RF PHASE FEEDBACK AT KEK e-/e+ INJECTOR LINAC

T. Miura[1,2,†], T. Matsumoto[1,2], H. Katagiri[1], T. Natsui[1,2], T. Kudo[3]
[1]High Energy Accelerator Research Organization (KEK), Tsukuba, Japan
[2]The Graduate University for Advanced Studies (SOKENDAI), Tsukuba, Japan
[3]Mitsubishi Electric System & Service Co., Ltd, Tsukuba, Japan

Abstract

The KEK e-/e+ injector LINAC provides the beams to four storage rings with the top-up injections by switching the beam mode in 50 Hz repetition rate. The beam charge, energy, and number of bunches (one or two) are different for each ring. Therefore, the settings of RF timing and phase are adjusted in each beam mode independently. To stabilize the RF phase drifts caused by the cooling water and accelerating structure temperature, the RF phase feedback was introduced. The correction phase amount is determined by the feedback calculation for the RF at the accelerating structure outlet in non-injection mode (NIM) without beam acceleration. This value is then added to set phase as an offset phase value in each mode. This method has stabilised the RF phase in all modes without considering complex operating conditions.

INTRODUCTION

The KEK e-/e+ injector LINAC [1] provides the beams with top-up injection to four storage rings (SuperKEKB HER, LER, PF, and PF-AR) which require different beam energy, beam charge, and number of bunches as shown in Fig. 1. The beam mode is switched pulse by pulse at a 50-Hz repetition rate of the LINAC by the event timing system [2].

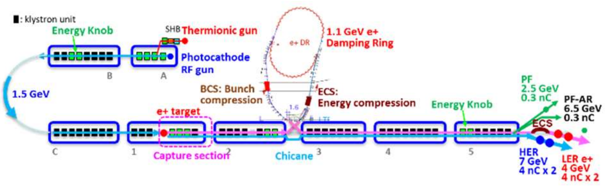

Figure 1: Layout of the KEK e-/e+ injector LINAC.

Figure 2 shows the RF drive system [3] in the injector LINAC. The RF frequency is 2856 MHz, and the RF pulse width from klystron is 4 μs. The RF power is compressed by SLED, then the RF is fed to four accelerating structures. The low-level RF (LLRF) unit [4] receives beam mode information and RF setting phase directly from the event timing system via optical fiber for each pulse and generates RF pulses. The LINAC is divided into eight sectors (A-C and 1-5). In a normal RF drive system, one LLRF control unit per sector supplies RF to up to 8 klystrons. Special units used for energy knobs to fine-tune beam energy, energy compression systems (ECS), bunch compression systems (BCS), etc., are one-to-one independent drive systems.

Each klystron unit is equipped with an RF monitor [5], which measures the RF amplitude and phase of the klystron, SLED, and accelerating tube outlet for every pulse.

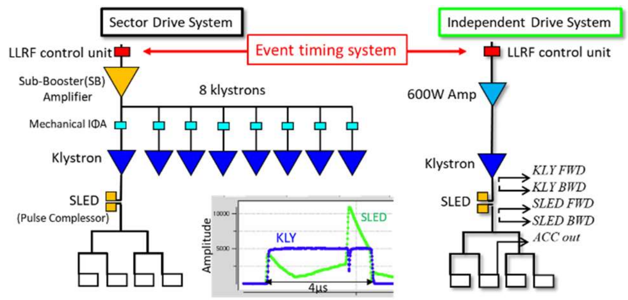

Figure 2: Klystron drive line using sub-booster amplifier (left) and individually drive system (right).

The RF amplitude is driven near the saturation region of the klystron. The RF phase stability is highly dependent on the cooling water temperature. Due to the aging of the equipment, control was not properly executed, and the phenomenon of cooling water temperature hunting frequently occurred. In such a case, stable beam acceleration becomes difficult, so we newly introduced RF phase feedback. The stabilization by feedback should be established for various operation patterns simultaneously. This paper describes the details of phase feedback and the operational precautions.

PHASE FEEDBACK

As the cooling water temperature changes, the resonant frequency of the accelerating tube changes, causing a phase shift. There are three types of accelerating structures with different iris diameters. The total phase shifts of each are 7.80, 8.60, and 9.44 deg/°C in the design. Figure 3 shows an example of the temperature drift of the cooling water and the RF phase drifts for the accelerating structure outlet (ACC) and SLED output in the cooling water temperature control malfunction case. In Fig. 3, a maximum water temperature fluctuation of 0.27°C is observed, and the corresponding phase shifts calculated using the design parameters are equivalent to 2.10°, 2.32°, and 2.55°. The observed phase change of ACC is large at 5.6 deg for a change of 0.27 °C, and one of SLED is 2.9 deg. That means the phase shift in the accelerating structure is equivalent to the difference of them, 2.7 deg. This value is almost consistent with the design value. Therefore, the RF phase feedback is performed to keep the RF phase at ACC constant.

† takako.miura@kek.jp

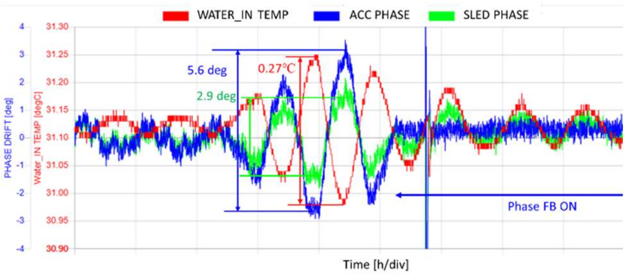

Figure 3: Hunting of cooling water temperature and RF phase drift of ACC and SLED output during cooling water control troubles.

The injector LINAC provides beams to four rings, but depending on the operation, there are times when the beam is not emitted. If acceleration begins with a shifted phase when re-injecting, beam loss will occur. Therefore, phase fluctuations caused by changes in water temperature must always be corrected, even if there is no beam acceleration. The injector LINAC has Non-Injection-Mode (NIM) that does not involve beam injection. The phase correction amount, φ_{corr}, is determined by feedback calculation in the NIM mode. As shown in Eq. (1), the sum of the RF phase of each mode, θ_{mode}, and φ_{corr} is set in the LLRF control unit.

$$\theta_{set} = \theta_{mode} + \varphi_{corr}. \quad (1)$$

Since the NIM mode is used for feedback, at least 1 Hz out of 50 Hz is allocated for it. The RF phase changes significantly with different klystron voltages, so a logic was designed to monitor the RF amplitude and provide feedback if it is within ±1% of the operating value. However, due to amplitude change caused by seasonal temperature fluctuations, the current amplitude tolerance is set to ±2%. Additionally, due to aging, poor contact in the coaxial cables can cause sudden changes in amplitude and phase. When this happens, the feedback stops as the amplitude falls outside the acceptable range, preventing malfunction.

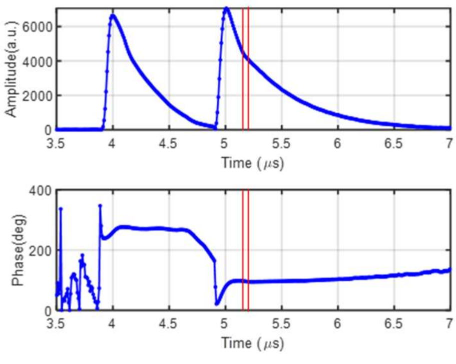

Figure 4: The reflection waveform of the RF gun. The red line indicates the gate for the data to use feedback calculation.

The phase feedback was also introduced to the 114 MHz and 571 MHz subharmonic bunchers used on the thermionic gun side. On the other hand, the RF electron gun [6] for generating low-emittance beams employs feedback based on the reflected wave shown in Fig. 4, as there is no pickup inside the standing wave cavity. The second peak waveform of the amplitude data is the RF accumulated in the cavity that is output immediately after the input RF is turned off. Feedback is performed using the phase information of this part. Finally, phase feedback has been introduced to all RF units.

Case of All RF Off

Figure 5 shows the response of cooling water temperature and RF phase feedback before and after tunnel entry work for 70 min. The ACC phase for all modes was well stabilized, although some residuals were observed. Prior to the introduction of the phase feedback, after all klystrons turn on, it was necessary to wait for an hour until the water temperature stabilized before resuming beam operation. However, with the introduction of phase feedback, beam operation can be resumed within a few minutes after RF on. The resumption of beam operation in such a short time is supported not only by RF phase feedback but also by beam energy feedback and orbit feedback.

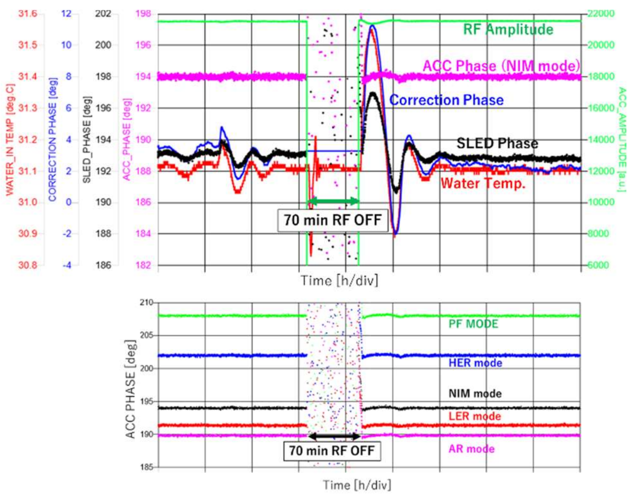

Figure 5: Response of cooling water temperature and RF phase feedback before and after tunnel entry work.

Case of Individual RF Off

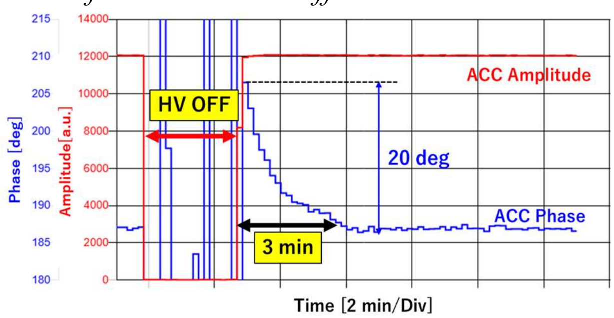

Figure 6: RF amplitude and phase without phase feedback after the klystron output is turned off for a few minutes due to an interlock.

During steady operation, if the RF is turned off due to the VSWR interlock, the RF is usually turned on immediately after waiting for 5 seconds, resulting in almost no phase fluctuation. On the other hand, if the klystron high voltage turns off due to an interlock, there is a downtime of a few minutes as it requires verification work before resuming operation. In this case, since the RF turns off at only one klystron unit, there is no change in the cooling water temperature. However, the SLED and accelerating structures cool down, causing a significant phase change immediately after recovery, as shown in Fig. 6. For the independent drive system, phase feedback is started immediately after resuming. However, for the sub-booster drive system, if feedback is applied to correct this, it will affect other units that are operating stably. Therefore, phase feedback is resumed after waiting for 3 minutes until the phase stabilizes as shown in Fig. 6. Accordingly, beam acceleration will also be on standby for three minutes.

LONG-TERM PHASE DRIFT

The long-term phase drift of the correction phases and the humidity are shown in Fig. 7.

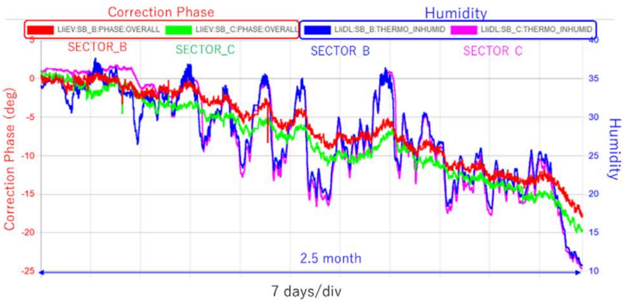

Figure 7: Long-term phase drift of the correction phase and the humidity.

The phase feedback correction amount is set to 0° at the start of operation, so it was expected to return to around 0° during normal operation. However, as the operation continued, an offset began to appear in the values. Upon investigation, it was found that, as shown in Fig. 7, there is a correlation with humidity. As the humidity decreases, the correction phase amount shifts to the negative side. The dependence on humidity suggests that the cause may lie in the signal transmission lines, RF drive system, or RF monitoring systems. The humidity dependence of phase drift in the reference signal transmission systems sent to each sector has already been reported [7]. The offset in the phase correction amount raises concerns about a relative phase shift with the beam. However, in practice, the set phase for each mode is adjusted regularly to ensure the appropriate phase while observing the beam's condition, so it has not become a serious issue.

SUMMARY

At the KEK e-/e+ injector LINAC, RF phase feedback has been introduced. The phase feedback determines the phase correction amount using the NIM mode, which does not involve beam acceleration, and sets it in the RF control unit in addition to the set values for each mode. Since the NIM mode continues at least at 1 Hz, it is possible to stabilize the phase of all modes continuously, regardless of whether injection into each ring is occurring. This method has made the RF phase stable in all modes without considering complex operating condition. The introduction of RF phase feedback has enabled stable beam acceleration even with fluctuations in the cooling water temperature.

A significant humidity dependency has been observed as a long-term phase drift. However, this has not been a serious problem in actual operation because humidity changes are fairly uniform throughout the facility, and the set phase is fine-tuned daily during operation.

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