

## DEVELOPMENT OF AN ULTRA STABLE KLYSTRON-MODULATOR FOR PAL XFEL\*

J. S. Oh<sup>#</sup>, Y. G. Son, J. H. Seo, S. D. Jang, S. J. Kwon, I. S. Ko, W. Namkung  
PAL/POSTECH, Pohang 790-784, Korea

### Abstract

The PAL (Pohang Accelerator Laboratory) is persuading to construct a SASE-XFEL facility (PAL XFEL) that supplies coherent X-rays. The bright and stable electron beam is essential for the PAL XEL. The electron beams has to have an emittance of 1.0 mm-mrad, a peak current of 3 kA, and a low energy spread of 1.0 MeV. In order to provide reasonably stable SASE output, the RF stability of 0.02% rms is required for both RF phase and amplitude. This is a technologically challenging issue for PAL XFEL. An inverter technology is to be applied to charge the PFN of a new modulator. Therefore, a new inverter system should provide very stable charging performances. This paper presents the development of an ultra stable klystron-modulator with an inverter power supply.

[3]. The tight jitter tolerance can be relaxed by operating more klystrons in one accelerating section. One klystron will be dedicated to two S-band accelerating columns from X1 to X5 sections to relax tight jitter tolerance. Since each two accelerating columns will be operated by their own klystrons under the same RF conditions, all units in the X-linac have the same jitter sensitivity. Since jitter tolerance is loose at the downstream of BC2, one klystron will be dedicated to four S-band accelerating columns to all the other sections of the linac. The RF stability is a key issue to get stable SASE output. The stability level of the modulator has to be improved 10 times better to meet the strict pulse stability. This paper shows the suitable upgrade scheme of the modulators and design considerations for the stability improvement of klystron-modulators for PAL XFEL.

### INTRODUCTION

PAL XFEL is a 4th generation light source that is a coherent X-ray free electron laser (FEL) by utilizing an existing 2.5-GeV linac [1], [2]. This source is based on the principle of Self Amplified Spontaneous Emission (SASE), single-pass high-gain FEL. The SASE is only possible by low emittance and extremely dense electron bunches moving in an undulator magnetic field. The linac system is characterized by two groups, X-linac and K-linac as shown in Figure 1. The X-linac is a new GeV-scale S-band linac and the K-linac is the existing 2.5-GeV injector linac for 2.5-GeV PLS ring.

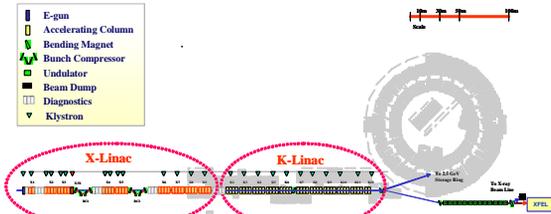


Figure 1: XFEL linac configuration.

In order to realize a stable beam at the end of linac, the linac system should meet a condition,  $\sum_{i=1}^n (P_{tolerance} / P_{sensitivity})^2 < 1$ ,

where  $P_{tolerance}$  is a technically achievable tolerance partly affecting the system performance and  $P_{sensitivity}$  is a maximum allowable tolerance assuming no any other error source. The previous jitter analysis shows that the RF gradient stability tolerance of the X-linac is 0.02% (RMS) which is almost 10 times tighter than the K-linac

### LINAC MODULATORS

The existing modulators in K-linac use traditional resonant charging scheme. The charging voltage regulation of K-linac is done by a de-Q'ing circuit. The existing system can be easily improved to match the stability requirement by adopting a standard de-Q'ing method with modern digital control circuit [4]. Figure 2 shows the modulator circuits adopting inverter power supplies as a charging system. The fine regulation of charging voltage is provided by a precise inverter without a de-Qing system. The bulky thyrite to present the inverse voltage for the switch recovery is not necessary due to the command charging scheme. It is inherently short-circuit safe and naturally compact. Other attractive features are expandability, easy maintenance, and flexible control interface. These features are matched to the stability and reliability requirements of X-linac modulators.

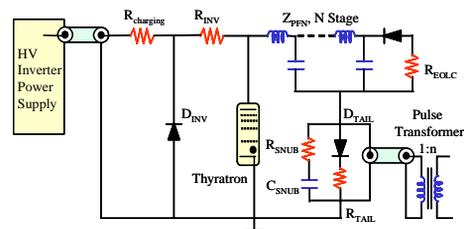


Figure 2: Modulator circuit with inverter power supplies.

### INVERTER SYSTEM

The present status of the pulse-to-pulse repeatability of available inverters is summarized in Ref. [4]. The thermal drift of 0.5% in the feedback and reference voltage components is possible for all inverter power supplies. The high voltage resistor has the temperature coefficient

\*Work supported by the MOST and the POSCO, Korea  
<sup>#</sup>jsoh@postech.ac.kr

of 100 PPM/°C. The long-term stability is 0.1% for 8 hours after 1.5-hour warm-up and 0.2% per hour after 1-hour warm-up. In conclusion, we have to improve the stability of inverter power supply to meet the tight requirements of PAL XFEL.

There are many possible inverter topologies to be applicable to XFEL modulators. A typical series-resonant inverter is simplest and oldest topology that uses on/off control of constant switching frequency. PWM (pulse width modulation) inverters use same circuit as series resonant inverter but a charge bucket can be reduced to 10% of the regular size. Then, the repeatability can be improved 2-3 times. A parallel resonant inverter has a parallel capacitor on the secondary side of the step-up high voltage transformer. Rapid charging at resonant frequency is commanded first then a current is reduced by increasing a switching frequency above a resonant frequency. The stored energy must be discharged between each pulse. A phase-shifting resonant inverter has two independent inverter circuits. It operates at a constant switching frequency with an independent phase control of each inverter. A rapid charging is done at synchronized or in phase switching then a current reduction is done by phase shift between the switching cycles. The most simple and straight way is to use several inverters in parallel such as shown in Figure 3. Rapid charging is done by high power units and a fine regulation is done by a small power unit. Repeatability is depends on the small charging unit. The cost effective and simple approach for the inverter topology for X-linac modulator is the parallel operation with matched fine charging unit. The coarse charging and fine charging is arranged to get the regulation with optimum power sharing.

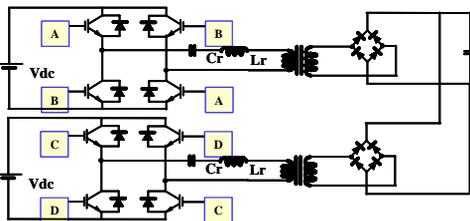


Figure 3: Parallel operation of inverters.

Figure 4 shows the charging schedule with parallel operation of inverters. Total charging time  $T_c$  and charging voltage  $V_o$  are given by the following equations,

$$(m+n) t_o = T_c, \quad m(D+d) + n d = V_o, \quad n d = j D,$$

$$m+n = \alpha, \quad m^2 - \alpha m + (\alpha + \beta) j = 0,$$

where  $t_o$  is inverter switching time,  $m$  is total switching number of coarse charging,  $n$  is switching number of fine charging after coarse charging,  $\alpha = T_c / t_o$ ,  $\beta = V_o / d$ , fine charging step  $d = I_f t_o / C$ , coarse charging step  $D = (I_c + I_f) t_o / C$ ,  $C$  is a load capacitance,  $I_f$  is charging current of a fine inverter,  $I_c$  is charging current of a coarse inverter,  $j$  is the number of coarse charging steps to be charged by a fine inverter.

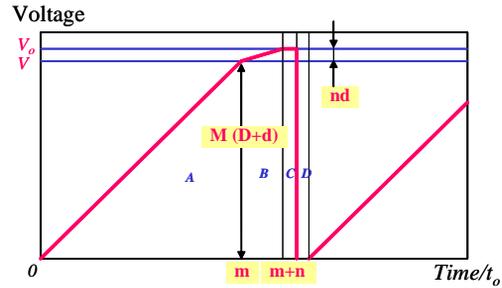


Figure 4: Charging schedule with parallel operation.

Typical parameters for PAL XFEL modulator are PRR = 60 Hz,  $f_r = 30$  kHz,  $V_o = 50$  kV,  $C = 1.2 \mu\text{F}$ ,  $j = 2$ ,  $\beta = 5,000$ . Then  $T_c = 14.7$  msec considering 2 msec dead time for charging regulation and a switch recovery,  $t_o = 33.3 \mu\text{sec}$ ,  $\alpha = 440$ ,  $P_{av} = 90$  kJ/sec. The main inverter charging current,  $I_c$  is 4.4 A, and a fine charging current,  $I_f$  is 0.18 A. The main charging power,  $P_c$  is 110 kJ/sec, and fine charging power,  $P_f$  is 4.5 kJ/sec.

In order to verify and figure out the technical difficulties of this scheme, the prototype inverter charging system is tested with a 150-MW test modulator of which the PFN capacitance is 0.88  $\mu\text{F}$ . Two inverters with 16.5 kJ/s charging speed are used as coarse charging inverters. A inverter with 4.61 kJ/s charging speed is used as a fine charging inverter. Figure 5 is the simulation circuit of this configuration, in which the left hand side is the IGBT gate control system for inverters and a main switch triggering, and the right hand side is the inverter power supplies and modulator HV sections including a PFN, a pulse transformer, and a klystron load.

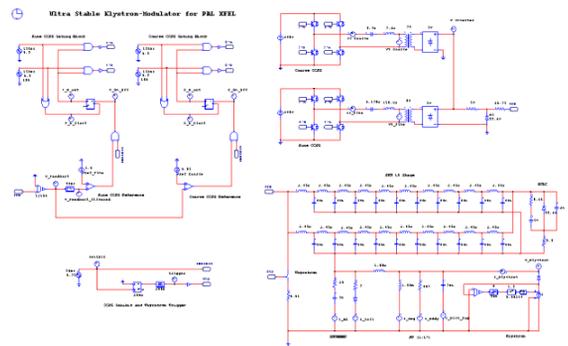


Figure 5: Simulation circuit of a XFEL modulator.

Figure 6 shows the simulated charging stability. Due to the difference of bucket size of A and B resonant currents, there are two type of charging steps as shown in the simulated result. Also, a gating signal is occasionally assigned to the same switches as last switching ones, and then the actual charging is possible after one-cycle delay due to the opposite potential of the resonant capacitor. The charging level will drop more during the delay time, which increases the fluctuation magnitude further. The charging level is regulated within 4.4 Vp-p fluctuations in this simulation.

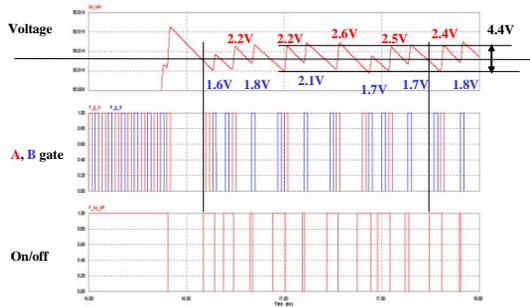


Figure 6: Simulated charging stability.

### TEST RESULTS

Figure 7 shows detailed charging waveforms of each bucket. The size of average charging step is 4.67 V from the measured voltage by three steps (lower trace). There are voltage spike in the charging voltage waveform. The peak level of the spike is larger than the charging level but it is easily filtered by a low pass filter with cut-off frequency of 3 kHz. Actually the charging current flows through the complicated load impedance network  $Z_L$  as shown in Figure 8. The spike voltage is generated by damped oscillation caused by the stray capacitance of a pulse transformer and a load (klystron), a magnetizing inductance of a pulse transformer, and a resistive load by a klystron tube.

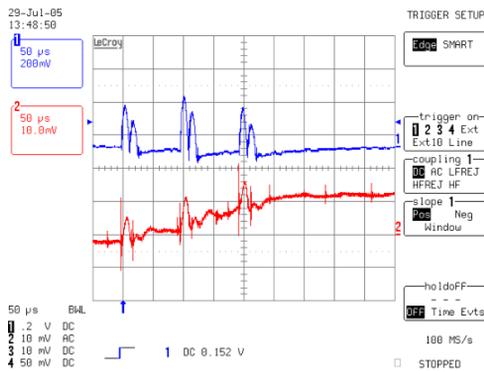


Figure 7: Waveforms of single charging bucket. (Upper: charging-I, 0.2 V/div, Lower: PFN-V, 10 V/div)

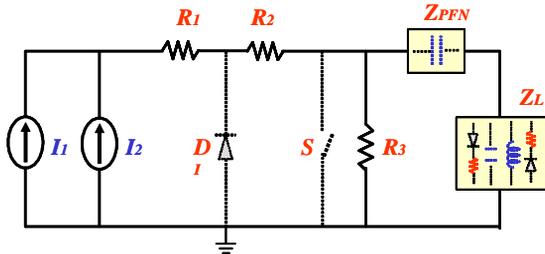


Figure 8: Equivalent charging circuit.

Figure 9 shows the measured charging stability under normal operating condition. The charging voltage fluctuation is 2.43 V RMS at the 10 kV charging level, which agrees well with the simulated results. The last charging bucket is inhibited within 80  $\mu$ s before a switch trigger point to keep stable condition.

### DISCUSSION

The jitter tolerance of X-linac for PAL XFEL is tight. Especially jitter tolerance of a photo-injector is so tight. The test result of the charging voltage stability of 2.43 V RMS shows the stability of the proposed scheme will provide the stability of 0.005% at the 50 kV level. We need further test to examine the effects of operational and environmental conditions such as working voltage and temperature. The matching of temperature and voltage coefficient between resistors and capacitors are also important. Stable temperature control is essential for stable feedback. The charging current is gradually decreasing according to a charging voltage due to discontinuous diode current in the inverter circuit. This will help to get smaller charging step at the higher level.

### REFERENCES

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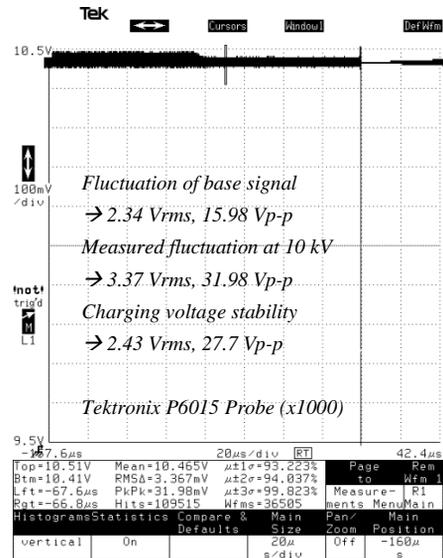


Figure 9: Measured charging stability.