# STABILITY ANALYSIS OF A KLYSTRON-MODULATOR FOR PAL XFEL

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*Abstract*

The PAL (Pohang Accelerator Laboratory) is persuading to construct a SASE-XFEL facility (PAL XFEL). The stable electron beam is essential for the single-pass free electron laser facility. The beam stability requirement for XFEL linac is determined from XFEL physics analysis. We need to find correlation between the beam parameters and related sub-system parameters to define the stability criteria of each sub-system. The beam stability is governed by an accelerating RF field, of which fluctuation is mainly caused by the modulation of a klystron voltage pulse. Therefore, it is directly determined by the charging stability of a modulator. This paper shows the detail analysis of the stability dependency of a klystron-modulator on the related parameters.

## INTRODUCTION

PAL XFEL is a 4th generation light source that is a coherent X-ray free electron laser by utilizing an existing 2.5-GeV linac [1]. In order to provide reasonably stable SASE output, the RF stability of 0.02% rms is required for both RF phase and amplitude [2]. This is a technologically challenging issue for PAL XFEL.

The beam stability is given by the fluctuation of both RF power and phase driven by a klystron voltage pulse that is directly determined by the PFN (pulse forming network) charging voltage of a modulator. Therefore, it is useful to define the stability by using a sensitivity of the system parameters such as klystron voltage, RF phase and RF power by its relative stabilities to the one of a charging voltage. This paper analyzes the sensitivities of RF parameters and beam energy related to the PAL XFEL, in which Toshiba E3712 klystron (S-band, peak power of 80 MW) is to be used as main klystrons driving a XFEL linac [3].

## MODULATOR SENSITIVITY

From the Ohm's law for a modulator and a klystron, $V_O = V_K + Z_{PFN} \times I_K$ and the klystron beam current, $I_K = k\, V_K^{1.5}$ with given klystron perveance $k$, we can define the sensitivity of a klystron voltage by

$$s_V = \left(\frac{dV_K}{V_K}\right) / \left(\frac{dV_O}{V_O}\right) = \left(1 + \frac{Z_{PFN}}{Z_K}\right) / \left(1 + 1.5\frac{Z_{PFN}}{Z_K}\right) \quad (1)$$
$$= \left(1 + \sqrt{\frac{V_K}{V_{K,nom}}}\right) / \left(1 + 1.5\sqrt{\frac{V_K}{V_{K,nom}}}\right)$$

where $V_o$ is a PFN charging voltage, $V_K$ is a klystron voltage, $V_{K,nom}$ is a nominal klystron voltage where the impedance is designed to be matched, $Z_{PFN}$ is PFN impedance, $Z_k$ is klystron impedance. Figure 1 shows the equation (1) with measured data of E3712 klystron for PAL XFEL. At the klystron voltage where the impedance is matched, the sensitivity of a klystron voltage is 0.8 and it is slowly varying over wide range of beam voltage.

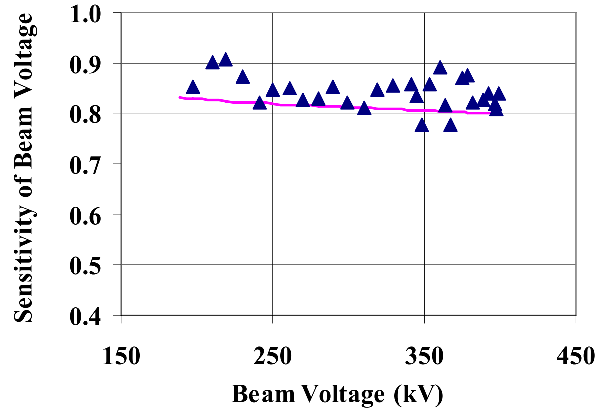


Figure 1: Sensitivity of klystron beam voltage (line: equation (1), triangle: measured data of E3712 klystron).

The sensitivity of a klystron beam current in the Figure 2 is given by

$$S_I = \left(\frac{dI_K}{I_K}\right) / \left(\frac{dV_O}{V_O}\right) = \left(\frac{V_O}{I_K}\right) / \left(\frac{dV_O}{dI_K}\right) = \left(1 + \frac{Z_{PFN}}{Z_K}\right) / \left(2/3 + \frac{Z_{PFN}}{Z_K}\right). \quad (2)$$
$$= \left(1 + \sqrt{\frac{V_K}{V_{K,mon}}}\right) / \left(2/3 + \sqrt{\frac{V_K}{V_{K,mon}}}\right)$$

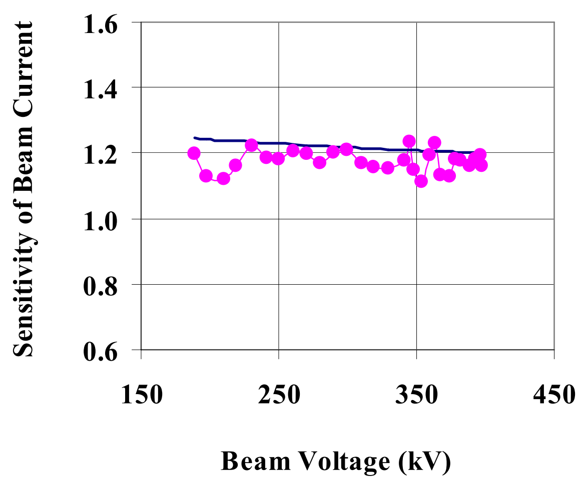


Figure 2: Sensitivity of klystron beam current (line: equation (2), circle: measured data of E3712 klystron).

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At the klystron voltage where the impedance is matched, the sensitivity of a klystron current is 1.2 and it is also slowly varying over wide range of beam voltage.

## KLYSTRON SENSITIVITY

The delayed RF phase $\phi_{RF}$ from a driving input RF phase $\phi_o$ of a klystron is given by

$$\phi_{RF} = \phi_o - 2\pi f t_{transit} = \phi_o - 2\pi\left(\frac{c}{\lambda_{RF}}\right)\left(\frac{L_{KLY}}{v}\right) \quad (3)$$

where $t_{transit}$ is the transit time of a drift length $L_{KLY}$ between the input cavity and the output cavity of the klystron with an electron velocity $v$ and $\lambda_{RF}$ is a wavelength in a free-space, and $c$ is the speed of light in vacuum [4]. Therefore, sensitivity of the RF phase is

$$s_\phi = \left(\frac{d\phi_{RF}}{2\pi}\right)/\left(\frac{dV_O}{V_O}\right) \approx \left(\frac{L_{KLY}}{\lambda_{RF}}\right)\left(\gamma^2-1\right)^{-1.5}(\gamma-1)\times s_V \quad . \quad (4)$$

where γ is the Lorentz factor of the electron. Figure 3 shows the phase shift and sensitivity of E3712 klystron of which the drift length of 64.6 cm. The sensitivity of the RF phase is slowly varying over wide range of beam voltage even though the phase change is large. The phase variation is 1.4°/kV and phase sensitivity is 1.53 at the beam voltage of 400 kV.

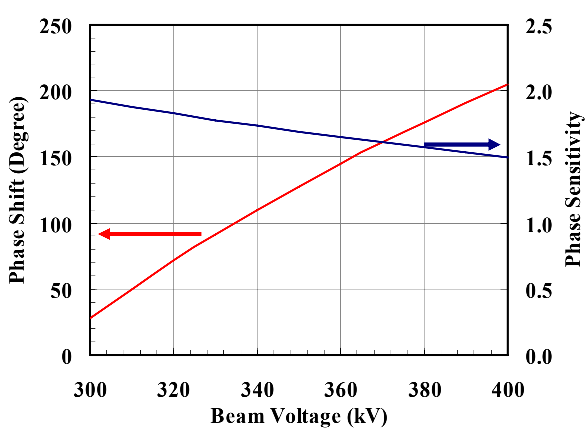


Figure 3: Phase shift and sensitivity of E3712 klystron.

The RF power of a klystron is given by $P_{RF} = \eta I_K V_K = \eta k V_K^{2.5}$ where $\eta$ is the RF conversion efficiency. Therefore, the RF power fluctuation is

$$\left(\frac{dP_{RF}}{P_{RF}}\right)/\left(\frac{dV_K}{V_K}\right) = \left(\frac{d\eta}{\eta}\right)/\left(\frac{dV_K}{V_K}\right) + \left(\frac{dk}{k}\right)/\left(\frac{dV_K}{V_K}\right) + 2.5 \quad . \quad (5)$$

Figure 4 shows the relative fluctuations of RF power, efficiency and perveance of the E3712 klystron. The perveance dependency is relatively so small that it is neglected in the sensitivity of the RF power

$$s_P = \left(\frac{dP_{RF}}{P_{RF}}\right)/\left(\frac{dV_O}{V_O}\right) \approx s_\eta + 2.5 s_V \quad (6)$$

where $s_\eta = (d\eta/\eta)/(dV_o/V_o)$ is the sensitivity of efficiency.

The efficiency variation of a klystron at low voltage has large effect on the sensitivity of RF power so that the power sensitivity is getting up from 3.1 at 400 kV to 8 at 250 kV for E3712 klystron. Therefore higher the beam voltage is, better the stability of RF power is.

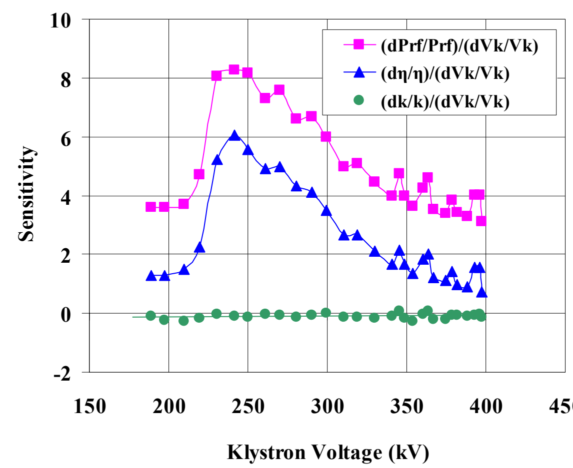


Figure 4: Sensitivity of RF power, efficiency, and perveance of E3712 klystron.

## ENERGY GAIN SENSITIVITY

According to the energy gain of an accelerating unit $E \propto \sqrt{P_{RF}}\cos\phi_{RF}$, its relative fluctuation by a klystron is

$$\frac{dE}{E} = 0.5\times\left(\frac{dP_{RF}}{P_{RF}}\right) - \left(2\pi\times\tan\phi_{RF}\right)\left(\frac{d\phi_{RF}}{2\pi}\right) \quad . \quad (7)$$

Using Egs. (4) and (6), the sensitivity of energy gain is

$$s_E = \left(\frac{dE}{E}\right)/\left(\frac{dV_O}{V_O}\right) = 0.5 s_\eta + 1.25 s_V - 2\pi\tan\phi_{RF}\, s_\phi \quad . \quad (8)$$

Figure 5 shows the relative energy gain with charging voltage variations at the klystron voltage of 400 kV.

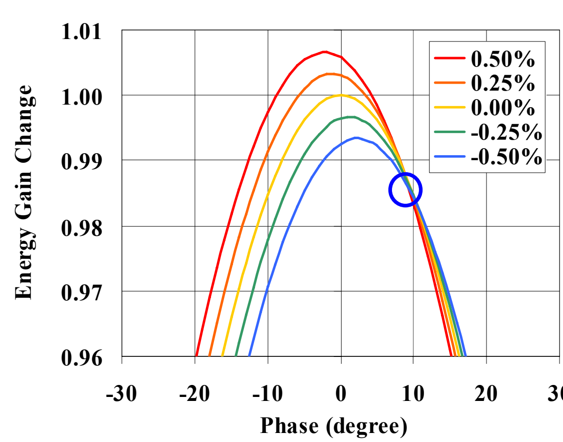


Figure 5: Relative energy change within 1% charging voltage variations at 400 kV level with E3712 klystron.

Around RF phase marked by the circle in the figure, the energy gain is almost same even though charging voltage is fluctuating. This RF phase is about +10 at the 400 kV level, which is given by following condition

$$\tan\phi_{RF} = \left(\frac{1}{2\pi s_\phi}\right)\left(0.5 s_\eta + 1.25 s_V\right) \quad . \tag{9}$$

Figure 6 shows the sensitivity of energy gain for the crest phase and the off-crest phase. The typical sensitivity of the energy gain at 400 kV is 1.3 for the crest operation and is getting larger up to 2.0 at the voltage lower than 350 kV. We can make the energy gain insensitive down to 350 kV at the off-crest phase of +10°. The loss of energy gain by the off-crest acceleration is 1.5%. We can increase the off-crest phase more to tune the energy gain insensitive lower than 350 kV level. For example, the off-crest phase of +12° makes the energy gain insensitive around 320 kV level with the energy loss of 2.2%.

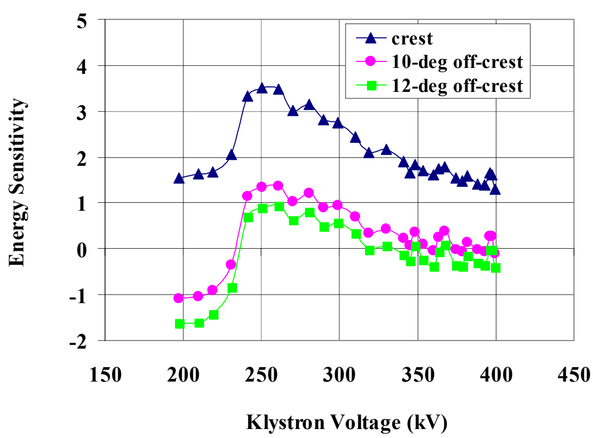


Figure 6: Sensitivity of beam energy gain for crest phase and off-crest phase of +10° and +12° with E3712 klystron.

If we consider the effect of relative phase jitter $\sigma_\phi$ between injected beams into the accelerating structures and corresponding klystron station, the sensitivity of energy gain becomes

$$s_E^2 = \left(0.5 s_\eta + 1.25 s_V - 2\pi \tan\phi_{RF} s_\phi\right)^2 + \left(2\pi\tan\phi_{RF}\right)^2 \left(\frac{\sigma_\phi}{2\pi}\right)^2 / \left(\frac{dV_o}{V_o}\right)^2 \quad . \tag{10}$$

## SUMMARY AND DISCUSSION

The sensitivity of RF power is amplified at the lower klystron voltage due to the quick drop of conversion efficiency. Therefore, it is possible to provide better stability by tuning the RF system at the higher working voltage. The off-crest phase ranging from +10° to +12° provides better stability in case of the PAL XFEL linac. The reduction of beam energy due to off-crest acceleration is just less than 2%. The low-level RF control has to provide better stability than the one of a klystron modulator for this scheme to be effective.

The RF unit for bunch compressors is more sensitive to the RF fluctuation because the necessary off-crest phase is typically much larger than 10° to provide a necessary energy chirp. In this case, the RF unit has to satisfy more strict stability requirement than normal accelerating units.

## REFERENCES

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