

# DEVELOPMENT STATUS OF RF REFERENCE PHASE STABILIZATION SYSTEM FOR SUPERKEKB INJECTOR LINAC

N. Liu<sup>\*,1</sup>, T. Miura<sup>1,2</sup>, T. Matsumoto<sup>1,2</sup>, T. Kobayashi<sup>1,2</sup>, F. Qiu<sup>1,2</sup>, D. Arakawa<sup>2</sup>, H. Katagiri<sup>2</sup>, Y. Yano<sup>2</sup>, S. Michizono<sup>1,2</sup>, B. T. Du<sup>1</sup>, <sup>1</sup>SOKENDAI, Kanagawa, Japan, <sup>2</sup>KEK, Tsukuba, Japan

## Abstract

SuperKEKB injector linear accelerator (LINAC) has 600 m beam lines which consist of 8 sectors. The 2856 MHz RF reference signals are distributed to each sector with long phase stabilized optical fiber (PSOF). The RF reference phase stability requirement is estimated to be  $0.2^\circ$  (RMS) corresponding to 200 fs. The prototype of RF reference phase stabilization system with single mode optical circulator was implemented and demonstrated in the laboratory. The returned phase drift is compensated by a piezo-driven fiber stretcher. The transmitted phase through 120 m PSOF is stabilized to 41 fs (pk-pk), which fulfilled the requirement. This paper introduces the RF reference phase stabilization system and reports the preliminary feedback result.

## INTRODUCTION

SuperKEKB injector linear accelerator (LINAC) has 600 m beam lines which consist of 8 sectors (sector A-C, 1-5) [1]. The accelerating structures at each sector are operated at 2856 MHz (S-band). The S-band radio frequency (RF) reference signals are distributed to each sector by phase stabilized optical fiber (PSOF). Different lengths of PSOF (max. 380 m) are located in LINAC gallery where the temperature fluctuation is controlled within  $\pm 1^\circ\text{C}$  and the humidity varies from 10%RH to 50%RH without control. During long-distance transmission, PSOF suffers the slow phase drift due to the temperature and humidity changes. The thermal propagation delay of PSOF is  $-1.92\text{ ps/km}/^\circ\text{C}$  at 1550 nm [2]. The transmitted phase through different lengths of PSOF drifts varying from  $3^\circ$  to  $5^\circ$  at sector 2 to 5 [3]. SuperKEKB injector LIANC has been upgraded from KEKB. The bunch charge is increased from 1 nC to 4 nC and more tight energy spread is required, e.g. 0.125% to 0.07% for electron beam at the end of LINAC. Stabilization of RF reference phase over long distance transmission is very important for stable RF operation. The RF reference phase stability requirement is estimated to be  $0.2^\circ$  (RMS) at 2856 MHz, corresponding to 200 fs, including short-term timing jitter and long-term phase drift. A RF reference phase stabilization system is proposed to compensate the long-term phase drift.

The reference phase stabilization system is implemented by using two single mode optic circulators (SMOC) and a piezo-driven fiber stretcher (PDFS) is adopted to compensate the phase drift. The same optical wavelength (1550 nm) is used for the forward and backward signals. In this paper, an overview of the reference phase stabilization system is presented firstly. Then the main optical devices are introduced. Finally, the long-term performance is evaluated.

## SETUP OF RF REFERENCE PHASE STABILIZATION SYSTEM

A prototype of reference phase stabilization system with SMOC is proposed. The schematic diagram is shown in Fig. 1. The 2856 MHz reference signal (REF) is generated by a signal generator. The electric signal is converted to the optical signal with 1550 nm wavelength by a optical transmitter (E/O). The optical signal is transmitted with 120 m PSOF, which is situated inside the temperature and humidity controlled chamber (THC) so that we can simulate the environment changes near PSOF as that of LINAC gallery. Finally, the optical signal is converted to the electric signal by a optical receiver (O/E). This transmitted signal (TRS) is further used as local oscillator (LO) for low-level RF (LLRF) system and the reference signal for beam diagnostic system in SuperKEKB injector LINAC.

Usually, the reference signal is distributed with hundreds of meters PSOF from master oscillator (MO) to the receiver. Two SMOCs are used to return the signal. The phase drift of the returned signal (RTN) is expected to be twice that of TRS. The RTN phase drift is compensated by the active optical length control with PDFS so that the TRS phase is stabilized. The same optical wavelength (1550 nm) is applied for the transmitted and returned line.

The S-band frequency is down-converted to the intermediate frequency (IF, 14.28 MHz) by mixing with LO (2870.28 MHz). The IF signal is sampled by 16-bit analog-to-digital converter (ADC) with the sampling rate (SR) 114.24 MHz using oversampling technique ( $\text{SR} = 8 \times \text{IF}$ ). Finally, the RF phase is obtained [3]. The phase error between RTN and REF is calculated and fed to a PDFS so that the optical length is adjusted to compensate the phase drift. An integral (I) controller is applied for precise feedback control. The TRS phase is monitored to evaluate the system performance. Beside this, the phase drift of E/O, O/E modules is also measured to study its phase drift contribution. The E/O and O/E modules are provided by TAMAGAWA Inc. and the specification is listed in [3, 4]. To reduce the system phase drift due to the temperature and humidity changes, the monitor system and all the RF/optic devices are situated inside the temperature stabilized chamber (TC) with  $\pm 0.1^\circ\text{C}$ .

## Single Mode Optic Circulator

The transmitted signal is sent back by single mode optic circulator. The SMOC is non-reciprocating, one directional, three-port devices. It allows light to travel only from port 1 to port 2, port 2 to port 3 with minimal loss. It is provided by Thorlabs Inc. [5] and the specification is listed in Table 1.

\* liuna@post.kek.jp

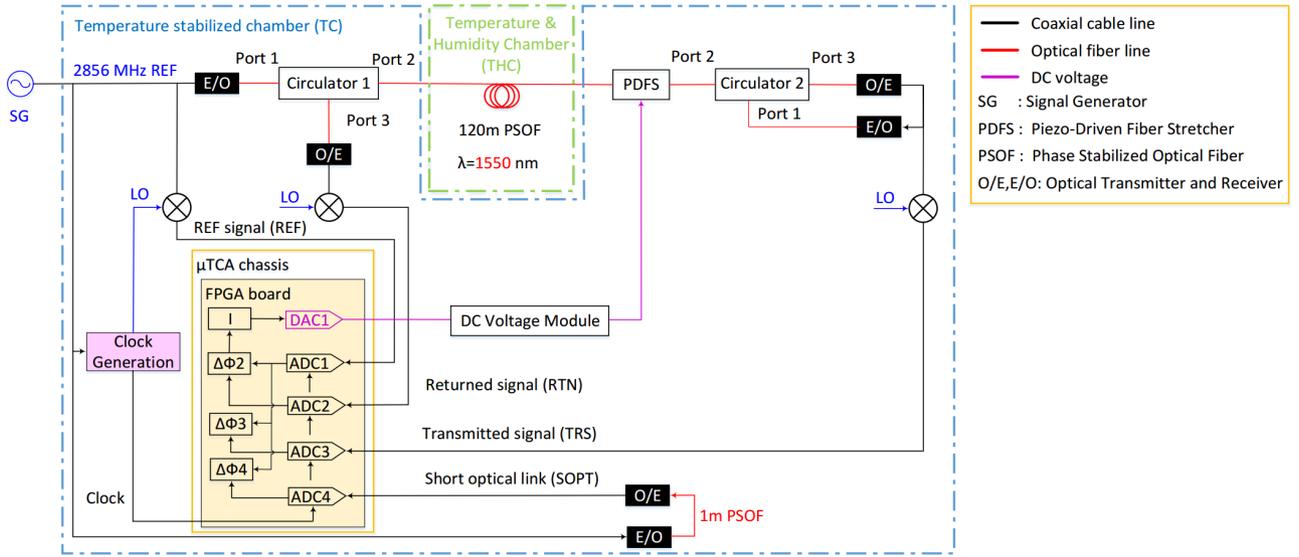


Figure 1: Schematic diagram of RF reference phase stabilization system with two optical circulators.

Table 1: Specification of Single Mode Optical Circulator

| Specification                  | Value                   |
|--------------------------------|-------------------------|
| Wavelength Range               | 1525-1610 nm            |
| Insertion Loss                 | 0.8 dB Typ./1.0 dB Max. |
| Isolation                      | >40 dB                  |
| Directivity (port 1 to port 3) | >50 dB                  |
| Return Loss                    | ≥50 dB                  |
| Max. Optical Power             | 500 mW                  |
| Operating Temperature          | 0 to 70 °C              |
| Operating Relative Humidity    | 5% to 60%               |

### Piezo-Driven Fiber Stretcher

To compensate the phase drift of long optical link caused by the temperature and humidity fluctuation, the mechanical variable optical delay line (VODL) and PDFS are widely used for optical length control. The VODL is driven by a stepping motor with low resolution and large optical delay range up to hundreds of millimeters. The PDFS is driven by an electrical piezo with high resolution and small optical delay range limited to several millimeters. In our system, the RF phase at 2856 MHz is very sensitive to the mechanical structure. 0.25° phase jump was observed when the stepping motor changed the direction of rotation [2]. For precise optical length control, PDFS is adopted for the phase drift compensation. The PDFS is provided by General Photonics Inc. [6]. The optical delay range is up to 3 mm with maximum (max.) input voltage 4.7 V. The device is controlled by four independent piezoelectric ceramics (PZTs) so that we have the option to drive each PZT individually for high resolution or collectively for large stroke. In addition, each PZT can be controlled either with an analog signal or a 12-bit transistor-transistor logic (TTL) signal. In our case, 4

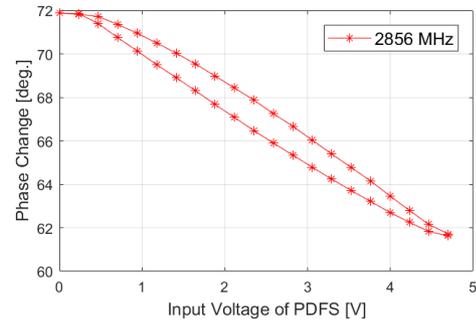


Figure 2: Phase change as a function of the input voltage of PDFS.

cascaded PZTs are driven by a 16-bit digital-to-analog converter (DAC). Figure 2 shows the relationship between the RF phase change and the input voltage of PDFS. The phase range of PDFS is up to 10.5° at 2856 MHz, which covered the phase drift of optical link in the gallery (max. 5°). The sensitivity is 2.23°/V.

### PERFORMANCE EVALUATION

To evaluate the performance of the phase stabilization system, a test feedback system is implemented in the laboratory as shown in Fig. 1. The temperature inside THC is changed from 25 °C to 40 °C and down to 25 °C at stable humidity 40%RH. The temperature step is 5 °C per 2 hours. Figure 3 shows the phase drift without feedback (DAC=0V). The TRS and RTN phase are changed 5.16° and 10.3°, respectively. The RTN phase is twice the TRS phase as expected. The feedback result is shown in Fig. 4. It is clear to see that the phase drift of the long optical link is compensated by PDFS. The RTN and TRS phase are stabilized within 0.73 fs (RMS)

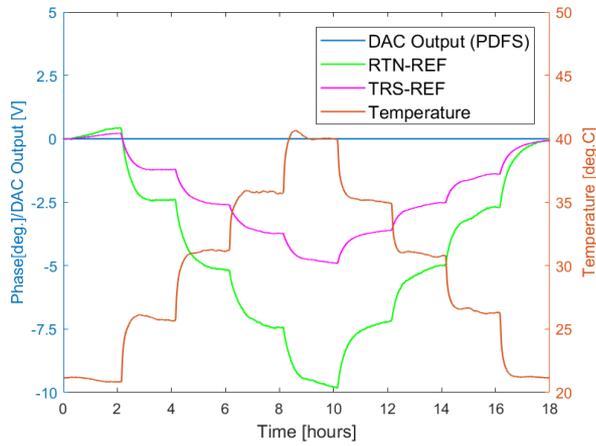


Figure 3: Long-term phase drift without compensation.

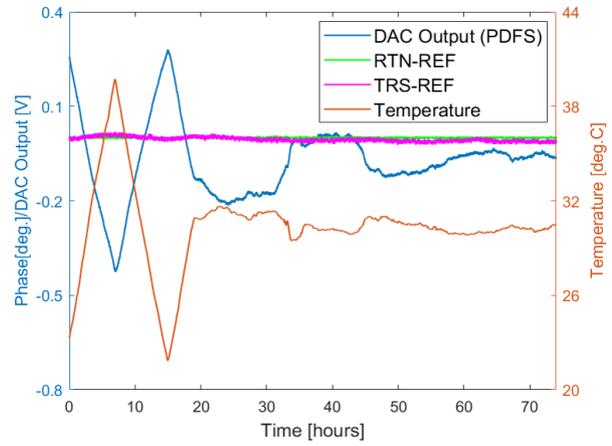


Figure 5: Long-term phase drift with compensation for 72 hours.

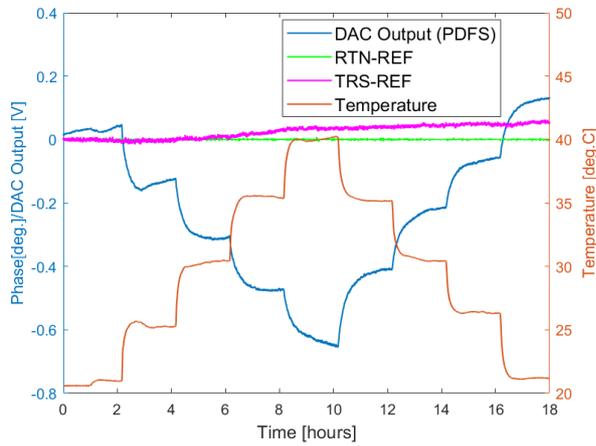


Figure 4: Long-term phase drift with compensation for 18 hours.

and 111 fs (pk-pk). Figure 5 shows the long-term feedback result for 72 hour. The TRS phase is stabilized to 41 fs (pk-pk). In the above measurements, all the system phase drift is rejected from TRS and RTN phase. The RTN phase can be controlled very well but small phase drift still reminds for TRS. We found that TRS phase has weak correlation with the temperature and humidity inside TC, moderate correlation with outside humidity, very weak or no correlation with outside temperature. Thus, the humidity effect on the optic devices is the main reason for the residual TRS phase drift. The moisture can enter through the holes or the small gaps from the outside into the thermostats. It is considered to seal the optical devices with stable humidity.

## CONCLUSION

A phase stabilization system with optic circulator is developed and demonstrated. The returned phase was controlled

within 0.73 fs (RMS) and the transmitted phase was stabilized to 41 fs (pk-pk) which fulfilled the requirement 200 fs (RMS). We found that the transmitted phase is influenced by outside humidity because all the optical components are only temperature stabilized, not humidity controlled. It is considered to seal the optical components with more stable humidity to improve the transmitted phase stability. The other two different phase stabilization systems will be implemented and tested. Finally, the long-term performance of these three phase stabilization systems will be compared to be a candidate scheme for SuperKEKB injector LINAC.

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