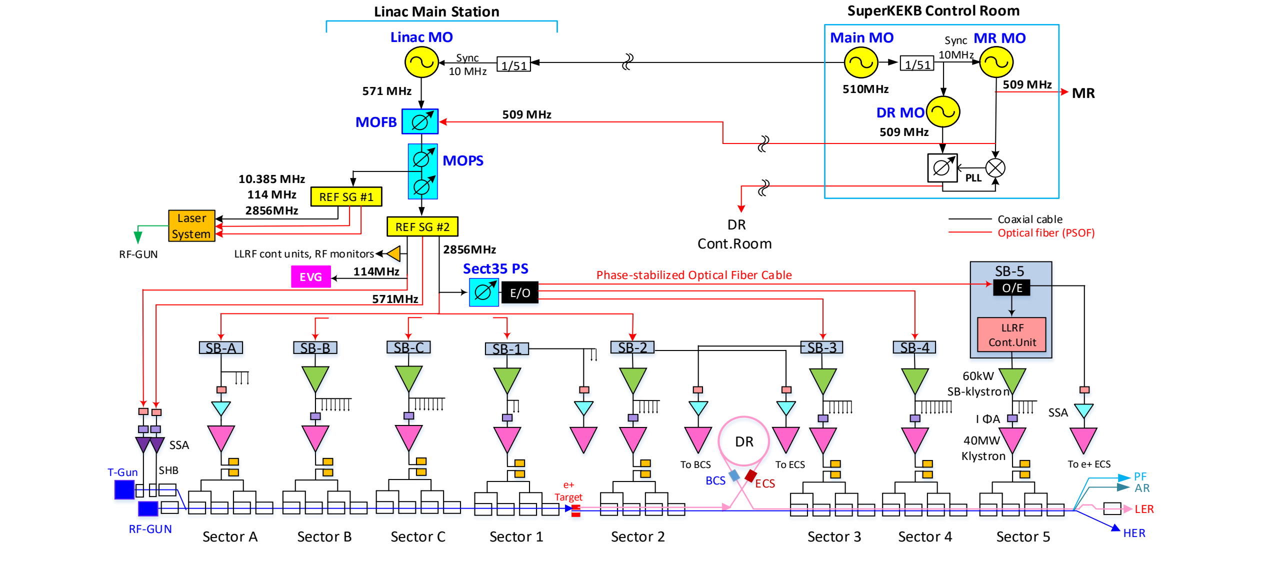

Figure 1: Layout of the RF reference control and distribution system at SuperKEKB injector linac.

† takako.miura@kek.jp

outputs: one for the laser and the other for all equipment in the linac, except for the laser system.

The third is a phase shifter of the 2856 MHz (S-band) RF reference downstream of the DR, which is sectors 3 to 5 (SECT35). Owing to the relationship between the DR and MR harmonic numbers (DR:230, MR:5120) and the linac RF frequency of 2856 MHz, synchronization took time, and it became difficult to freely select the LER bucket at 50 Hz. To shorten the synchronization time, the linac RF reference phase for SECT35 has been changed pulse to pulse according to the bucket selection system [3].

These RF reference phase control modules are used in thermostatic chambers for temperature stabilization.

MO PHASE FEEDBACK (MOFB)

The MO phase feedback allows the LMO phase to follow the RMO for phase drift compensation. To measure the phases of LMO and RMO with a frequency ratio of 55:49, the same circuit was used to avoid the effect of circuit drift. A direct under sampling technique using the same sampling frequency has been adopted to measure LMO and RMO. In a previous system [4], the MOPS module was diverted as a phase shifter, complicating the operation. Currently, a dedicated MOFB module has been installed and is running. Figure 2 shows the schematics of the MO phase feedback and sampling clock (f_s) generation. Here, f_s is 62.3 MHz, which is six times the common frequency of the LMO and RMO, 10.385 MHz. The frequencies of LMO and RMO are represented by f_s as follows:

$$f_{LMO}(571.2\ \text{MHz}) = (9 + 1/6)f_s, \quad (1)$$
$$f_{RMO}(508.9\ \text{MHz}) = (8 + 1/6)f_s. \quad (2)$$

Both LMO and RMO have one cycle per six data samples. As shown in Fig. 2, this module contains three analog-to-digital converters (ADCs) and two digital-to-analog converters (DACs). The ADC is an LTC2208 with a bandwidth of 700 MHz, 130 Msps, 16 bits, and small nonlinear

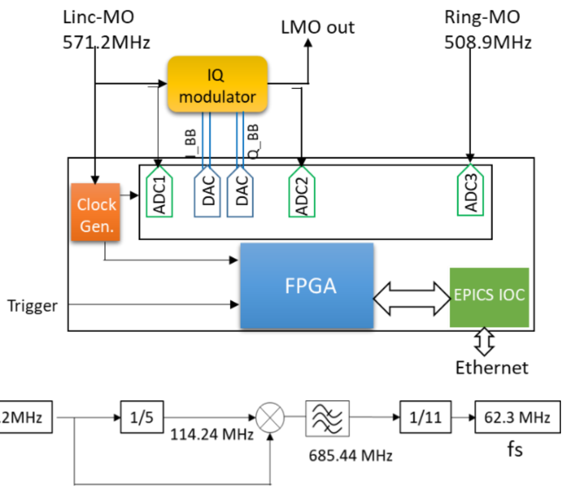

Figure 2: Schematics of the MO phase FB module and the sampling clock generation.

errors. The in-phase (I) and quadrature (Q) components are obtained by digital down-conversion (DDC) in the field-programmable gate array (FPGA) based on Eq. (3) and (4).

$$I = \frac{2}{M}\sum_{n=0}^{M-1}\cos\left(\frac{2\pi}{M}\cdot n\right)\cdot D(n), \quad (3)$$
$$Q = -\frac{2}{M}\sum_{n=0}^{M-1}\sin\left(\frac{2\pi}{M}\cdot n\right)\cdot D(n), \quad (4)$$

where $D(n)$ represents the ADC sampled data and M is 6. The phase is calculated from the IQ data. The RMO phase is normalized to the phase that corresponds to 571.2 MHz, $\theta_{RMO571MHz}$, by multiplying 55/49. The phase difference $\Delta\theta$ at 571.2 MHz is expressed as

$$\Delta\theta = \theta_{RMO571MHz} - \theta_{LMOout}, \quad (5)$$

where θ_{LMOout} denotes the phase of the LMO output signal from the IQ modulator. The LMO phase is changed to make $\Delta\theta$ constant using feedback control. The speed of the phase shifter is limited to less than 0.1 deg/s and changed smoothly not to affect the various systems in the downstream. The results of the MO phase feedback and room-temperature the MR CCR are shown in Fig. 3. The LMO phase is well controlled to follow to the RMO. In the RMO, phase drift, which is correlated with room temperature in the MR CCR, was observed. Generally, the MOFB continues to work, but is stopped when the RMO frequency is changed for dispersion measurement in the MR. As a result of the introduction of the MOFB, the frequency of the injection phase adjustment is decreased. Furthermore, the orbital change caused by the MO phase drift in the arc section of the bunch compression system (BCS) at the beam transport line from the DR to the linac (RTL) disappeared [4].

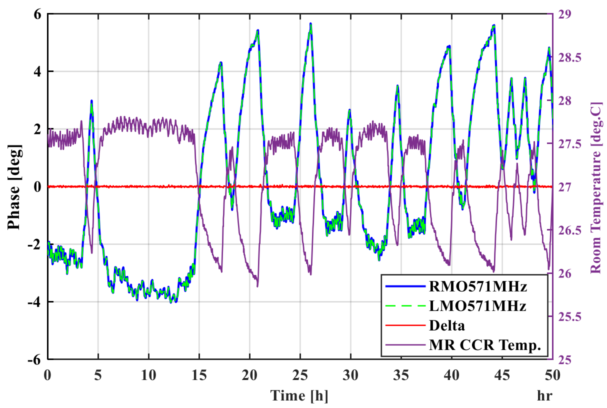

Figure 3: Result of MO phase feedback and MR CCR temperature.

MO PHASE SHIFTER (MOPS)

The MOPS contains two phase shifters, PS1 and PS2, connected in series, as shown in Fig. 4. Each injection phase θ_{HER} and θ_{LER} for HER and LER is set from MR CCR via EPICS [5], which works on the CPU board (Armadillo). The beam mode is discriminated based on the level signal generated by the event-timing system. The phases ϕ_1 and ϕ_2 of PS1 in upstream and PS2 in downstream are set as follows:

$$\text{HER: } \phi_1 = \theta_{HER},\ \phi_2 = 0, \quad (6)$$
$$\text{LER: } \phi_1 = \theta_{HER},\ \phi_2 = \theta_{LER} - \theta_{HER}. \quad (7)$$

In PS1, $\phi_1$is always set to θ_{HER} and is unchanged by the mode. The output of PS1 is transmitted to the laser system of the photocathode RF gun. In PS2, $\phi_2$is changed based on the beam mode at 50 Hz. The output phase from PS2 is $\phi_1 + \phi_2$, which corresponds to θ_{HER} in HER mode and θ_{LER} in LER mode. The output of PS2 is fed to the reference signal generator, and the 2856 MHz, 571.4 MHz, 114.24 MHz, and 10.385 MHz signals are generated and used for all the systems in the linac, except for the laser system. The phase must rotate smoothly. The phase change speed can be set from 1 deg/ms to 1000 deg/ms via EPICS, and phase changes linearly with a 0.01 deg step resolution using 16-bit DACs. The speed was set to 1 deg/ms for PS1 and 100 deg/ms for PS2. If LER set phase θ_{LER} is changed, the RF phase of DR must be changed by $\Delta\theta_{LER} \times (49/55)$ simultaneously. Because the phase change step is limited to 1 deg/s by the RF system in DR, the set value θ_{LER} and the RF phase of DR are changed by using the EPICS sequencer. The LTC2208 ADC was placed at three locations: the input (ADC1), PS1 output (ADC2), and PS2 output (ADC3), as shown in Fig. 4. The amplitude and phase data at each ADC are calculated from the IQ data obtained using the same method used for MOFB. If the phases derived from each ADC are P1, P2, and P3, the output phase of PS1 is obtained from P2-P1 and PS2 from P3-P1.

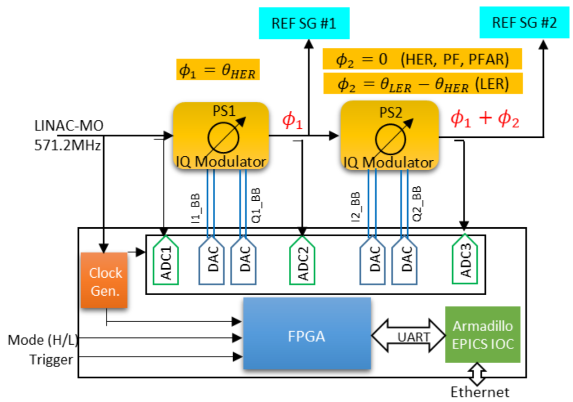

Figure 4: MO phase shifter (MOPS)

S-BAND SECT35 PHASE SHIFTER

To reduce the synchronization time among the DR, linac, and LER, the phase of the linac RF reference downstream of the DR is changed on a pulse-by-pulse basis according to a bucket selection system. The diagram of the S-band phase shifter is shown in Fig. 5. The S-band RF reference phase is specified by the bucket selection system [3]. An event receiver (EVR) was built into the FPGA in this module to avoid delays and to directly receive the event signal sent via an optical fiber cable from an event generator (EVG) [6]. The EVG sends event codes and a data array called a data buffer to each pulse. A certain area of the data buffer is used to transmit the array of phase and amplitude settings of the RF devices, such as multiple LLRF control units [7]. The set phase is obtained by reading the data at the address assigned to each device. The phase of the S-band RF reference is changed using the IQ modulator immediately after the set phase is received. The phase change can be verified by measuring the phase difference between the RF references upstream and downstream of the DR.

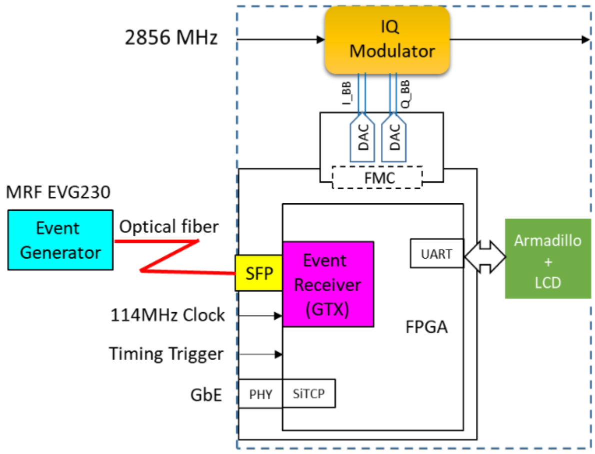

Figure 5: SECT35 S-band phase shifter.

SUMMARY

With the upgrade to SuperKEKB, three new phase controllers, namely MOFB, MOPS, and SECT35PS, were introduced for the linac RF reference. They were installed in a thermostatic chamber to prevent the temperature drift. The phase control system worked well, and stable injection into the main rings.

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