MEASUREMENT OF THE RF REFERENCE PHASE STABILITY IN THE SUPERKEKB INJECTOR LINAC

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Abstract

The SuperKEKB injector is a more than 600 m J-shaped LINAC. The requirement of the RF phase reference stability is 0.1 degree (RMS) at 2856 MHz for SuperKEKB PHASE-2 commissioning. In order to clarify and improve the reference line performance, the RF reference phase stability is measured. The phase noise of the RF reference at each sector is shown in this paper. A new phase monitor system is implemented to measure the short-term stability and long-term drift due to the temperature and humidity fluctuations in the klystron gallery.

INTRODUCTION

The SuperKEKB injector LINAC is utilized as a multi-purpose injector, which delivers 7 GeV electron beams to the KEKB high-energy ring (HER) and 4 GeV positron beams to the low-energy ring (LER) and provides electron beams of 2.5 GeV and 6.5 GeV for the Photon Factory (PF) and the Photon Factory Advanced Ring for pulse x-rays (PF-AR), respectively [1]. The J-shaped LINAC comprises of 124.8 m long and 488.3 m long straight beam lines, which consist of 8 sectors (sector A-C and 1-5). The layout of the RF reference distribution for the SuperKEKB Injector LINAC is shown in Fig. 1. Sector A consists of two sub-harmonic bunchers (SHB1 is operated at 114 MHz and SHB2 is operated at 571 MHz), an S-band (2856 MHz) pre-buncher, and a buncher [2, 3]. The other sectors are operated at 2856 MHz as the regular accelerating sectors, which comprise of the sub-booster klystron (SBK)/solid-state amplifier (SSA), high-power klystron, pulse compressor, and normal conducting accelerator structure. Reference signals of three different frequencies (114 MHz, 571 MHz, and 2856 MHz) are generated by the Master Oscillator (MO, 571 MHz) system [4]. The 2856 MHz reference signal (REF) is delivered to the SBK at each sector through long coaxial cables (sector A-C,1) or optical links (sector 2-5) [4]. The requirement of the energy spread for SuperKEKB injector LINAC is 0.1% in [5] so that the RF phase reference stability is estimated with the requirement of 0.1 degree (RMS) at 2856 MHz. In order to clarify the REF phase stability, the RF phase noise, the short-term stability and the long-term phase drift are measured.

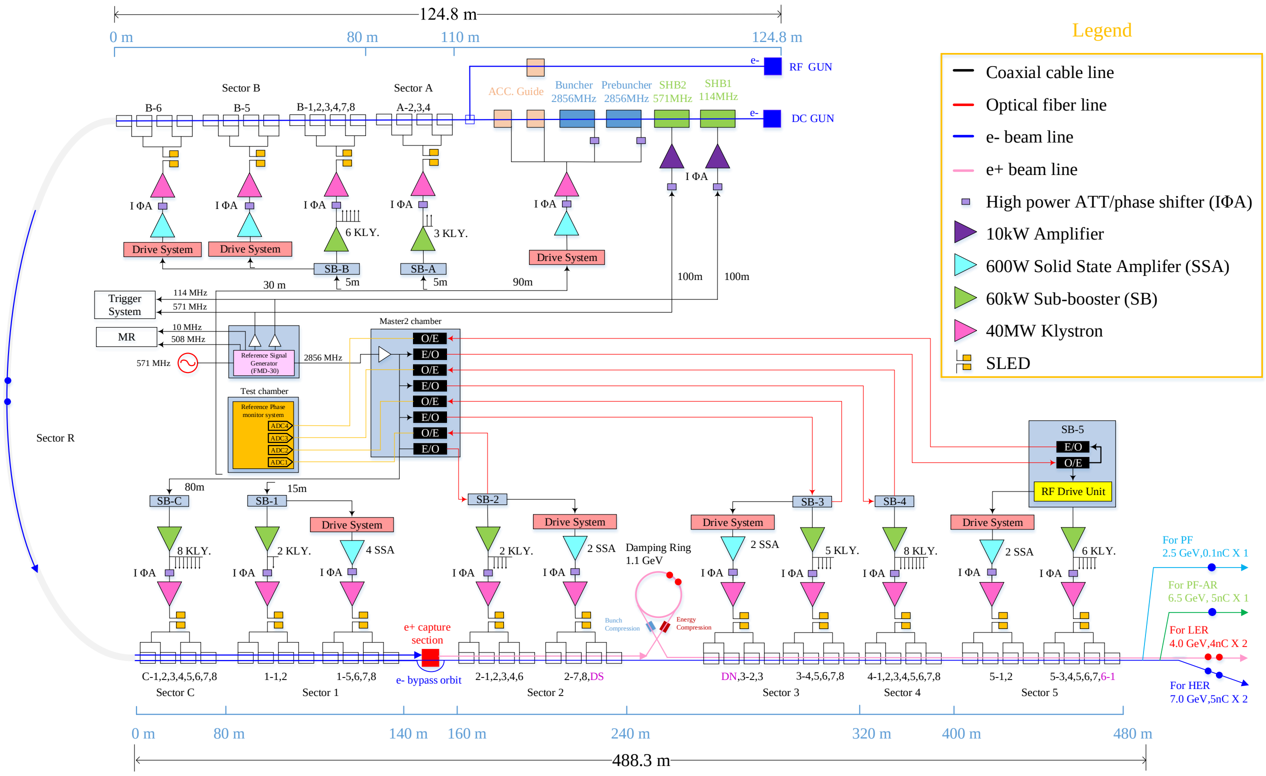

Figure 1: Layout of the RF reference distribution for the SuperKEKB Injector LINAC.

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RF PHASE NOISE MEASUREMENT

For the optical link, the 2856 MHz REF signal is converted into an optical signal by an optical transmitter (E/O), and transmitted by the single-mode phase stabilized optical fiber (PSOF). Then, the optical signal is converted into a 2856 MHz electrical signal by an optical receiver (O/E). This converted electrical signal is used as the local oscillator (LO) for the Low-Level Radio Frequency (LLRF) control system and the RF monitor in each sector. The electrical and optical components are inside the temperature-stabilized chamber without humidity control, except for the long PSOF, which is distributed in the klystron gallery. The PSOF was provided by Furukawa Inc., and the propagation delay temperature coefficient is 5 ps/km/ºC from −10 ºC to 35 ºC in the specification. TAMAGAWA E/O and O/E are installed in sector 2-5.

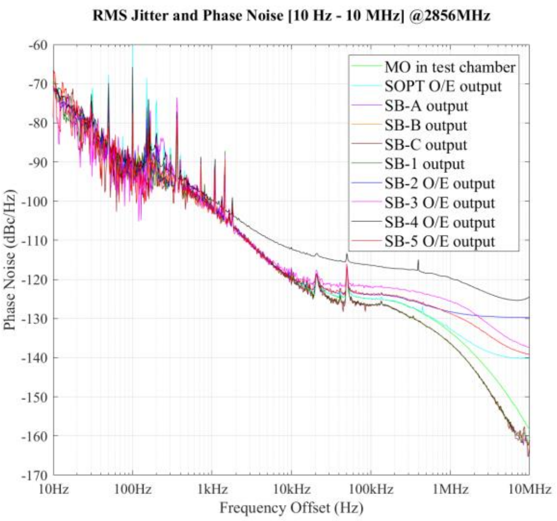

Figure 2: Single side-band phase-noise power spectrum of 2856 MHz REF of the optical links.

Table 1: Phase noise for sector A-5 [10 Hz–10 MHz]

Signal	Power [dBm]	Jitter [fs]	Phase Noise [°]
2856 MHz REF	+6.47	106.08	0.109
SOPT O/E output	+4.39	159.58	0.164
SB-A output	−8.56	103.03	0.106
SB-B output	−9.16	98.33	0.101
SB-C output	−11.38	90.99	0.094
SB-1 output	−12.32	93.13	0.096
SB-2 O/E output	−8.90	134.67	0.138
SB-3 O/E output	−11.25	127.06	0.131
SB-4 O/E output	−8.22	216.35	0.222
SB-5 O/E output	−8.09	103.89	0.107

The phase noise of the transmitted 2856 MHz REF in each sector was measured using the Signal Source Analyzer (SSA) (Agilent E5052B). Fig. 2 shows the single sideband phase-noise power spectrum of the 2856 MHz REF, 1 m short optical link (SOPT) and the forward signal (O/E output) from 2856 MHz generator side to sector A-5. The results are summarized in Table 1. Due to the phase change for different injection mode, there is no filter after the O/E output. Therefore, the frequency offset of the phase noise integrated from 10 Hz to 10 MHz is considered. Most of the phase noise at each sector is 100 -200 fs. It is roughly meet the requirement of 0.1 deg.

SHORT-TERM AND LONG-TERM PHASE STABILITY MEASUREMENT

Phase Monitor System for Sector 2 to 5

In order to monitor the 2856 MHz REF phase drift of the optical link during the beam operation, a similar configuration of optical link is used to deliver the converted electric RF signal back from sector 2-5 to 2856 MHz MO side. A new phase monitor system is implemented in LINAC. The schematic diagram of the monitor system including LO generation is shown in Fig. 3. The S-band 2856 MHz reference signal is down-converted to intermediate frequency (IF, 14.28 MHz) by the LO (2870.28 MHz). The IF signal is sampled by a 16-bit ADC with a sampling rate (SR) of 114.24 MSPS and processed in the FPGA board based on μTCA. When the SR and IF signals satisfy the condition $N \cdot SR = L \cdot IF$ (L is an integer greater than 3 and N is an integer), the IQ component of the sampled IF signal can be calculated by the following equation [6-7].

$$I = \frac{2}{L}\sum_{n=0}^{L-1} x[n]\cos\left(\frac{2\pi \cdot N}{L} \cdot n\right)$$

$$Q = \frac{2}{L}\sum_{n=0}^{L-1} x[n]\sin\left(\frac{2\pi \cdot N}{L} \cdot n\right)$$

where $x[n]$ is the sampled signal. Here, $L = 8$ and $N = 1$

Take the system latency and the ADC sampling rate limitation into consideration, $SR = 8 \cdot IF$ is selected. The I/Q signals are filtered by the digital infinite impulse response low-pass filter (IIR LPF) with 100 kHz bandwidth to suppress the ADC noise. Then the amplitude (A) and phase (φ) of the IF signal is calculated with $A = \sqrt{I^2 + Q^2}$ and $\varphi = \tan^{-1}(Q/I)$.

The injector LINAC is operated in the pulse mode and the reference phase of the injector is changed depending on the injection mode of HER/LER at 50 Hz. The short-term and long-term data taking should be synchronized with the beam trigger 50 Hz, and should exclude the phase changing timing. The optical link returned back signals from sector 2-5 (SBxxOPTR) are measured by the ADC with100 kHz bandwidth IIR LPF. The 2856 MHz REF signal is also measured to detect the monitor system drift including frequency divider, mixer, 2870 MHz band pass filter (BPF) and the S-band amplifier. The optical link phase stability is processed to reject the phase drift of the monitor system itself. All the RF components of the monitor system are inside the temperature-stabilized chamber with 0.1 °C peak-peak stability. The 1 ms short-term stability is summarized in Table 2. All the short-stability values are within 0.1 deg. RMS except sector 5. We are trying to find out the reason.

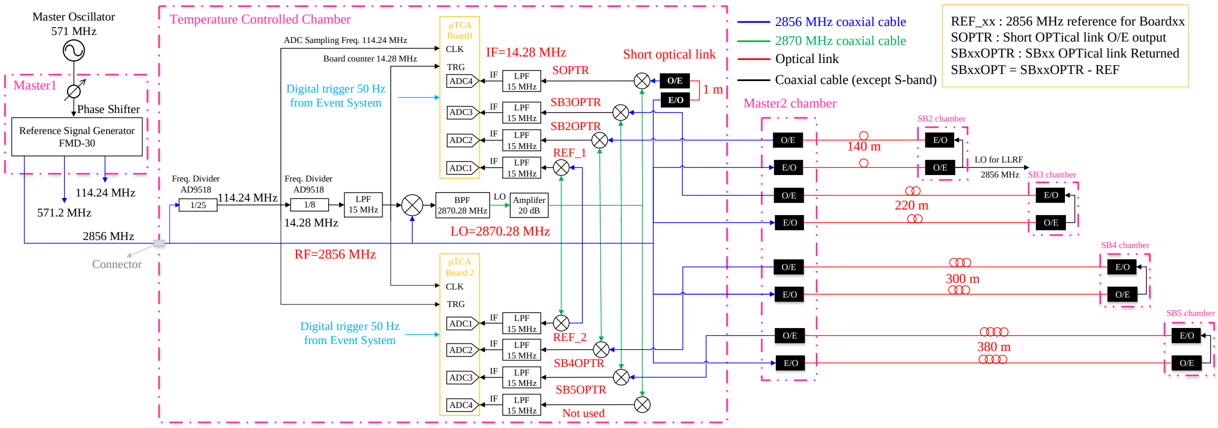

Figure 3: Schematic diagram of the 2856 MHz RF reference phase-monitor system based on μTCA.

Table 2: 1ms short-term optical link phase stability

REF [deg.]	**Sector2** [deg.]	**Sector3** [deg.]	**Sector4** [deg.]	**Sector5** [deg.]
0.028	0.055	0.068	0.067	0.22

In order to study the 2856 MHz reference phase dependence with humidity and temperature, the long-term phase drift of the optical link from the 2856 MHz reference to sector 2-5 (round way), the humidity fluctuation and the temperature drift in the klystron gallery are monitored for 7 days.

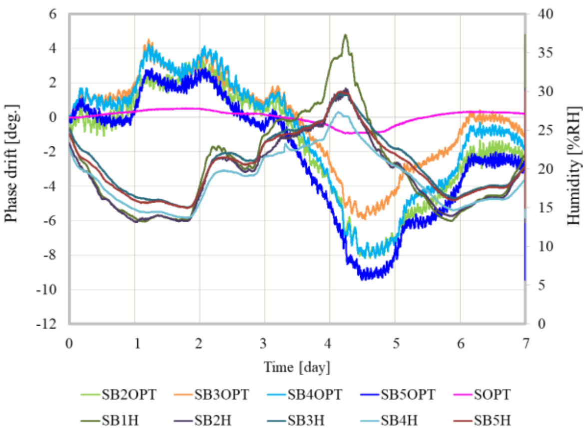

Figure 4: Long-term phase drift of the reference phase and the humidity fluctuation in the gallery.

Fig. 4 shows the long-term phase drift and the humidity fluctuations in the klystron gallery. The humidity fluctuation is around 25%RH and almost in the same trend for sector 2-5. The phase drifts of the short and long optical links are 1.5° and 12°, respectively. We found that the phase drift depends on the humidity fluctuation clearly. The short optical link (SOPT) consists of 1m PSOF and a pair of E/O and O/E. It is in the temperature stabilized chamber but no humidity control. So the phase drift of SOPT indicates the phase drift of E/O and O/E module due to the humidity fluctuation. The phase drift of the long optical link (LOPT) for each sector include 2 pairs of E/O and O/E modules and the long PSOF. Fig. 5 shows the phase drift and the temperature drift. Because the temperature drift trends are very different from sector to sector, the temperature dependence is not so clear.

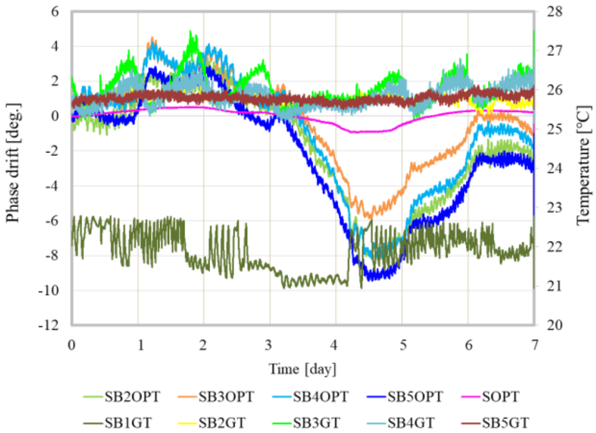

Figure 5: Long-term phase drift of the reference phase and the temperature fluctuations in the klystron gallery.

CONCLUSION

The phase noise of the 2856 MHz RF phase reference was measured, and all the values of RMS jitter were found to be less than 220 fs. A new phase monitor system based on μTCA is implemented to monitor the RF reference phase stability for sector 2-5. All the short-term phase stability values for sector 2-5 are less than 0.1 deg. RMS, except SB5. But the reason is not clear for us. The long-term phase drift is more than 10 degrees. We found that the phase drift depends on the humidity fluctuation clearly. A feedback control system is necessary for the RF reference phase stabilization to fulfill the requirement of the SuperKEKB injector LINAC. Based on the present system configuration, a feedback system, which includes a wavelength-division multiplexing device and variable optical delay line, is proposed [8-9]. The performance evaluation of the feedback system is in progress.

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