A Stability of LCLS Linac Modulators

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ABSTRACT

Information concerning to a stability of LCLS RF linac modulators is allocated in this paper. In general a "pulse-to-pulse" modulator stability (and RF phase as well) is acceptable for the LCLS commission and FEL programs. Further modulator stability improvements are possible and approaches are discussed based on our experimental results.

1 INTRODUCTION

The principal 6575 SLAC line type modulator considerations were described for the original 24 MW peak XK-5 klystron loads (250kV, 250A, 2.8usec) by Robert Bradford, et. al. [1]. Original modulator stability requirements:

- Pulse height deviation from flatness +/- 0.5% (max)
- Pulse-to-pulse time jitter +/- 10 nsec
- Pulse-to pulse amplitude jitter +/- 0.25%

The original modulator stability was depended on the thyratron stability. The tube stability was controlled by a setup of PFN-Load impedance match, by an employment of the deQ'ing and end of line clipper subsystems. It is important to note the following fact. Early in 1963 efforts were concentrated upon the evaluation of hydrogen thyratrons for the SLAC modulators (no single tube which would meet all the SLAC specification was available). Tube manufactures worked together with SLAC to design the thyratron suitable for the initial 6575 modulators that drove XK-5 klystrons. Both the Tung-Sol CH1191 and the I.T.T. KU275A thyratrons were accepted at that time.

A high energy physics program (to reach the 50 GeV output beam energy) induced to upgrade the accelerator. The program completed in end of 80th [2]. XK-5 klystrons were replaced by 5045 ones with a 50 MW peak (320 kV, 360A, 5 usec). Introduced in RF system SLED cavities were gained the beam energy by factor 1.7 with the increased modulator pulse length that was set to be slightly over 5 usec. The increase in klystron beam voltage and pulse length results to:

- Decrease the PFN impedance from original 7 Ohm down to 5 Ohm and
- Employ a new pulse transformer turn ratio with increased core cross section

Original Tung-Sol and I.T.T. thyratrons were showed a high fault rate and several alternative tube designs were tested.

A result of testing of an alternative type of the thyratrons was described by D. Ficklin Jr. in 1994 [3]. There was a period when such vendors as OmniWave, Litton, EEV, and ITT modified their thyratron to meet the new specification to increase the primary peak current through the thyratron from 5kA to 7kA. A. Donaldson and J. Ashton analyzed and published paper concerning the SLAC modulator reliability and availability for the high energy program [4]. There was a period when the SLAC modulator experts were deeply involved in considerations in modulator approaches for the room temperature NLC concept. The modulator stability was not analyzed in detail at that time. Modulator stability was not analyzed also during a period when the SLAC linac was used as whole energy injector for the high energy PEP-II program because the modulator stability was not so critical during the PEP-II era. The modulator stability issues became important when the SLAC linac had turned into service of FEL programs (LCLS-I, LCLS-II, etc.)

The LCLS linac employs the last ten sectors consisting of eighty of these existing modulators to accelerate the 150 MeV beam from the injector to a final energy between 4.54 GeV and 14.35 GeV. It requires a high brightness electron beam with very low timing and intensity jitter. Critical sectors at the front end of the linac requires RF phase jitter of $\leq 0.07^0$, which corresponds to modulator output voltage stability of $\leq 0.01\%$ or 100 ppm rms. Depending on thyratron conditions and operating voltage levels, some modulators meet this requirement for short-term (≤ 10 seconds) stability at trigger rates ≤ 60 Hz . Most modulators, however, have voltage stability > 150 ppm rms.

This paper focuses on identifying the source of modulator instability, and discussing solutions to improve the modulator short-term performance for LCLS users. In addition, a highly accurate pulse measurement device was developed to measure along with an oscilloscope the klystron beam voltage stability.

2 SOURCE OF MODULATOR INSTABILITY

The current modulators for LCLS programs run mostly 24 hours per day at 120 Hz. The modulators are working on the klystron type load through 1:15 pulse transformers. Original 1:13 x-fmrs were replaced during the linac upgrade for the high energy program in the end of the 1980s. During this period of linac upgrade it was found that the 5045 tubes can mostly reliable operate at 350 kV with 60+ MW peak (the reflected to the primary circuit klystron impedance is in a range 3.7-4.3 Ohm). In general "pulse-to-pulse" modulator stability (and RF phase as well) is acceptable for the LCLS commission and FEL programs. Further modulator stability improvements are possible and approaches are discussed based on our experimental results.

It was realized that a main source of modulator instability is processes in the thyratron which take place after an anode pulse is delivered through the pulse x–fmr. After the anode pulse, a reactive energy that is accumulated in the x-fmr is

acting on the modulator components and in particularly on the thyratron that is on the recovery process. This stored magnetic energy in x-frm is proportional to the modulator peak power and the pulse length. Both the peak power and the pulse length were increased during the SLAC linac program and the linac upgrades. However the thyratrons employed were not modified accordingly in respect to a new specification: *the thyratron must have immunity for the peak inverse voltage including spike more than 10 kV for the first 25-30 usec after the anode pulse*. Hence the main source of modulator instability is processes in the thyratron that are driven by reactive components of the pulse x-frm. The SLAC modulators employ the thyratrons from several vendors (L3, E2V, and ITT). There is no difference in the thyratron behavior from the stability point of view.

Regarding the stored magnetic energy effects on the modulator stability, fig. 1 (a) and (b) show the normal and abnormal klystron beam voltage pulses.
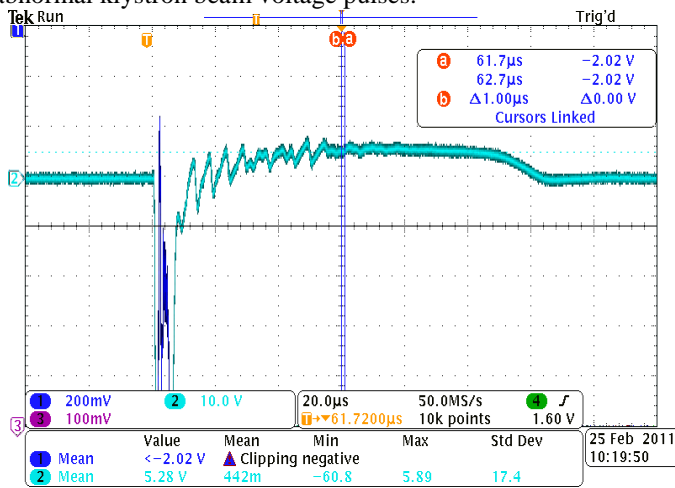

Fig. 1(a). A normal klystron beam voltage waveform is shown with a 20 usec/div horizontal scale. Mainly it is seen a trace after main negative pulse. The thyratron reservoir voltage was set in such a way that the stored in x-fmr energy was dissipated in modulator components.
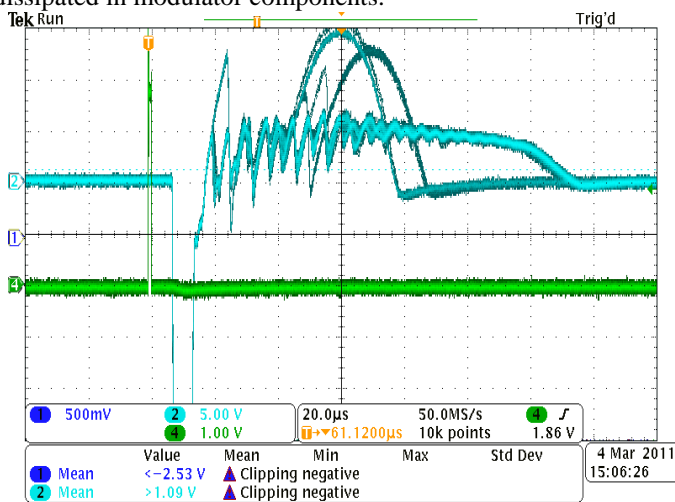

Fig. 1(b) Ch2 shows the same as for Fig. 1(a) waveform. A case of unstable recovery in thek thyratron is shown.

The abnormal beam voltage was formed when the stored magnetic energy in the pulse x-fmr produces the inverse voltage and current from the anode to the cathode. The thyratron tube can cease to conduct this current and an abruption forms the inverse voltage on the klystron gun. The plasma erosion processes (a fast recombination) inside of thyratron are not stable from pulse-to-pulse. One can see that thyratron may be ON and OFF several times during first tens of microseconds after the anode pulse. At that time, a process of the PFN charging starts also for the next pulse. As a result of the instability there is vagueness in PFN initial storage energy conditions for the next pulse. Moreover, the fast (during several tens of nanoseconds) plasma erosion inside thyratron capable provokes the inverse breakdown voltage on the klystron gun also. This klystron voltage breakdown results on a reduction of its life time. The bottom-line of this paragraph is a fact: the main source of the present 120MW peak modified 6575 SLAC modulator is the 1:15 pulse transformer that stores reactive energy after delivery time. This reactive energy results in unstable thyratron recovery processes.

To get a stable mode of modulator operation we evaluated the traditional following receipts.

- Positive mismatch PFN tuning
- Thyratron reservoir voltage range
- Effectiveness of tail clipper installation
- Improving of PFN charging voltage regulation
- Effectiveness of the high voltage charging supply decoupling by command charge mode employment

2.1 EVALUATION OF POSITIVE MISMATCH FOR 150MW PEAK MODULATORS

A positive mismatch is a known receipt [1] for a healthy thyratron recovery. An essence of a positive mismatch is as follows. If the PFN impedance is tuned less than the klystron impedance, then a small positive voltage on anode will allow finishing thyratron recovery after the pulse end. It is clear that mismatch will help approximately during 2*tp period, where tp is the anode pulse width. For example, beam voltage is 350kV and klystron beam current is 360 A. The rough klystron impedance reflected to the primary (for the 1:15 x-fmr turn ration) is 4.3 Ohm. To get a 10% positive mismatch, the PFN must be tuned for 3.5 Ohm. This will be a challenging task for the present modulator PFN because the inductance of employed 44nF capacitors would be comparable with the cell inductance. First of all a pulse top tune ability would be problematical. Moreover a reduction of cell inductance results the pulse width reduction. If we assume that the 3.5 Ohm PFN is feasible and could be assembled in the given modulator space, then the PFN must be charged up to 41 kV to get on the primary 23 kV peak. A reduction of thyratron anode voltage could benefit for the RF phase stability. However the effectiveness of this method is reduced when the power transmitted through the pulse x-fmr is increased

because the stored magnetic core energy acts on the recovery processes in the opposite direction of the mismatch.

Another fact of the modulator peak power rise is a release of the stored energy in x-fmr takes much longer compared to the mismatch action. Thus the recommendation to tune the 10% mismatch may be not enough for the stable recovery of existing thyratrons that severs 60+ MW klystrons.

2.2 RESULT OF THYRATRON RESERVOIR VOLTAGE RANGE

A traditional method is to range the thyratron reservoir pressure [1]. It is clear that the magnetic storage energy can be dissipated effectively if a longer conductive mode is kept in the thyratron tube. This mode assumes that the current can run in both directions (from cathode to anode and from anode to cathode). The mode, when the current leaks from anode to cathode, is not normal for a thyratron. This mode contributes greatly to the tube dissipation, electrode damage and deposit of electrode material on the ceramic envelope. The thyratron life time and voltage hold off are reduced. This method is expensive from (1) the rate of consumption of thyratrons and from (2) an operation point of view (personnel are required consistently to adjust the reservoir of all thyratrons)

2.3 AN EFFECTIVENESS OF TAIL CLIPPER IN 150MW MODULATORS

The next known method (see, for example [5]) was employed in the L1S LCLS station. This station is more sensitive for the X-Ray beam stability [6]. Tail clipper components were installed across the sending end of the triaxial pulse cable. Of course the best place for installation would be closer to the pulse x-fmr however for the operation simplicity the sending end is acceptable too.
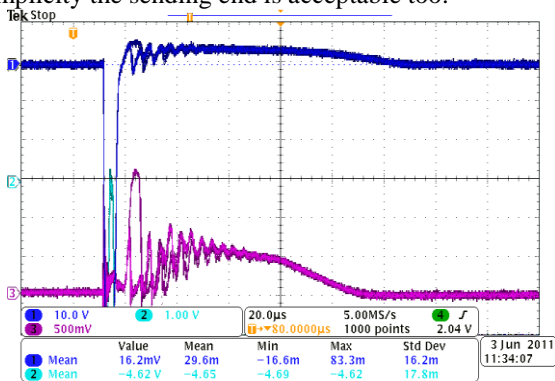
Fig. 2 A Beam voltage (blue trace, top) and tail clipper (purple trace, bottom) waveforms are shown with 20 usec/div horizontal scale.

A part of the magnetic stored energy will be dumped into a resistor. The circuit offers to help stable thyratron recovery. However the effectiveness of circuit action is limited by a speed of employed solid state diode stack. A discussion of employment a special designed fast tube is in progress.

2.4 INACCURATE DE-Q'ING SIGNAL COMPENSATION

The next method to stabilize the amount of the PFN charge

is an improvement of the PFN charging voltage regulation. Existing resonant charging system relies on a single-shot voltage regulation for each main pulse. There is no feedback or time to develop fine corrections of the PFN voltage. As such, this method of regulation by De-Q'ing the charging inductor requires sensing the PFN voltage from a compensated divider to compare with a precision DC reference source that ultimately determines the level of PFN voltage regulation. However, since there is a certain fixed time delay in the overall regulation circuits, changes in slope of the resonant charging voltage also produce DC voltage errors on the PFN. The errors or percentages of voltage regulation can be minimized if the charging divider signal is accurately compensated. That is the divider signal is advanced in phase an equal amount of the time delay in the regulation system.
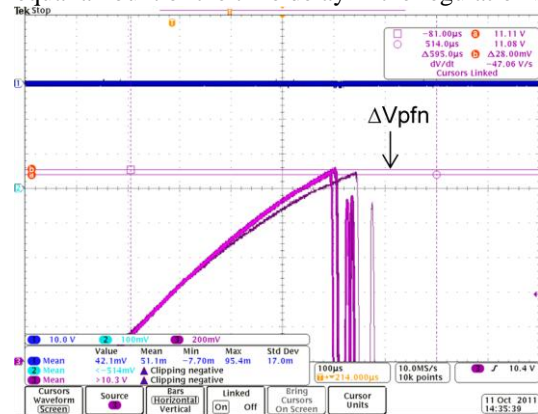
Fig. 3 Waveforms shows the PFN charging voltage variation (ΔVpfn) for the next pulse in the case of unstable recovery in the thyratron. A small variation results to RF phase pulse-to-pulse jitter.

This degree of phase advance depends on many factors such as the percentages of required regulation and related response time of the regulation circuit – a small time rate of voltage changes might produce longer comparator response time, while a faster rate might reduce the delay. So for a high level of accuracy, it was necessary to empirically determine the degree of compensation on the field with the modulator operated in normal condition. The compensation elements consist of an inductor and capacitor to form an LC delay network, which is connected in series between De-Q'ing divider signal and the regulation circuit. The inductance was set at nominal value of 5 mH and the capacitance was adjusted through a decade-capacitor box. Optimal phase advanced compensation is determined when the monitored beam voltage stability is at highest level.

2.5 EVALUATION OF PFN COMMAND CHARGE MODE

The essence of this method is based on the following statement. Let us decouple the PFN charging for a period while there is decay and completely stop all transient processes in the modulator circuit. After that we turn ON the high voltage power supply to charge PFN capacitors. In this case each pulse looks like a new one and does not depend on the recovery processes in the thyratron and does not depend

how much reactive energy was accumulated in the x-fmr. In this case we also do not care about the rate of the thyratron consumption. This approach is rather expensive because it requires integrating the controllable switch into the modulator circuit. However the cost investment in the switch assembly may be compensated by a reduction of the operating cost (less technician intervention). Reliability issues of controllable switch are also important.
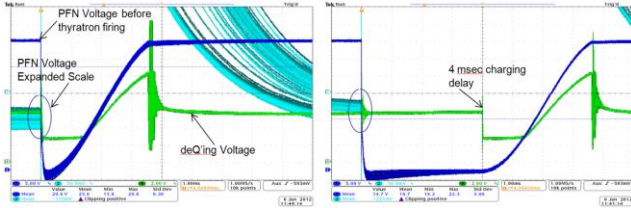

Fig. 4. Effect of modulator stability improvement for the case of command charge mode operation with 4 msec delay. The thyratron has unstable recovery. After all transients are decayd, the high voltage is turned ON to charge PFN for the next pulse.

3 PULSE-TO-PULSE STABILITY MEASUREMTS

A several approaches were used. More sensitive one is a beam acquisition method [6]. Another approach is to record the RF phase jitter of the 5045 klystron (which also very sensitive parameter for modulator stability measurement). On the field modulator stability were performed with DPO4054B oscilloscope. All methods correlate each other.

4 EVIDENCE OF MODULATOR STABILITY IMPROVEMENTS

Fig 5 shows a stability of klystron beam voltage and phase variation at the LCLS L1S station during 30 sec.
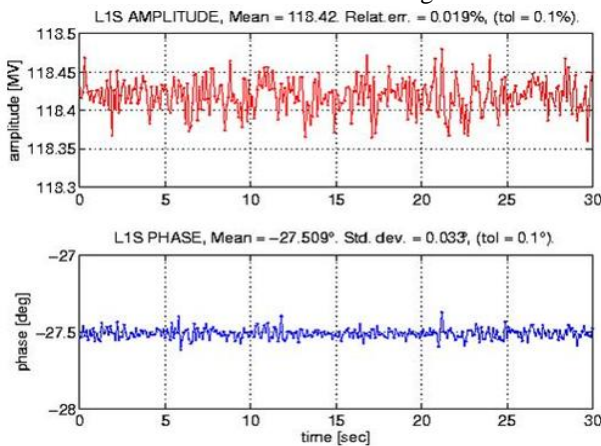

Fig.5

Figure 5 illustrates a short-range stability when 6575 modulator serves the 5045 klystron with 120PPS repetition rate. In this case the klystron is working in SLED detuned mode. The klystron feeds three accelerator sections. The total energy gain is 118.4 MeV with 0.02% RMS pulse-to-pulse jitter. The measured output RF phase is stable at 27.5 deg during 30 sec with a standard deviation 0.033 degree at 2856MHz. This measurement was done when other nearest

stations were OFF, i.e. an EM noise environment is not the same as for the LCLS beam deliver program.

Fig. 6 illustrates the same stability measurements when all LCLS stations run for the LCLS user programs.
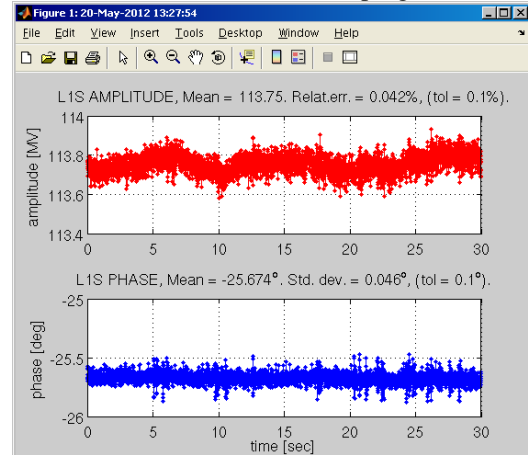

Fig.6

One can see that the stability of both the modulator and the RF source are much better than required tolerances.

5 CONCLUSIONS

The present 6575 SLAC modulator stability satisfies for the current FEL LCLS X-ray users. The evolution of FEL program (for example from SASE to self seeding mode) will require improving modulator and RF source stability. The known approaches such as positive mismatch PFN tuning, thyratron reservoir voltage range, effectiveness of tail clipper installation, improving of PFN charging voltage regulation, and effectiveness of the high voltage charging supply decoupling by command charge mode employment are evaluated and discussed. An evidence of modulator stability improvements (0.042% RMS jitter and 0.046 deg phase standard deviation) is demonstrated.

ACKNOWLEDGMENT

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