LASER-TO-RF SYNCHRONIZATION AND ITS EFFECT ON THE ELECTRON BEAM STABILITY AT THE KEK ATF

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Abstract

The Low-Level RF (LLRF) system at the KEK Accelerator Test Facility (ATF) is based on a signal generator architecture. Synchronization of the RF-Gun laser system to the accelerating field is achieved via piezoelectric (piezo) feedback. However, reference line, High Power RF jitter and/or drift can significantly degrade Laser-to-RF synchronization. The synchronization stability of the RF-Gun laser pulse arrival relative RF pulse and its impact on electron beam parameters immediately downstream of the gun was investigated.

INTRODUCTION

Low-Level Radio Frequency (LLRF) systems in accelerators must meet stringent requirements on stability, accuracy, reproducibility, and real-time monitoring to ensure reliable facility performance [1–4]. To achieve this, dedicated signal distribution architectures are employed to synchronize the accelerating field phase with the arrival time of the RF-gun laser pulse. The synchronization stability of the RF-gun laser pulse relative to the RF field, and its influence on the electron beam parameters immediately downstream of the gun, is a critical factor for the injector linac's stable operation [5].

At the KEK Accelerator Test Facility (ATF) [6–9], the master signal generator provides the accelerating frequency, which is subsequently divided down to obtain lower-frequency subharmonics. The RF-gun laser system [10] is synchronized to the facility LLRF system [11] through a piezo-based feedback loop, which operates with an input reference frequency of 178.5 MHz. This reference corresponds to the 16th subharmonic of the KEK ATF Linac RF system, ensuring precise timing alignment between the laser pulses and the accelerating structures.

KEK ATF RF-GUN SECTION LOW-LEVEL RF SYSTEM ARCHITECTURE

The KEK ATF RF-Gun section Low-Level RF system consists of Agilent E8663B Master Signal Generator (SG), frequency multiplier and divider, RF-Gun laser synchronization unit, I/Q modulator and demodulator units, RedPitya STEMlab 125-14 FPGA board [12], phase shifters, pulse modulator. The schematics is demonstrated on the Fig. 1. The SG generates 1428 MHz sinewave signal. On the next stage, the signal is spitted into 2 branches. Then, the first branch frequency is doubled to get 2856 MHz sinewave for the accelerating cavities, while the second branch frequency is divided 8 times to get 178.5 MHz for the laser system synchronization unit. The reference clock for the klystron is transferred to the klystron RF station via fiber over 30 m. The laser clock is sent to the laser hut via RF cable over 30 m too.

The klystron branch RF signal phase and amplitude are modulated by I/Q modulator unit. The RedPitaya STEMlab 125-14 FPGA board is the inter-pulse phase&amplitude Low-Level RF feedback controller [12, 13]. The phase shifter is devoted for the manual phase scan control. At the final stage of the klystron Low-Level RF branch, the sinewave signal is modulated by the pulse. Then, the RF pulse is amplified by the drive amplifier up to 600 W before sending to the klystron. The klystron amplifies the RF pulse from 600 W to 40 MW peak power. Meanwhile, the laser RF clock signal is injected into dedicated phase shifter to control its phase. Then, it is sent to the RF-Gun laser piezo feedback synchronization unit to phase-lock the laser with the high power RF pulse.

The klystron output RF pulse is picked up by directional coupler. The directional coupler attenuates the RF pulse power by 50 dB. Then, the attenuated pulse is transferred to the I/Q demodulator unit to be down-converted 2856 MHz sinewave to I and Q DC signals [12]. At the next stage, the I and Q signals are processed by the digital LLRF feedback controller based on the FPGA logic.

EXPERIMENTAL SETUP

The experimental measurements were conducted at the KEK Accelerator Test Facility, particularly its RF-Gun section. Figure 2 shows the RF-Gun section beamline schematics. The electron beam is generated by the Cs_2Te photocathode irradiation by 1 laser pulse, which wavelength and repetition rate are 266 nm and 3.125 Hz, correspondingly. At the beginning, the electron beam is accelerated by the 3.6-cell RF-Gun. After acceleration, the beam enters a solenoid installed at an outlet of the RF-Gun cavity. Then, the emittance compensated electron beam passes through the first beam intensity monitor (GUN ICT) [14] and chicane. At the next stage, the beam passes through the 3 m length traveling wave type accelerating cavity. So, it is accelerated up to 74 MeV energy. Then, it propagates through the second beam intensity monitor (L0 ICT) [14]. At the final stage, the electron beam is deflected by the bending magnet and hit the screen.

MEASUREMENT RESULTS

The phase&amplitude stabilities of the Low-Level RF signals associated with the RF-Gun section were measured (see Fig. 3). These are following:

1. The laser piezo feedback synchronization unit read-out;

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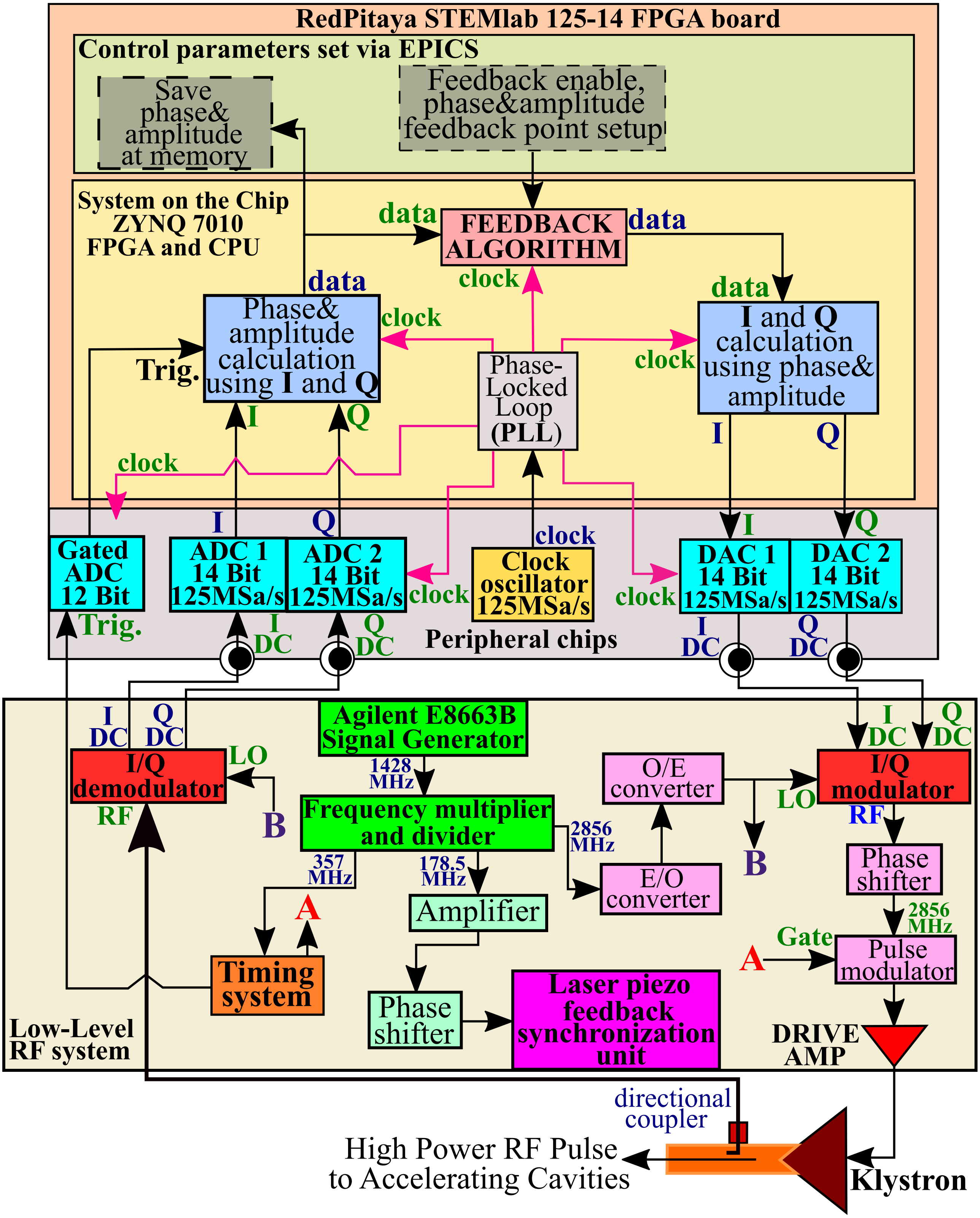

Figure 1: KEK ATF RF-Gun section Low-Level RF system architecture block-diagram.

2. The synchronization jitter between klystron clock and laser clock signals;
3. The klystron output high power RF phase and amplitude jitter and drift/or fluctuation;

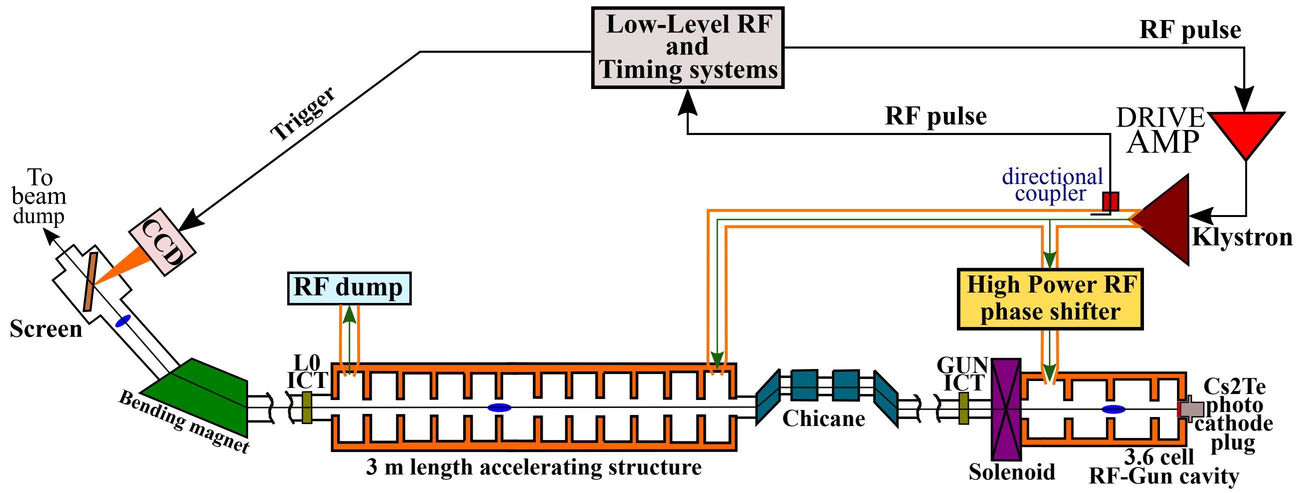

Figure 2: Experimental setup.

Written above signals phase&amplitude stabilities affect the following beam parameters:

1. The beam intensity at the RF-Gun outlet (see Fig. 2);
2. The beam intensity at the 3 m length accelerating cavity output (see Fig. 2);
3. The beam transmission;
4. The beam energy;
5. The beam energy spread;

These beam parameters are vital for the facility operation. So, it was synchronously measured with LLRF signals phase and amplitudes. The results were acquired during the RF-Gun section operation on July 2025. The time span is 1 hour (see Fig. 3). The digital Low-Level RF inter-pulse phase&amplitude feedback [11] was enabled during the data acquisition.

The RF-Gun laser output power jitter is equal approximately 1.0% (RMS) [10]. However, the UV photodiode signal [15] stability is equal to 1.16% (RMS) over 1 hour. The laser system piezo feedback synchronization unit sends the phase noise value once per 10 s. These laser piezo feedback phase noise data depicts stable value equal to 200 fs, but sometimes its value is doubled (see Fig. 3).

The klystron output high power RF pulse amplitude jitter is 0.04% (RMS). It demonstrates that the klystron output is highly saturated. Therefore, the amplitude jitter does not affect beam parameters [11]. Although, the high power RF pulse phase jitter is equal to 90 fs (RMS). The laser piezo feedback synchronization unit demonstrates 2 and 4 times higher noise than the klystron high power RF pulse for accelerating cavities. As a result, beam intensity jitter at the outlet of the RF-Gun and 3 m accelerating cavity (see Fig. 2) equals to 1.40% and 1.22%, correspondingly. As a consequence, these beam intensity jitters induces the transmission jitter at 1.84% (RMS) of original transmission value.

LASER-TO-RF SYNCHRONIZATION LIMIT DISCUSSION

According to the LLRF system architecture, there are 3 aspect, which can affect the electron beam intensity stability from the Low-Level RF side. Also, these aspects define the laser-to-RF synchronization limit.

These are the following:

1. The phase&amplitude jitter, drift and/or fluctuation of the klystron high-power RF;
2. The RF-Gun laser piezo feedback quality and its loop latency;
3. The RF-Gun laser reference clock drift relative the klystron RF clock;
4. The signals phase noise power spectrum distribution (PN PSD) and absolute phase jitter associated with it (see Fig. 4);

The klystron RF and laser clock PN PSD are shown on the Fig. 4. The PN PSD was integrated from 10 Hz to 10 MHz frequency offset. The klystron clock phase jitter (RMS) is equal to 0.207° or 201 fs, while the laser clock phase jitter (RMS) is 0.019° or 294 fs. The PN PSD was measured by the Keysight SSA E5052B Signal Source Analyzer [12, 13].

Its settings are 30 dB IF signal amplification, 10 correlations and 100 averagings. If the both clocks' phase jitters are considered as incoherent, the Laser-to-RF synchronization limit in time domain is calculated according to Eq. 1.

$$\sigma_{\text{sync}} = \sqrt{\sigma_{\text{laser}}{}^2 + \sigma_{\text{RF}}{}^2}, \qquad (1)$$

where σ_{sync} is the Laser-to-RF absolute synchronization limit (RMS), σ_{laser} is the laser clock phase jitter (RMS), σ_{RF} is the klystron clock phase jitter (RMS).

So, the Laser-to-RF synchronization limit is equal to 356 fs (RMS) at the KEK Accelerator Test Facility, particularly its RF-Gun section. The phase noise higher than 356 fs (RMS) is induced by the reason 1 and/or 2 and/or 3.

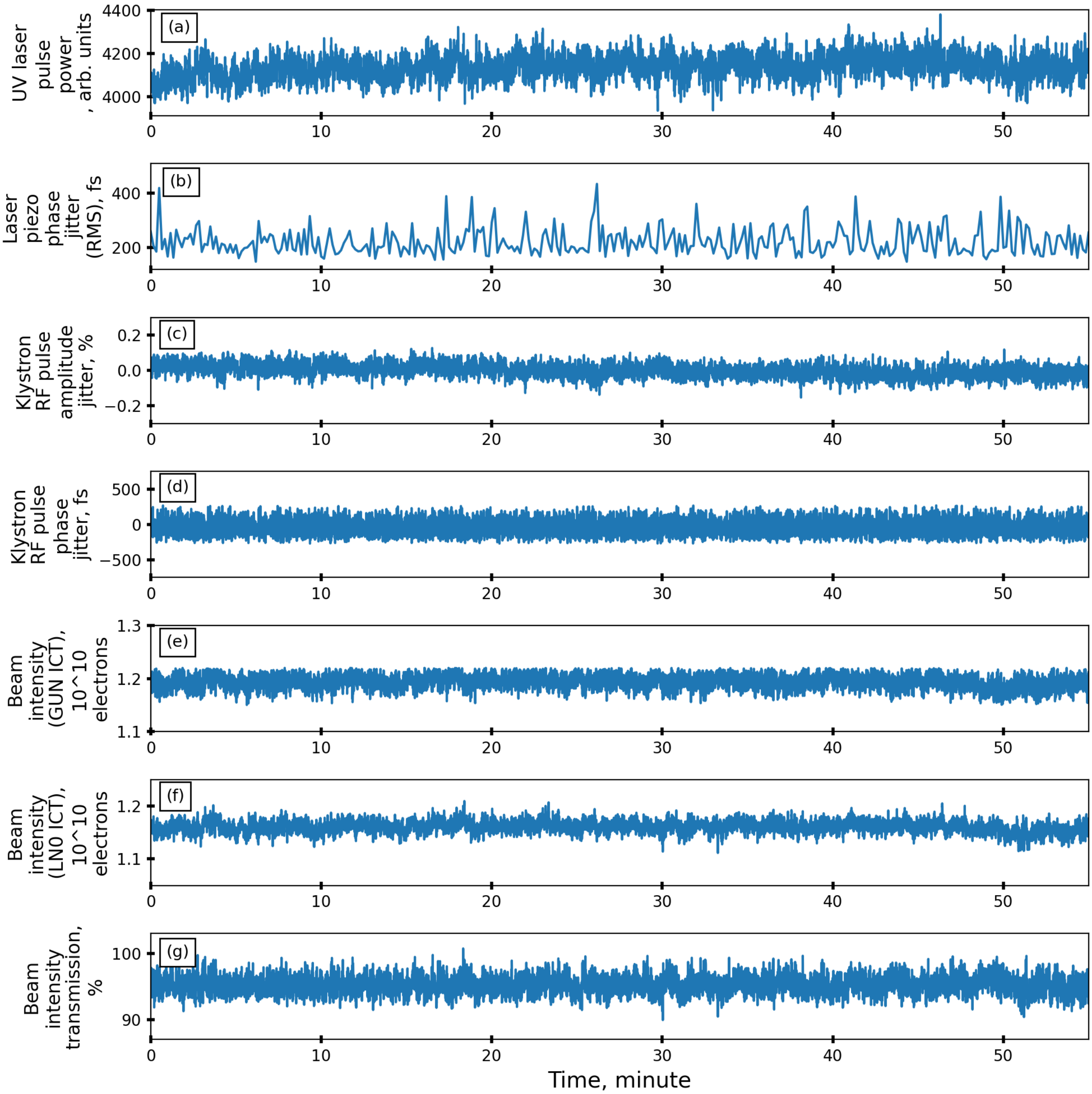

Figure 3: Experimental results: (a) is the UV laser pulse power vs time, (b) is the laser piezo feedback phase jitter (RMS) vs time, (c) is the klystron RF high power RF pulse amplitude jitter vs time, (d) is the klystron high power RF pulse phase jitter vs time, (e) is the beam intensity at the outlet of the RF-Gun vs time, (f) is the beam intensity at the outlet of the 3 m accelerating cavity vs time, (g) is the beam intensity transmission over RF-Gun section vs time.

CONCLUSION

The KEK ATF RF-Gun laser piezo feedback phase noise is dominating factor of the laser pulse to RF synchronization. Also, the phase noise of the laser reference clock itself is dominating factor too. These can possibly affect beam intensity stability immediately downstream of the RF-Gun. The laser clock Low-Level RF branch improvement, such as E/O and O/E modules implementation and frequency multiplier&divider module, can significantly decrease the laser piezo feedback phase noise in the future.

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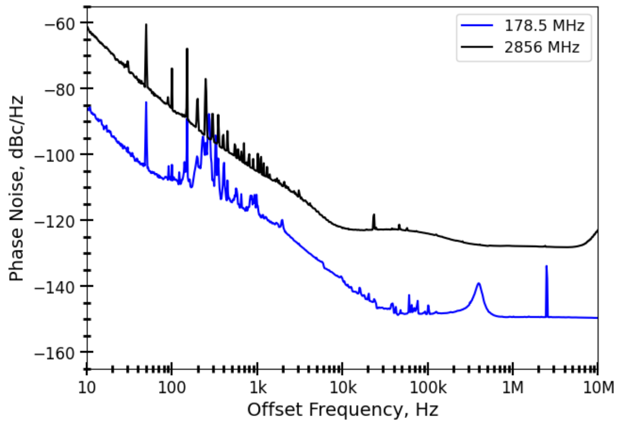

Figure 4: KEK ATF clock signals PN PSD: (blue) is the laser clock equal to 178.5 MHz, (black) is the klystron clock equal to 2856 MHz.

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