KEK LUCX FACILITY LASER-TO-RF&RF-TO-RF STABILITY STUDY AND OPTIMIZATION

K. Popov[†], The Graduate University for Advanced Studies (SOKENDAI), Shonan Village, Hayama, Kanagawa 240-0193, Japan
A. Aryshev, N. Terunuma, J. Urakawa, High Energy Accelerator Research Organization (KEK), 1-1 Oho, Tsukuba, Ibaraki 305-0801, Japan

Abstract

The KEK LUCX facility is a linear accelerator devoted to the beam instrumentation R&Ds for present and future accelerator systems and colliders. Also, it is used for the development of a compact and intense source of monochromatic X-rays based on the Compton backscattering phenomena and for development of cost-effective LLRF feedback systems. We aim to achieve RF-gun Laser-to-RF&RF-to-RF phase stability of 0.35°(RMS) and amplitude stability of 0.07%(RMS) with implementation of the Digital LLRF feedback based on commercially available FPGA board and digital trigger system.

As the first step to achieve that level of stability, present RF phase and amplitude jitters were measured using time- and frequency-domain techniques. After that, jitter influence on beam parameters after RF-gun and main solenoid magnet was simulated with ASTRA tracking code and results were cross-checked during LUCX facility beam operation. Finally, a stable digital trigger system and digital LLRF phase monitor based on SINAP EVG&EVR and STEMlab 125-14 modules were implemented.

This report demonstrates the results of Laser-to-RF&RF-to-RF phase and amplitude jitter measurements cross-checked with ASTRA simulation and real beam parameters measurements.

INTRODUCTION

The KEK LUCX facility [1] (Fig. 1) is the compact linear accelerator employing an Nd:YAG laser system to generate a multi-bunch electron beam of a Cs:Te photocathode and accelerate it in a 3.6-cell S-band (2856 MHz) standing wave RF-gun and 12-cell S-band standing wave booster. The beamline electron optics includes a solenoid, quadrupole, steering and bending magnets. Beam diagnostics include Inductive Current Transformers (ICTs), button type Beam Position Monitors (BPMs) and ceramic luminophore screen (DMQ), YAG and OTR screens. With the help of Nd:YAG laser it is possible to generate a nC bunches of the picosecond duration. The development of a compact and intense source of monochromatic X-rays based on the Compton backscattering [2] at the KEK LUCX facility faces a few technical challenges affecting the stability of X-ray photon flux characteristics due to Laser-to-RF, RF-to-RF phase and amplitude jitter. Therefore it was decided to develop a new LLRF feedback system for S-band RF-gun and 12-cell accelerating structure to achieve 300 fs phase stability of the accelerating field 2856 MHz using cost-effective and commercially available FPGA boards [3]. The realistic way to stabilize RF and timing systems to the abovementioned level is to employ a digital trigger/gate/delay generators, digital Low-Level RF (LLRF) and digital feedback systems.

The common trigger/timing distribution systems are semi-analogue solution, which are based on the NIM Linear Synchronization modules fed by a Signal Generator Continuous Wave and analogue NIM FANOUTs, gate generators, NIM/TTL or TTL/NIM level converters with digital CAMAC/VME time delay modules. Many of the LLRF distribution systems are still based on NIM frequency dividers/multipliers, power dividers, RF amplifiers and attenuators modules with semi-analogue feedback modules of a different architectures (I/Q demodulators, CPU, FPGA [4] with implemented PID controllers, I/Q modulator) based on different standards (VME, microTCA, etc). Moreover, all three subsystems should be phase-locked on each other.

It was decided to follow the cutting-edge approach to achieve extremely low Laser-to-RF and RF-to-RF phase jitter of a 300 fs (RMS) of 2856 MHz at KEK LUCX. It is based on a digital multichannel programmable trigger/delay/gate generator as a stand-alone module (Highland Technology [5], Berkley Nucleonics [6] or SINAP EVG&EVR [7]), as well as utilizing the optical fibers for LLRF distribution instead of coaxial RF cables. Furthermore, modern cost-effective feedback systems can be based on RedPitaya FPGA boards (for example STEMlab 125-14 [3]) which can sample the down-converted from 2856 MHz to 10 MHz signals. These feedback systems have 2 ADC input and 2 DAC output channels for RF pulses from RF-gun and 12-cell booster and a separated input channel for a trigger signal and external synchronized RF clock.

STABILITY MEASUREMENT TECHNIQUES

It was necessary to measure KEK LUCX facility RF phase&amplitude stability as initial step of the timing and feedback systems upgrade, thereafter simulate its jitter influence on the beam characteristics along beamline, especially at Compton Interaction Point (IP). The Tektronix DPO 7354 oscilloscope with DPX option [8] was used to measure Laser-to-RF and RF-to-RF phase&amplitude stability. The “interpolation” measurement mode with 40 GSa/s sampling rate and 250 fs/point resolution was set during these measurements. The display horizontal scale was equal to 62.5 ps.

[†] popovkon@post.kek.jp.

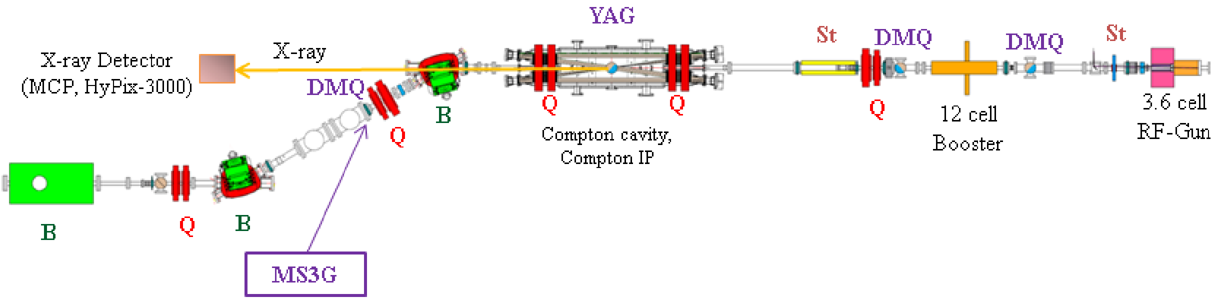

Figure 1: KEK LUCX facility beamline layout. Abbreviations: St - steering magnet, Q - quadrupole magnet doublets, B - bending magnets, DMQ - ceramic luminophore screen, YAG is the yttrium aluminium garnet screen.

Figure 2: Laser-to-RF short-term stability measurement result within 100 machine cycles at 3.13 Hz. Laser-to-RF short-term jitter is equal to 4.7 ps.

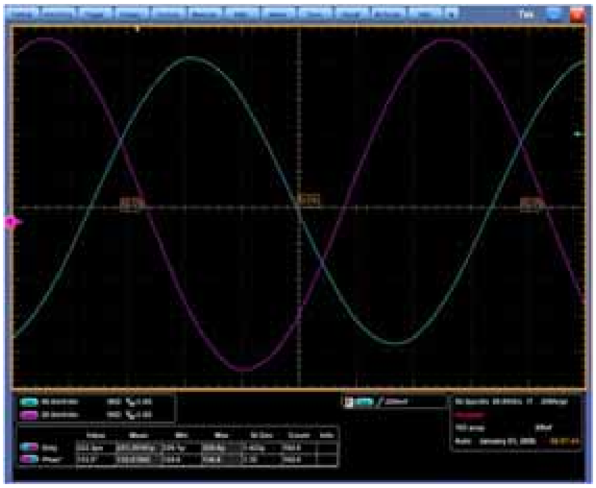

Figure 3: RF-to-RF short-term stability measurement result within 100 machine cycles at 3.13 Hz. RF-to-RF short-term jitter is equal to 1.5 ps.

The internal conventional oscilloscope "Time Delay" measurement function was applied to quantify phase&amplitude jitter value. The 100 waveforms were sampled in each measurement and the same approach was applied to measure RF-to-RF phase&amplitude jitter between RF-gun and 12-cell booster.

Measured Laser-to-RF and RF-to-RF short-term jitters were equal to 4.7 ps and 1.5 ps of S-band 2856 MHz frequency (see Figs. 2 and 3).

However, Laser-to-RF short-term jitter was decreased down to 2.5 ps of S-band after the SINAP EVG&EVR trigger and digital clock modules [7] implementation into LUCX timing system. CW signal stability of RF gun Nd:YAG laser system oscillator was analyzed separately with Agilent E5052A Signal Source Analyzer [9]. The phase noise map shows no spurs and high integrated jitter at 2.826 ps from 10 Hz to 40 MHz frequency offset for 357 MHz carrier frequencies of Nd:YAG laser.

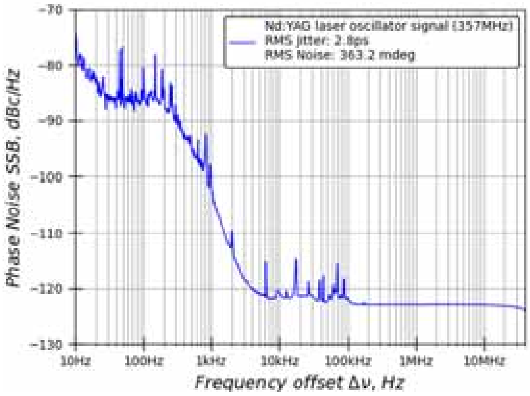

Figure 4: Nd:YAG laser oscillator phase noise map.

KEK LUCX STABILIZATION SIMULATION

The ASTRA (A Space Charge Tracking Algorithm) code [10] was chosen to simulate the beam dynamics in the LUCX beamline. 3D space-charge forces along the whole beamline and the Schottky effect at the RF-gun are accounted during the simulation tracking (see Fig. 5) which is started from the photocathode and finished at MS3G screen monitor (see Fig. 1).

Transverse beam size at the Compton IP is calculated as 92x51 μm^2 for 250 pC charge, longitudinal size as 1.2 mm or 4 ps, while energy spread is 80 keV (or ΔE=0.357% of E_e=21.34 MeV) and normalized transverse emittance is 7.180 π mrad mm x 4.129 π mrad mm. However, the realistic beam parameters are also defined by machine Laser-to-RF and RF-to-RF phase&amplitude jitter.

ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-TUPOPT066

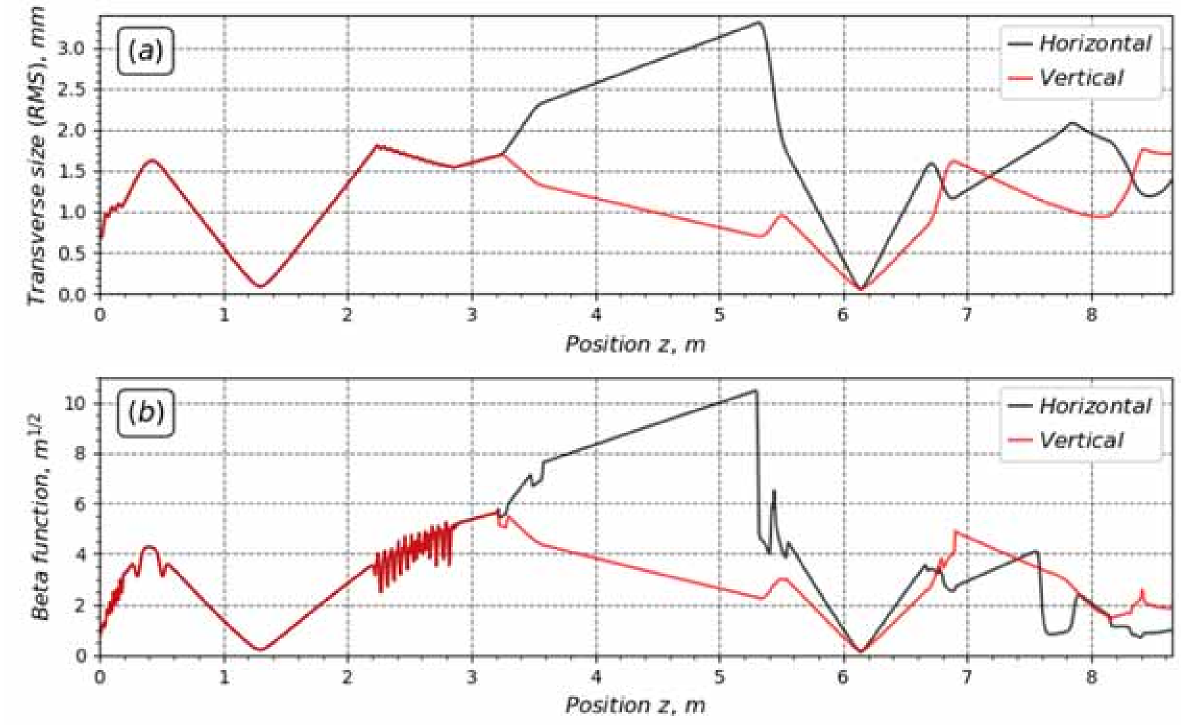

Figure 5: KEK LUCX facility beamline simulation in ASTRA. (a): transverse size (RMS) vs position along beamline, (b): beta function vs position along beamline.

Luckily, it is possible to take into account the random distributed errors of the beamline components' parameters at the ASTRA code.

Also, the influence of abovementioned jitters on the beam characteristics at the Compton IP was simulated.

Laser-to-RF and RF-to-RF phase&amplitude jitter of 2.5 ps and 1.5 ps transfers to 1.14 ps RMS time of flight (TOF) jitter, which leads to 28.5% synchronization error with laser pulse at the Compton IP, because electron beam longitudinal RMS size is 1.2 mm or 4 ps. Moreover, beam mean energy jitter and energy spread jitter are both equal to 20 keV, which is 25 % of beam energy spread at 80 keV. The value of Laser-to-RF jitter induces bunch charge jitter of 12.3 pC or 4.93% of 250 pC via the Schottky effect.

RF system and its instabilities lead to transverse horizontal emittance jitter of 0.87π mrad x mm (or 12.18% of 7.14π mrad x mm), transverse vertical emittance jitter of 0.27π mrad x mm (or 6.54% of 4.13 π mrad x mm).

Laser-to-RF and RF-to-RF jitter will be decreased to 300 fs after the introduction of the feedback system and further optimization of the LUCX facility timing, LLRF and feedback systems.

Decreased subsystems jitter values will influence on the beam parameters at IP roughly 10 times less than before the upgrade (see Fig. 5). Especially, the biggest TOF and transverse emittance jitters' values will be about 10 times improved.

TOF jitter and the Compton laser phase jitter at IP (see Fig. 4) induce the collision rate loss of a 40-50%. Therefore, Compton X-ray photons rate loss will be 4-5% after the upgrade. The spectral purity jitter will be decreased by 10 times, because it is mainly limited by the transverse emittance mean value and its jitter at IP as [11]:

$$\frac{\sigma_{E_x}^2}{E_x^2} \sim \frac{\varepsilon_n^2}{\sigma_{tr}^4} + 4 \cdot \frac{\sigma_{E_e}^2}{E_e^2}, \tag{1}$$

where σ_{Ex} is the Compton X-ray photons energy spread, E_x is the Compton X-ray photons mean energy, ε_n is the normalized transverse beam emittance, σ_{tr} is the transverse RMS beam size, σ_{E_e} is the electron beam energy spread, E_e is the electron beam mean energy.

$$\frac{\sigma_{Ex2}}{E_{x2}} = \frac{\sigma_{Ex1}}{E_{x1}} \approx 6.9\%, \tag{2}$$

where $\frac{\sigma_{Ex1}}{E_{x1}}$ and $\frac{\sigma_{Ex2}}{E_{x2}}$ are the Compton X-ray photons spectral purity mean values before and after the upgrade.

Conventional indirect error calculation gives the spectral purity jitter in absolute units as:

$$\Delta\frac{\sigma_{Ex1}}{E_{x1}} / \Delta\frac{\sigma_{Ex2}}{E_{x2}} = 3.179\%/0.33\% = 9.63 \tag{3}$$

CONCLUSION

KEK LUCX facility timing, LLRF, and feedback subsystems upgrade will increase stability of RF system jitter up to 300 fs, which will improve Compton X-ray photons spectral purity jitter 10 times and collision rate losses from 40-50% down to 4-5%.

ACKNOWLEDGEMENT

Special thanks to Toshihiro Matsumoto for his help with Agilent E5052A Signal Source Analyzer.

REFERENCES

[1] A. Aryshev *et al.*, “Femtosecond response time measurements of Cs2Te photocathode”, *Appl. Phys. Lett.*, vol. 111, p. 033508, 2017. `doi:10.1063/1.4994224`

[2] F. R. Arutyunian and V. A. Tumanian, “The Compton effect on relativistic electrons and the possibility of obtaining high energy beams”, *Phys. Rev. Lett.*, vol. 4, p. 75, 1963.

[3] RedPitaya company official webpage, `https://redpitaya.com`

[4] E. Cicek *et al.*, “Present Status of Digital Feedback and Feedforward Project Using RedPitaya STEMlab”, presented at PASJ2020, Online, Sept. 2020, paper WEOO09.

[5] Highland technology company official webpage, `https://www.highlandtechnology.com`

[6] Berkley Nucleonics company official webpage, `https://www.berkeleynucleonics.com`

[7] M. Liu, K. C. Chu, C. X. Yin, and L. Y. Zhao, “Development Status of SINAP Timing System”, in *Proc. IBIC'14*, Monterey, CA, USA, Sep. 2014, paper MOPD23, pp. 199-201.

[8] Tektronix company official website, `https://www.tek.com`

[9] Keysight company official website, `https://www.keysight.com`

[10] ASTRA official webpage, `https://www.desy.de/~mpyflo/.`

[11] T. Suzuki, “General formulae of luminosity for various types of colliding machines”, KEK, Japan, Rep. KEK-76-6, Jul. 1976.