

THE CONSIDERATION OF RF PHASE REFERENCE DISTRIBUTION SYSTEM FOR THE INJECTOR LINAC OF SUPERKEKB*

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Abstract

Stabilization of RF phase reference for long distance transmission is very important for stable RF operation, especially in the large accelerator facilities. Coaxial cables and optical links as the distribution medium without phase feedback control are used for the present system of the SuperKEKB injector LINAC. A more stable RF phase distribution system using single-mode optical links with feedback control is required to improve the phase stability. For SuperKEKB PHASE-2 commissioning, the phase stability requirement is within 0.1 deg. rms including the short-term and long-term stability. This paper describes the main design considered issues and shows the current test results of the optical devices, transmission medium and RF components. A high precision phase monitor system with two-tone calibration is being considered.

LINAC is shown in Fig. 1 [2]. The J-shaped linac comprises 124.8 m long and 488.3 m long straight beam lines which consist of 8 sectors (sector A-C and 1-5). 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 [3]. Other sectors are operated at 2856 MHz as the regular accelerating sectors which comprise sub-booster klystron (SB)/solid state amplifier (SSA), high power klystron, pulse compressor and normal conducting accelerator structure. The reference signals of three different frequencies (114 MHz, 571 MHz and 2856 MHz) are generated by the Master Oscillator (MO, 571 MHz) system and delivered to each sector in the two beam lines through long coaxial cables and optical links. The RF reference phase stability depends on the short-term RF phase noise jitter and the long-term phase drift due to the temperature and humidity variations in environment, especially for the S-band signal. Taking into account the large amount of the RF devices to be synchronized, necessity of delivering different frequencies in long distance, the long-term phase drift of the RF/optical components and long cables, the stabilization of the RF phase reference becomes one of the critical issues for the large accelerators. A phase monitor and feedback system is being considered to monitor and compensate the phase drift of the optical links.

INTRODUCTION

The SuperKEKB injector linac is utilized as a multi-purpose injector, which not only delivers 7 GeV electron beams to the KEKB high-energy ring (HER) and 4 GeV positron beams to the low-energy ring (LER), but also 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]. Layout of the RF reference distribution system for SuperKEKB Injector

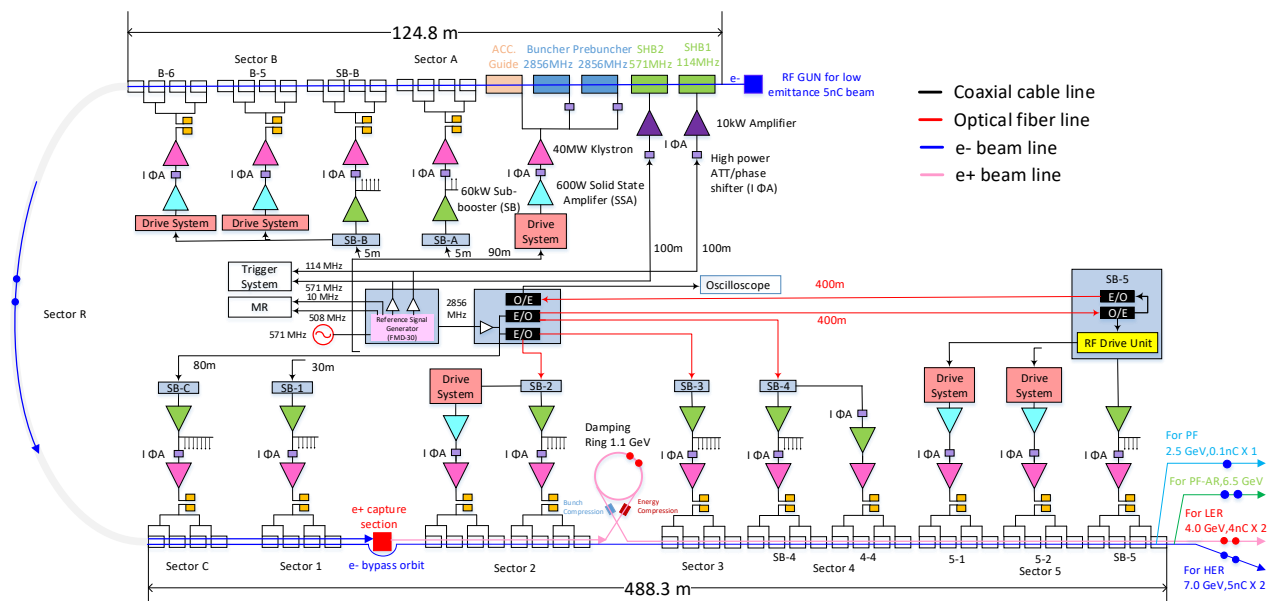


Figure 1: Layout of the RF reference distribution system for SuperKEKB Injector LINAC.

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OPTICAL TRANSMITTER & RECEIVER

As shown in Fig. 1, the electrical RF reference signals (114MHz, 571 MHz and 2856 MHz) are delivered to sector A-C and sector 1 through coaxial cables. Compared to coaxial cable, optical link has many advantage in long distance transmission such as lower transmission loss, smaller electrical noise. Part of the S-band reference signal (2856 MHz) is converted to optical signals by an optical transmitter (E/O) and delivered through the single-mode optical fiber. The transmitted optical signal is received by an optical receiver (O/E) and then converted to an electrical signal at sector 2-5 as the local oscillator (LO) of Low Level Radio Frequency (LLRF) control system. Therefore the reference phase stability directly affects the beam performance. The RF reference phase stability depends on short-term phase noise jitter and long-term phase drift of the optical link (E/O, O/E and optical fiber).

Short-term phase noise jitter

Take the phase stability requirement and S-band transmitted signal into consideration, the candidates are EOC-144/OEC-1041 which is used in the sector 2-5 of the SuperKEKB injector LINAC, MP-2320 TX/RX and WSM-1/WRU-2 which is used in SuperKEKB main ring. Due to the larger phase drift of S-band signal, the short-term phase noise jitter of E/O and O/E was measured at 2856 MHz with the Signal Source Analyzer (SSA, E5052, Agilent Technologies). Figure 2 shows the single sideband phase-noise power spectrum of three different types of the optical link for comparison. The result is shown in Table 1.

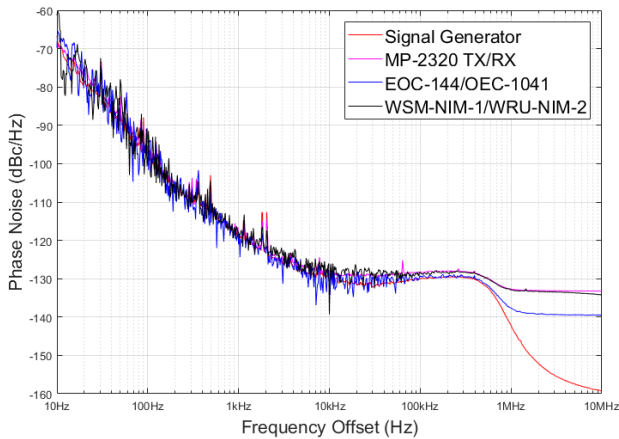


Figure 2: Single side-band phase noise power spectrum of the 2856 MHz RF signal of optical links.

Table 1: RMS Jitter and Phase Noise [10 Hz-10 MHz]

Model	Jitter [fs]	Phase Noise [°]
Signal Generator	60.2098	0.0701
MP-2320 TX/RX	94.3005	0.0970
EOC-144/OEC-1041	90.3788	0.0929
WSM-1/WRU-2	109.0993	0.1122

In contrast to the other two optical links, EOC-144/OEC-1041 has a lower phase jitter of 90 fs, corresponding to 0.093 deg. rms at 2856 MHz. The specification of EOC-

144/OEC-1041 is shown in Table 2. The modules are provided by TAMAGAWA Electronics Inc.

Table 2: The Specification of EOC-144/OEC-1041

Items	EOC-144/OEC-1041
RF Input range	10 ~ 3000 MHz
RF input level	-20 dBm (max. 0 dBm)
Optical power	+7.8 dBm /+7.0 dBm
Wavelength	1310 nm (standard)
Temperature range	+10 ~ +40 °C

Temperature and humidity characteristics

The long-term phase drift of the RF reference signal depends on the characteristics of E/O and O/E. Owing to the quantity limitation of the temperature and humidity controlled chamber (ESPEC PR-3J), we measured the optical link (EOC-144/OEC-1041 and 1m optical fiber) instead of E/O and O/E individually with only one chamber. The test bench is shown in Figure 3. The optical link was putted in the chamber and the phase of the required rf frequency (114 MHz, 571 MHz and 2856 MHz) signals was measured with Network Analyzer (NA, E5071C, Agilent Technologies). In order to cancel the phase drift of NA itself and the coaxial cable outside the chamber, the 5m Andrew coaxial cable (FSJ1RK-50B) was used as the reference cable on port1 due to its excellent thermal stability [4].

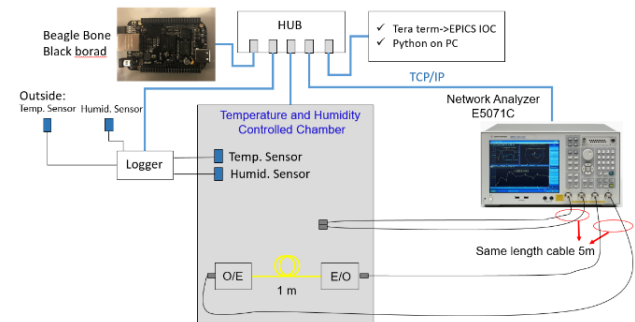


Figure 3: Test bench of the temperature and humidity characteristics measurement of the optical link.

The temperature and humidity characteristics of the optical link is shown in Fig. 4 and Fig. 5, respectively. The temperature is changed from 25 °C to 40 °C (round trip) every 5 °C/5 hours at fixed humidity 50 %RH. And the humidity is changed from 50 %RH to 70 %RH every 10%RH/10 hours at fixed temperature 30 °C. Table 3 summaries the temperature coefficient (T.C.) and the humidity coefficient (H.C.). The temperature and humidity rises and the phase drift decreases. We prefer use the test parameter of the S-band signal (2856 MHz) to estimate the phase drift in the following paragraphs.

Table 3: T.C. and H.C. of the Optical Link

Freq.[MHz]	T.C. [ps/°C]	H.C. [ps/%]
114	-0.9004	-0.0547
571	-0.7168	-0.0544
2856	-0.6154	-0.0382

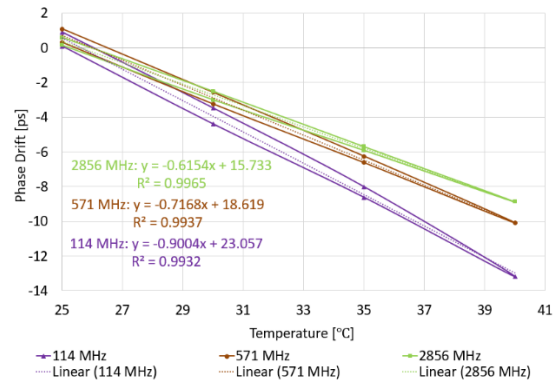
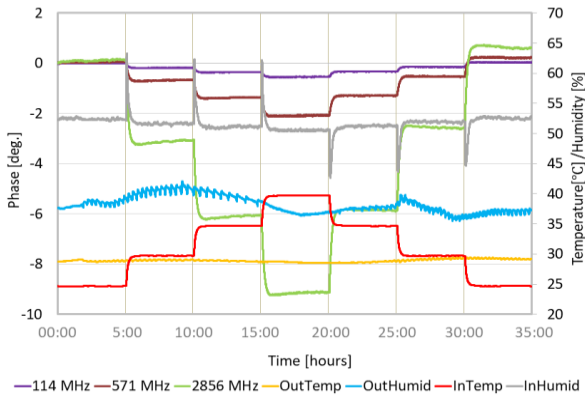


Figure 4: Temperature dependence (left) and thermal coefficient (right) of the optical link.

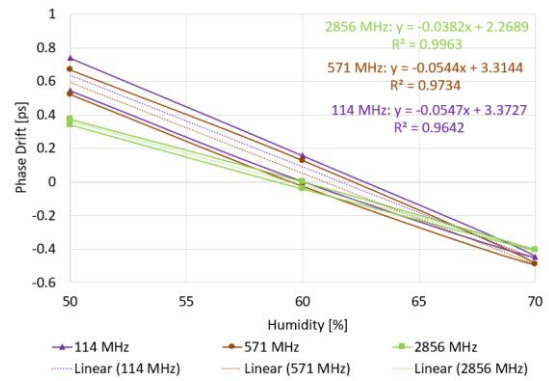
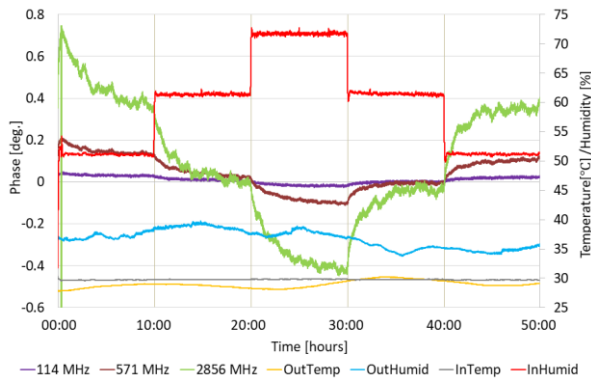


Figure 5: Humidity dependence (left) and humidity coefficient (right) of the optical link.

In present system, the E/O and O/E are putted inside the chamber at the temperature controlled $28 \pm 0.1 \text{ }^\circ\text{C}$ but the uncontrolled humidity. Figure 6 shows the fluctuation of temperature and humidity inside the chamber in sector 5 is $0.22 \text{ }^\circ\text{C}$ and 18 \%RH , respectively, in 30 days. Therefore the long-term phase drift of 2856 MHz transmitted signal through E/O and O/E is -0.14° and -0.71° , respectively. Due to the large humidity fluctuation, the humidity controlled chamber is necessary in each sector.

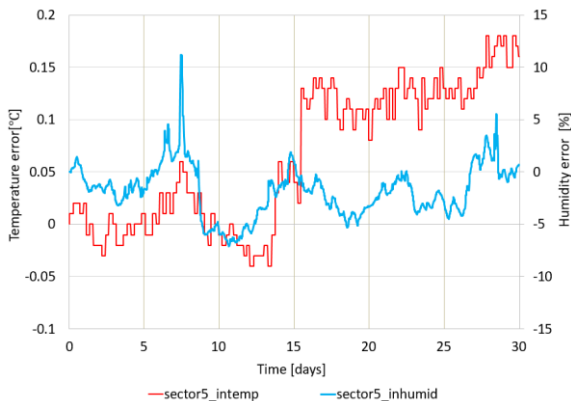


Figure 6: Long-term temperature and humidity fluctuation inside the chamber in sector5 for 30 days.

PHASE-STABILIZED OPTICAL FIBER

The RF reference signal is delivered through optical fiber from MO to sector 2-5. The temperature and humidity characteristics directly affect the reference phase stability.

The phase-stabilized optical fiber (PSOF) is required due to its excellent stability. The propagation delay temperature coefficient of PSOF provided by Sumitomo and Furukawa Inc. is $1 \text{ ppm}/^\circ\text{C}$ and $0.4 \text{ ppm}/^\circ\text{C}$ from $25 \text{ }^\circ\text{C}$ to $30 \text{ }^\circ\text{C}$ measured in [5]. Now only the Furukawa PSOF is available. The humidity coefficient of Furukawa PSOF (100m) was measured and the result is shown in Fig. 7.

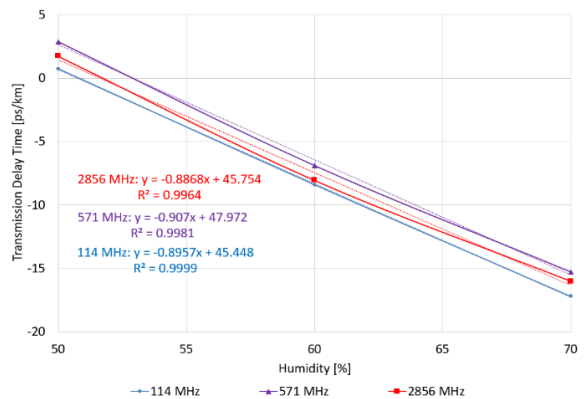


Figure 7: Humidity coefficient of Furukawa PSOF.

The humidity transmission delay time is about $-0.896 \text{ ps/km}/\%$, $-0.907 \text{ ps/km}/\%$, $-0.8987 \text{ ps/km}/\%$ at 114 MHz, 571 MHz and 2856 MHz, respectively. The temperature and humidity fluctuation of the injector linac gallery is $2 \text{ }^\circ\text{C}$ and 26 \%RH during operation in 30 days (April 1st ~ May 1st), respectively. When the thermal coefficient is $+0.4 \text{ ppm}/^\circ\text{C}$, the temperature and humidity phase drift is $+1.65^\circ$ and -9.48° at 2856 MHz for 400 m transmission from MO

to sector5, respectively. Thus the large humidity fluctuation has a big impact on the phase drift both E/O and O/E and PSOF. These characteristics does not satisfy the phase stability requirement. The phase feedback control system of optical link is necessary to compensate for the phase error in the propagation delay of the optical link.

In order to deliver the stable RF reference signal through the optical link over distances of a few hundred meters to several kilometres, several approaches have been implemented with the average uncertainties of 10 fs to a few hundred fs, such as 400-MeV proton linac of JAERI, KEKB main ring, SACLA, LCLSII and European XFEL.

PHASE MONITOR SYSTEM

The RF reference distribution system requires phase monitor system providing high measurement accuracy. The detected reference signal passes through coaxial cable and many RF components including attenuator, amplifier, mixer and Band Pass Filter (BPF). The measurement stability is mainly affected by the slow temperature and humidity variations effect on these components used in the monitor system.

Figure 8 shows the humidity dependence of 1.3 GHz RF reference phase obtained in compact Energy Recovery Linac (cERL) at KEK. In the figure, the unit of humidity (%RH) is voltage (V) of humidity sensor. Use the following equation to convert the voltage to %RH:

$$y (\%RH) = 26.774 * x (V) - 25.659 \quad (1)$$

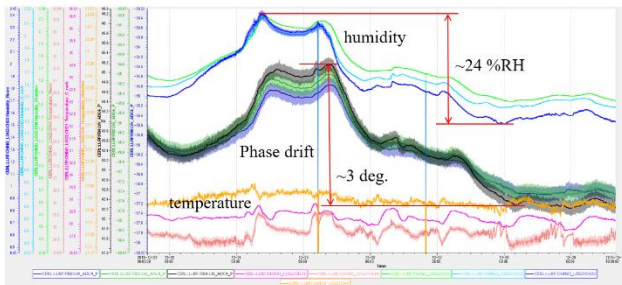


Figure 8: Humidity dependence of reference phase.

Most of RF components are putted inside the temperature controlled (28 ± 0.1 °C) but humidity uncontrolled chamber. The 1.3 GHz reference phase is down-converted to Intermediate Frequency (IF) 10 MHz with LO signal (1310 MHz) which is filtered by a narrow band BPF (1310 ± 5 MHz), then digitized and monitored with a Feedback FPGA (Field Programmable Gate Array) board. The BPF has high thermal coefficient -0.49 °/°C measured in [4]. The humidity coefficient is -0.16 ps/%RH from 50%RH to 70 %RH shown in Fig. 9. As shown in the Fig. 8, the total phase error is 3° . The humidity fluctuation is 0.9 V, corresponding to 24 %RH and 1.81° phase drift (60% of the total phase error). The desiccant (silica gel) is used in a box with BPF and the reference phase becomes more stable.

In the monitor system, the S-band signal is down-converted to IF and processed in the FPGA board. In order to eliminate the potential long-term phase drift of the phase monitor system itself, the two-tone calibration method was

implemented [6, 7]. The simulation and implementation is in progress.

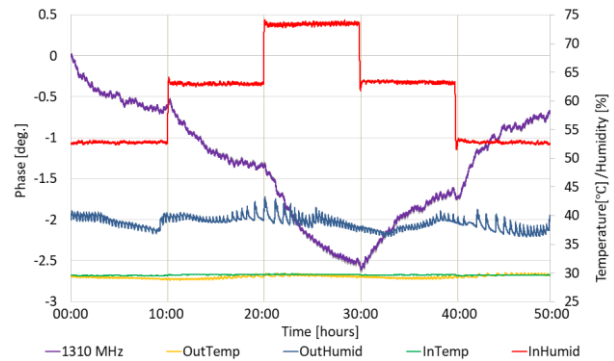


Figure 9: Humidity coefficient of 1310 MHz BPF.

CONCLUSION

The temperature and humidity characteristics of optical link were measured, and the thermal coefficient of -0.62 ps/°C and the humidity coefficient of -0.038 ps/%RH from were obtained at 2856 MHz. Also the humidity characteristics of PSOF and 1310 MHz BPF were measured. Compare to the thermal phase drift, the phase drift induced by the large humidity fluctuation makes more contribution. Actually the humidity coefficient is not high. The phase drift of optical link is not sufficiently low for the requirement. Therefore the phase feedback system is necessary in order to transmit the RF reference signal over distances of a few hundred meters. The high precision phase monitor system independent of temperature and humidity variations are simulated and the implementation is in progress. It will be used to measure the phase drift of optical link between MO and sector 5 in the SuperKEKB injector linac in September 2017.

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