SENSITIVITY ANALYSIS OF THE BEAM ENERGY OF A C-BAND MAIN LINAC FOR SCSS XFEL

Jong-Seok Oh[1, 2, #], Takahiro Inagaki[1], Katsutoshi Shirasawa[1], Toru Hara[1], Tsumoru Shintake[1]
[1]RIKEN Harima Institute, [2]PAL/POSTECH

Abstract

The SCSS (SPring-8 Compact SASE Source) XFEL (X-ray Free Electron Laser) [1] is a challenging machine that requires extremely stable RF system. Therefore, it is critical issue to realize stable RF system for both phase and amplitude to provide stable XFEL. In this paper, the beam energy sensitivity is analyzed in order to examine the degree of the stability contribution of parameters. The phase-dependent stability characteristics are in detail analyzed and examined. It is confirmed that the off-crest phase of about +10° provides better stability in case of the C-band main linac for SCSS XFEL if phase jitter is small.

INTRODUCTION

The fluctuation of RF output is mainly caused by the modulation of a klystron voltage pulse, which is directly governed by the charging stability of a modulator. Not only RF power but also RF phase from the klystron affected by the klystron voltage fluctuation. Therefore, it is useful to understand the stability relation of those parameters related to the charging voltage. This report shows the detail analysis of the sensitivity for klystron voltage, phase shift, RF power, and beam energy gain.

In general, an electron beam is accelerated at the peak RF field at the crest phase to maximize the acceleration efficiency. In this case, beam energy fluctuation due to the RF power fluctuation is considerably larger than the one due to the phase change. If the acceleration phase is off-crest, beam energy fluctuation due to the phase change becomes larger. However, at certain phase, it is possibility for this fluctuation to be same as the one due to power fluctuation with opposite polarity in the falling slop with respect to beam. This phase is preferable to get the stable beam energy even under the voltage fluctuation of the klystron. This paper shows the analytical relation of the stable phase and experimental confirmation.

SENSITIVITY OF RF PARAMETERS

Both the RF phase and the amplitude of the klystron are affected by the amplitude modulation of a klystron voltage pulse. The klystron voltage is directly determined by the charging voltage of the PFN (pulse forming network) in a modulator. Therefore, it is useful to define the sensitivities of the RF parameters such as klystron voltage, RF phase and RF power by its relative stabilities to the one of a charging voltage.

The sensitivity of a klystron voltage

$$s_V = \left(\frac{dV_K}{V_K}\right) / \left(\frac{dV_O}{V_O}\right) = \left(1 + \frac{Z_{PFN}}{Z_K}\right) / \left(1 + 1.5\frac{Z_{PFN}}{Z_K}\right) \tag{1}$$

is given by using the Ohm's law

$$V_O = V_K + Z_{PFN} \times I_K \tag{2}$$

and the klystron beam current

$$I_K = k\, V_K^{1.5} \tag{3}$$

where V_o is a PFN charging voltage, V_K is a klystron voltage, Z_{PFN} is PFN impedance, k is a klystron perveance, Z_k is klystron impedance. At the nominal klystron voltage where the impedance is matched, the typical sensitivity of a klystron voltage becomes 0.8.

The RF phase ϕ_{RF} from a klystron [2]

$$\phi_{RF} = \phi_o - 2\pi\, f\, t_{transit} = \phi_o - 2\pi\left(\frac{c}{\lambda_{RF}}\right)\left(\frac{L_{KLY}}{v}\right) \tag{4}$$

is delayed from a driving input RF phase ϕ_o by the transit time $t_{transit}$ of a drift length L_{KLY} between the input cavity and the output cavity of the klystron with an electron velocity v where λ_{RF} is a wavelength in a free-space, c is the speed of light in vacuum. The measured phase dependency of a C-band klystron (Toshiba E3746A) for SCSS XFEL shown in Fig. 1 agrees with Eq. (4) and the evaluated values from FCI code [3].

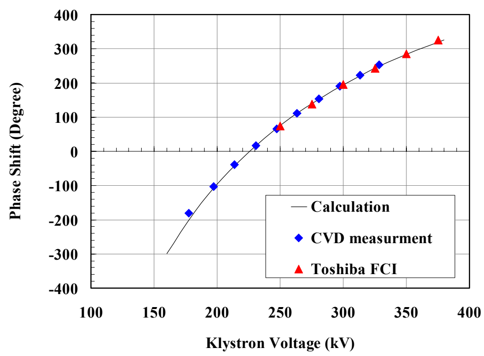

Figure 1: Phase shift of a C-band klystron (Line: analytical evaluation, Diamond: measured values, Triangle: calculated values by a FCI code).

The RF phase fluctuation of a klystron is

$$\left(\frac{d\phi_{RF}}{2\pi}\right) / \left(\frac{dV_K}{V_K}\right) = \left(\frac{L_{KLY}}{\lambda_{RF}}\right)\left(\gamma^2 - 1\right)^{-1.5}(\gamma - 1) \tag{5}$$

where γ is a relativistic mass factor. Therefore, the sensitivity of the RF phase is

$$s_\phi = \left(\frac{d\phi_{RF}}{2\pi}\right) / \left(\frac{dV_O}{V_O}\right) \approx \left(\frac{L_{KLY}}{\lambda_{RF}}\right)\left(\gamma^2 - 1\right)^{-1.5}(\gamma - 1) \times s_V\ . \tag{6}$$

The typical sensitivity of the RF phase at 350 kV is 1.26 for a C-band klystron.

[#]jsoh@postech.ac.kr

The RF power P_{RF} of a klystron is given by

$$P_{RF} = \eta I_K V_K = \eta k V_K^{2.5} \qquad (7)$$

where η is the RF conversion efficiency of a klystron. Therefore, the RF power fluctuation of klystron is

$$\left(\frac{dP_{RF}}{P_{RF}}\right) / \left(\frac{dV_K}{V_K}\right) = \left(\frac{d\eta}{\eta}\right) / \left(\frac{dV_K}{V_K}\right) + \left(\frac{dk}{k}\right) / \left(\frac{dV_K}{V_K}\right) + 2.5 \ . \qquad (8)$$

The relative variation of RF power, efficiency and perveance due to the klystron voltage fluctuation for a typical C-band klystron is shown in Fig. 2. The perveance dependency is relatively so small that it is neglected in the sensitivity of the RF power

$$s_P = \left(\frac{dP_{RF}}{P_{RF}}\right) / \left(\frac{dV_O}{V_O}\right) \approx s_\eta + 2.5 s_V \qquad (9)$$

where s_η is the sensitivity of efficiency given by

$$s_\eta = (d\eta/\eta)/(dV_o/V_o) \ . \qquad (10)$$

The efficiency variation of a klystron at low voltage has large effect on the sensitivity of RF power. Therefore, the nominal operating voltage is to be tuned to near around a maximum level to get better stability. The typical sensitivity of the RF power at 350 kV is 2.4 for a C-band klystron.

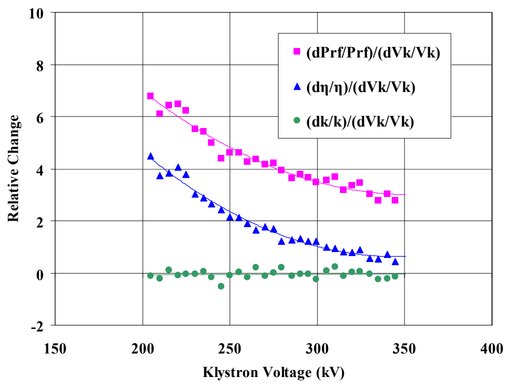

Figure 2: Relative variation of RF power (P_{rf}), efficiency (η), and perveance (k) of a C-band klystron.

SENSITIVITY OF BEAM ENERGY

The energy gain of an accelerating unit is

$$E \propto \sqrt{P_{RF}} \cos\phi_{RF} \ . \qquad (11)$$

Thus, its relative fluctuation by a klystron is

$$\frac{dE}{E} = 0.5 \times \left(\frac{dP_{RF}}{P_{RF}}\right) - \left(2\pi \times \tan\phi_{RF}\right)\left(\frac{d\phi_{RF}}{2\pi}\right). \qquad (12)$$

Using Egs. (6) and (9), the sensitivity of energy gain is

$$s_E = \left(\frac{dE}{E}\right) / \left(\frac{dV_O}{V_O}\right) = 0.5 s_\eta + 1.25 s_V - 2\pi \tan\phi_{RF} \ s_\phi \ . \qquad (13)$$

Figure 3 shows the energy gain of C-band units as a function of operating RF phase with different charging voltage variations of -0.5%, -0.25%, 0%, 0.25%, and 0.5%. On a certain RF phase of the falling slope with respect to beam, which is marked by the circle in the figure, the amplitude is somewhat constant because the both fluctuations are cancelled out, which provide constant accelerating field. The energy gain is insensitive to the modulator voltage fluctuation around the stable phase satisfying following condition

$$\tan\phi_{RF} = \left(\frac{1}{2\pi \, s_\phi}\right)\left(0.5 s_\eta + 1.25 s_V\right) \ . \qquad (14)$$

It depends on the klystron parameters such as the length of drift tube, operating voltage, efficiency.

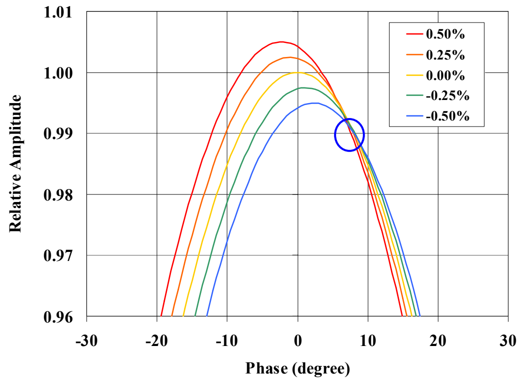

Figure 3: Energy gain vs. RF phase for charging voltage variations with a C-band klystron.

Figure 4 shows the sensitivity of energy gain for the crest phase and the off-crest phase. The typical sensitivity of the energy gain at 350 kV is 1.2 for a C-band unit. The energy gain is insensitive over wide range of klystron voltage at the off-crest phase of +9 degrees. The loss of energy gain by the off-crest acceleration is 1.2%.

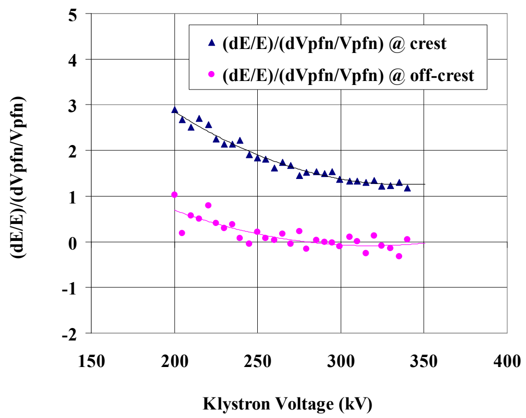

Figure 4: Relative variations of energy gain due to the fluctuation of the PFN charging voltage for crest and off-crest phase of +9 degrees.

Including the effect of beam phase jitter σ_ϕ at off-crest, the sensitivity of energy gain becomes

$$s_E^2 = \left(0.5 s_\eta + 1.25 s_V - 2\pi \tan\phi_{RF} \, s_\phi\right)^2 + \left(2\pi \tan\phi_{RF}\right)^2 \left(\frac{\sigma_\phi}{2\pi}\right)^2 / \left(\frac{dV_o}{V_o}\right)^2 . \qquad (15)$$

EXPERIMENTAL RESULTS

The SCSS prototype accelerator has a C-band main linac after an S-band unit of an injector [4]. The main linac has two RF sources and increases the beam energy from 50 MeV to 250 MeV. The beam energy fluctuation is measured for different RF phases by the screen monitor located at the middle of a chicane having a dispersion of 150 mm. Figure 5 shows the measured beam energy fluctuation of C-band main linac. The beam energy stability at crest for two C-band units is 0.34% (6σ) and the stability of energy gain per unit is 0.59% (6σ). The energy fluctuation is sensitive to the operating phase and asymmetric. The fluctuation is reduced to 50% level of the one of crest acceleration at the off-crest phase of +10 degrees.

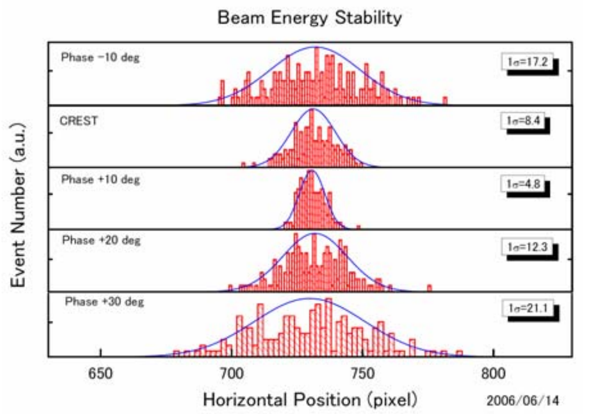

Figure 5: Beam energy fluctuation vs. RF phase of C-band main linac of SCSS prototype accelerator (0.01 mm/pixel).

Figure 6 shows the stability curves of energy gain per C-band unit normalized by the one at crest phase given by

$$\frac{\left(\frac{dE}{E}\right)^2}{\left(\frac{dE}{E}\right)^2_{crest}} = \left(1-\frac{2\pi\tan\phi_{RF}\, s_\phi}{0.5 s_\eta + 1.25 s_V}\right)^2 + (2\pi\tan\phi_{RF})^2\left(\frac{\sigma_\phi}{2\pi}\right)^2 \Big/ \left(\frac{dE}{E}\right)^2_{crest} \quad . (16)$$

Each curve has different relative phase jitter normalized by the energy stability at crest, $(\sigma_\phi/(2\pi))/(dE/E)_{crest}$. For example, with 0.2% energy stability at crest, 50% normalized phase jitter corresponds to 0.1% relative phase jitter that is equivalent to 0.36 degrees. Measured data (C-band 060614) in Fig. 5 agree to the case of 50% normalized relative phase jitter. It means that the phase jitter is about 1.1 degrees that corresponds to the timing jitter of 0.52-ps at C-band frequency.

At the off-crest phase satisfying Eq. (14), the energy stability becomes

$$\left(\frac{dE}{E}\right) = \left(\frac{0.5 s_\eta + 1.25 s_V}{s_\phi}\right)\left(\frac{\sigma_\phi}{2\pi}\right) . \quad (17)$$

It becomes ~ $\sigma_\phi/(2\pi)$ at 350 kV. Therefore, the total energy stability is directly determined by the phase jitter.

Measured data (C-band 060614) indicate that the minimum fluctuation of the beam energy is located at about +8 degree off from the crest as expected. The fluctuation at this phase is limited by the phase jitter. The different set of measured data (C-band 060711) shows that the normalized relative phase jitter is increased to about 100% by different machine condition.

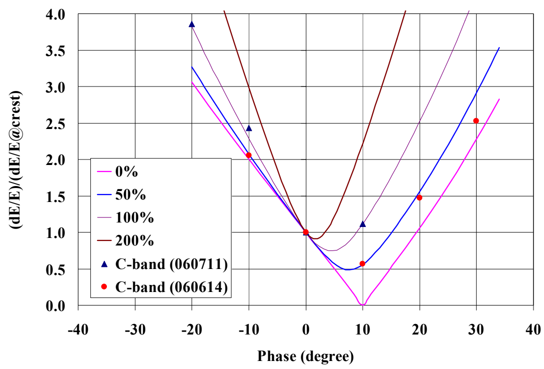

Figure 6: Stability of energy gain per C-band unit normalized by the one at crest phase for relative phase jitter of 0%, 50%, and 100%.

DISCUSSION

The beam energy sensitivity depends on not only the charging stability of the modulator but also the charging level and RF phase. The stability is always better at the higher klystron voltage due to the better stability of charging voltage of a modulator and relatively constant efficiency of a klystron.

The RF unit for a velocity buncher or a bunch compressor is more sensitive to the RF fluctuation because of the off-crest operation to provide a necessary energy chirp. The RF phase at the off-crest around +10 degrees provides better stability for C-band main linac. The low-level RF control has to provide better stability than the one of a klystron modulator for this scheme to be effective. The reduction of beam energy due to off-crest acceleration is about 1%.

The additional longitudinal energy spread due to the RF curvature is about 5% of the one caused by the longitudinal wake field and there is no appreciable degradation of the slice parameters [5].

REFERENCES

[1] http://www-xfel.spring8.or.jp

[2] Linear Accelerators, P. M. Lapostolle and A. L. Septier, editors, North Holland Publishing Company, p322 (1970).

[3] T. Shintake, "Klystron Simulation and Design using the Field Charge Interaction (FCI) Code", Nucl. Instrum. and Method in Physics Research A363 (1995) 83-89.

[4] T. Hara, "Electron Beam Simulations on the SCSS Accelerator," Proc. of FEL04.

[5] J. S. Oh, et. al., "Stable RF Phase Insensitive to the Modulator Voltage Fluctuation of the C-band Main Linac for SCSS XFEL," to be presented in the Proc. of FEL06.