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DEVELOPMENT OF A MODULATOR PULSE STABILITY MEASUREMENT DEVICE AND TEST RESULTS AT SLAC*

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Abstract

In this paper, the development of a pulse stability measurement device is presented. The measurement accuracy is better than 250uV, about 4.2ppm of a typical 60V input pulse. Pulse signals up to +/- 80V peak can be measured. The device works together with an oscilloscope. The primary function of the measurement device is to provide a precision offset, such that variations in the flattop of the modulator voltage pulse can be accurately resolved. The oscilloscope records the difference between the pulse flattop and the reference for a series of waveforms. The scope math functions are utilized to calculate the rms variations over the series. The frequency response of the device is characterized by the measured cutoff frequency of about 6.5MHz.

In addition to detailing the design and calibration of the precision pulse stability device, measurements of SLAC line-type linac modulators and recently developed induction modulators will be presented. Factors affecting pulse stability will be discussed.

I. INTRODUCTION

The Linac Coherent Light Source (LCLS) at SLAC requires very tight control of the klystron RF phase jitter [1]. The RF phase jitter is directly related to modulator output pulse amplitude stability [2]. The linac PFN modulators operate up to 120Hz with an output voltage of about 350kV. The pulse flat-top is nominally 3.6us. The goal for modulator pulse amplitude jitter is less than 30ppm rms. A pulse stability measurement device is required to measure ppm-level pulse amplitude stability. Short-term stability is very important to LCLS operation; long-term drift can be corrected with RF feedback.

II. MEASUREMENT DEVICE

A. Pulse Stability Measurement Scheme

Figure 1 shows the pulse stability measurement scheme. High voltage power operational amplifiers are used for voltage follower, differential amplifier and precision DC offset circuitry. The differential output signal is clamped to +/-5V, and the output buffer is used for the oscilloscope input.

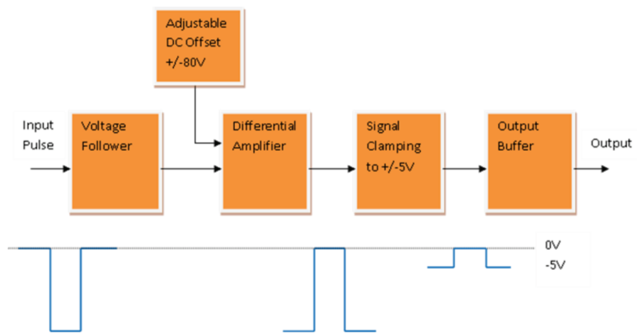

Figure 1. Pulse stability measurement scheme

B. Measurement Device with Oscilloscope

Figure 2 shows a photo of the pulse stability measurement device with an oscilloscope. Offset voltage can be adjusted within +/-80V for positive or negative pulse measurement, and monitored by a meter for easy operation. The input pulse, differential signal, offset voltage and output signal can be monitored and measured using an oscilloscope.

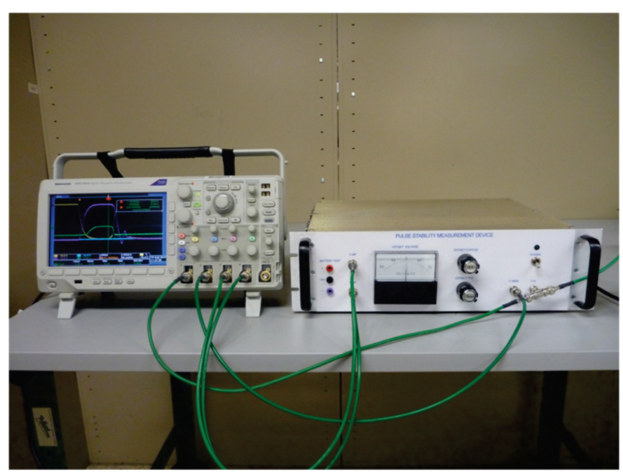

Figure 2. Measurement device with oscilloscope

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C. Pulse Stability Measurement

Pulse stability is defined by Eq. (1) as follow.

$$\text{Pulse stability} = \Delta V_{rms} / V \tag{1}$$

Where $$\Delta V_{rms} = \sqrt{\frac{\Delta V_1^2 + \Delta V_2^2 + \cdots + \Delta V_n^2}{n}} \tag{2}$$

V: mean pulse voltage

ΔVrms equals the standard deviation of a series of measured data, and is computed by an oscilloscope statistics function.

D. Pulse Stability Measurement Example

Figure 3 shows an example of a pulse stability measurement on LCLS linac modulator 28-2 running at 60Hz. The klystron voltage is measured through a high voltage divider with 5060:1 ratio. Ch1 is the Klystron negative pulse, which is about 57.4V between cursor a and b; Ch2 is the offset voltage; Ch3 is the differential signal; Ch4 is the output signal.

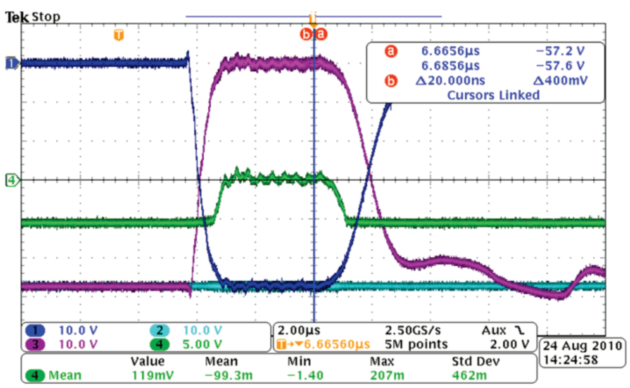

Figure 3. Pulse stability measurement example

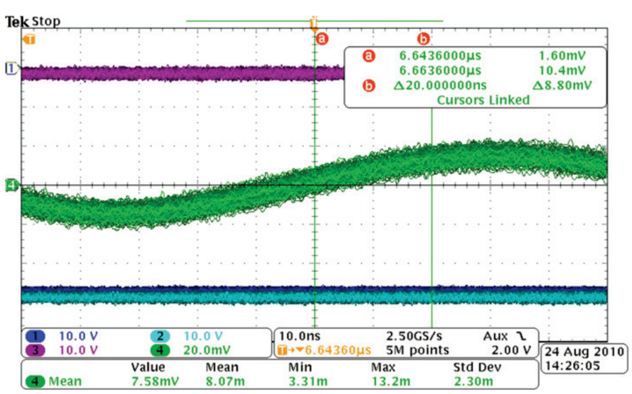

Figure 4. Pulse stability measurement at 60Hz
(Expansion of Figure 3)

Figure 4 is the expansion of Figure 3 in the horizontal and vertical scales (from 2µs/div to 10ns/div and 5V/div to 20mV/div) for the pulse stability measurement. The standard deviation is 2.30mV over 1000 sample pulse waveforms. Therefore the pulse stability is about 40.1ppm (2.30mV/57.4V) in this case.

III. DEVICE CALIBRATION

A. *Precision DC Voltage Calibration*

A Fluke 343A DC Voltage Calibrator was used as the input to the pulse stability measurement system. The short-term jitter of the Calibrator is less than 1 ppm. The stability measurement device was calibrated from -80V to +80V with 20V incremental steps. Figure 5 shows the calibration with -80V input voltage.

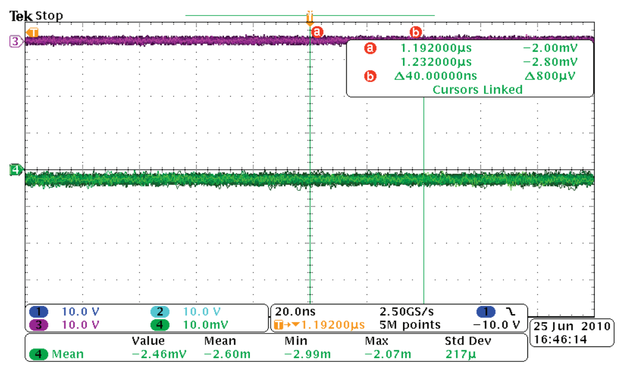

Figure 5. DC calibration with -80V input voltage

The output standard deviation is less than 250uV at all input voltages, which indicates the measurement system accuracy is better than 250uV from -80V to +80V.

B. Device Frequency Response

A 10V peak-peak sine wave signal from a SRS DS345 function generator was used to measure the frequency response of the device. Figure 6 shows the measurement at 1MHz without offset. Ch1 is input signal; Ch4 is output signal.

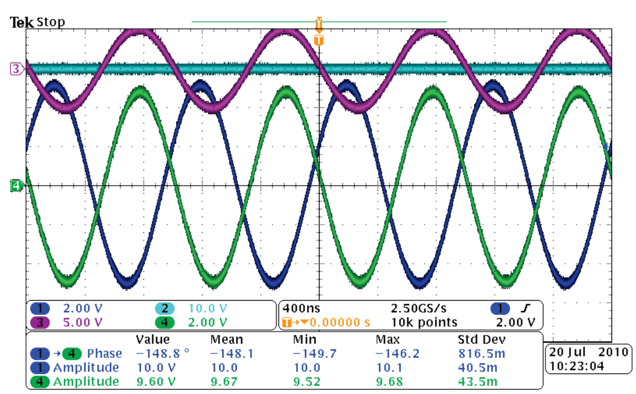

Figure 6. Frequency response at 1MHz without offset

Figure 7 is the amplitude response of the device; Figure 8 is the phase response of the device. Also in Figure 7 and 8 are the frequency response with +60V and -60V offset. The offset signal was provided by the Fluke Calibrator. Figure 9 is the circuit used for the frequency response measurement with DC offsets. A 1:1 transformer was used to add an AC signal on top of a DC offset.

One can see from Figure 7 that the 3dB cutoff frequency of the pulse stability measurement device is about 6.5MHz with or without DC offset.

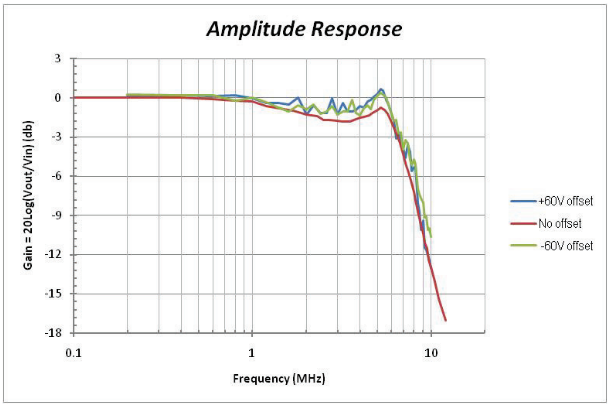

Figure 7. Amplitude response of the device

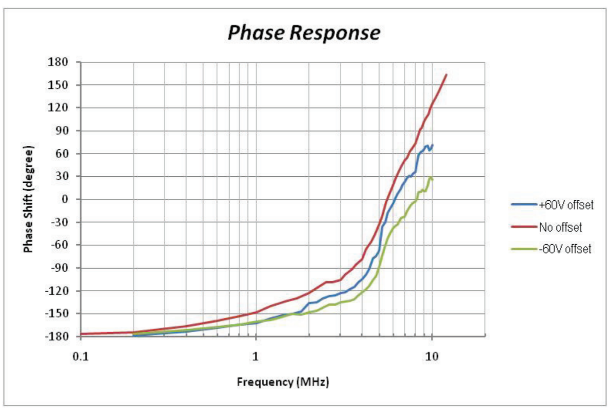

Figure 8. Phase response of the device

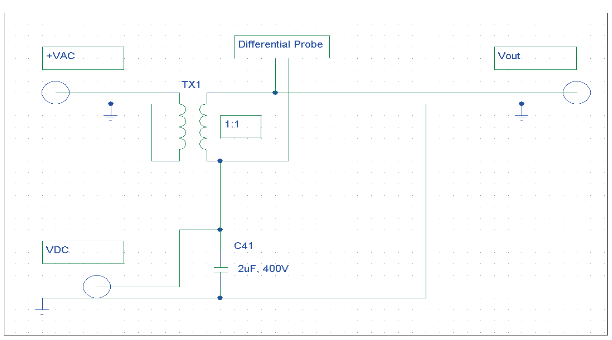

Figure 9. Frequency response measurement circuit with DC offset

IV. MODULATOR PULSE STABILITY MEASUREMENT AND IMPROVEMENT

A. Pulse Stability measurement of SLAC Modulators

Table 1 is the pulse stability measurement result of several modulators at SLAC.

Table 1. Pulse stability of SLAC modulators

Modulator	Rep-rate (Hz)	Pulse stability (ppm)	Note
Orion	10	30.1	
2-Pack	60	91.6	
NLTCA PFN	10	91.3	
Linac 20-6	60	55.1	
Linac 20-6	120	60.2	
Linac 21-1	60	124.9	
Linac 21-1	120	506.7	Two stage
Linac 28-1	60	154.8	
Linac 28-1	120	314.6	Two stage
Linac 28-2	60	41.6	
Linac 28-2	120	79.4	
Linac 28-3	60	118.4	
Linac 28-3	120	295.2	Two stage

Orion and 2-Pack are induction modulators [3]. The others are PFN modulators. Orion has the best pulse stability. Linac 20-6 and 28-2 are better than other PFN modulators, but still need improvements to achieve the 30ppm goal. Clearly, not all linac modulators are performing at the same pulse stability level.

Linac modulator pulse stability at 120Hz is worse than that at 60Hz. Modulator 21-1, 28-1 and 28-3 show a "two-stage" signal at 120Hz. This is a repeated effect which can be effectively compensated by the RF feedback system. It originates from the power-line derived SLAC timing system. Figure 10 shows the pulse stability of modulator 28-1 at 120Hz.

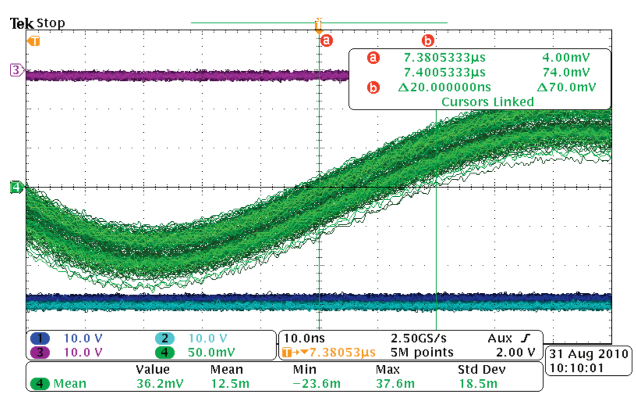

Figure 10. Pulse stability of modulator 28-1 at 120Hz

B. Linac Modulator Pulse Stability Improvement

To improve the pulse stability of a linac modulator, attention was focused on the PFN charging voltage stability which directly affects the modulator output pulse stability.

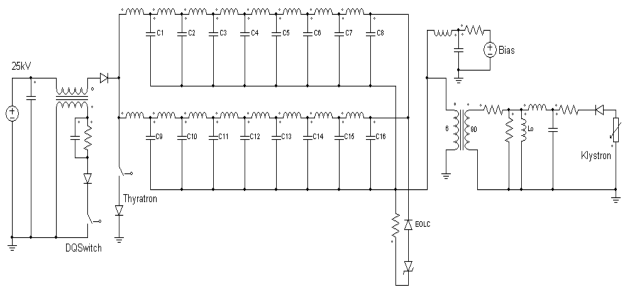

Figure 11. Linac PFN modulator simplified diagram

Figure 11 is the simplified diagram of linac PFN modulator. The PFN is charged by a resonant charging circuit with de-Qing regulation. The charging voltage stability is affected by the charging circuit, and thyratron turn-off behavior. Figure 12 shows unstable thyratron turn-off in modulator 28-3. Variations in thyratron turn-off alter the initial conditions for PFN charging of the next pulse, which is only partially compensated by de-Qing. Linac modulator pulse stability improvement is ongoing at SLAC.

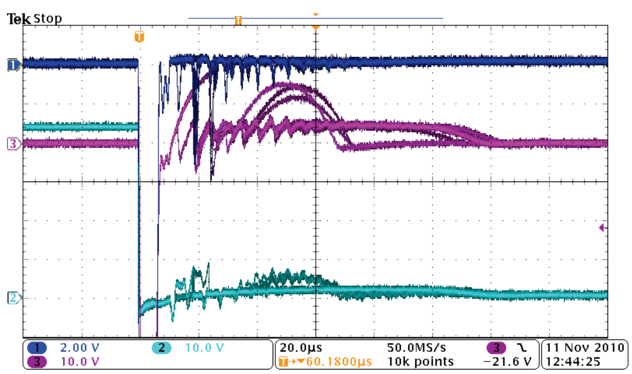

Figure 12. Modulator 28-3 thyratron turn-off performance
Ch1—Thyratron current (100:1)
Ch2—Thyratron voltage (1000:1)
Ch3—Klystron voltage

C. 2-Pack Modulator Pulse Stability Improvement

The 2-Pack hybrid modulator uses 15 single turn induction cells, each with two IGBT drivers. A single turn secondary drives a 1:10 pulse transformer which is capable of powering two XL4 klystrons (currently, only one is installed). Figure 13 shows the simplified diagram.

The 2-Pack modulator output pulse stability is about 90.1ppm. The major sources affecting induction modulator pulse stability are the capacitor charging voltage stability of each cell, and the induction core and pulse transformer bias current stability. The measured capacitor charge voltage stability ranges from 50 to 70ppm. Further investigation and improvement of pulse stability is underway.

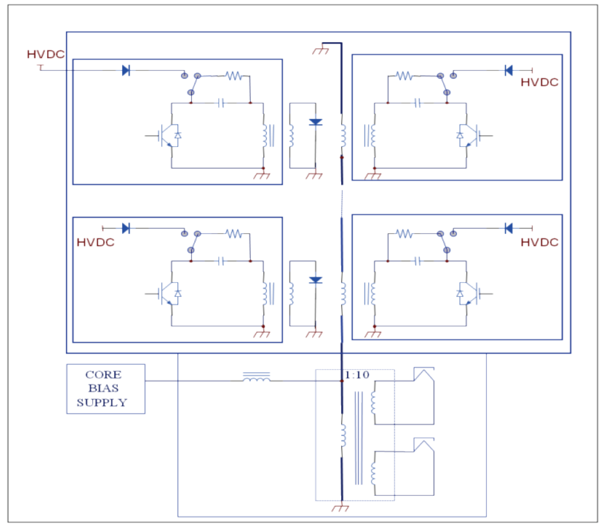

Figure 13. 2-Pack simplified diagram

V. SUMMARY

A pulse stability measurement device was developed at SLAC with accuracy better than 250uV, which is about 4.2ppm of a typical 60V input pulse. Pulse measurement range is from +80Vpeak to -80Vpeak, at higher input pulse voltage the relative measurement accuracy is increased. The measured cutoff frequency of the device is about 6.5MHz. It is a very useful tool for measuring and improving modulator pulse stability.

VI. ACKNOWLEDGEMENT

The authors would like to thank Patrick Shen for his contribution of the pulse stability measurement device development.

VII. REFERENCES

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