Life Review and Development of Thyratron in Linac Coherent Light Source*

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***Abstract*— Linac Coherent Light Source (LCLS) at SLAC has been running since April, 2009 and is driven by eighty-four klystrons. Each klystron is powered by a line-type modulator with a high power thyratron as a switch. The thyratron life has become an important concern. In this report, we will review thyratron life data in LCLS as well as thyratron development.**

Keywords—modulator; thyratron; pulsed power; switching

I. Introduction

In SLAC, klystron-modulator combination is utilized to generate microwave pulse to accelerate the e-beam. Eighty-four klystrons are used in LCLS. LCLS is a part of two-mile Linac in SLAC. LCLS began running April 2009 with modulators triggered at 30 Hz repetitive rate. In January, 2011, the modulators trigger rate was increased to 120 Hz. Modulators in LCLS utilize hydrogen-filled thyratrons as switches because of their fast recovery, but recently several deuterium-filled thyratrons have been installed because of their more stable recovery which improves the modulators' pulse to pulse stability.

The hydrogen thyratron is a switching device utilizing plasma as a conductive carrier. Generally, a high power thyratron is enclosed in a glass or ceramic housing and the electrode structure is optimized to operate at certain electric parameters. The housing is filled with hydrogen at a pressure necessary to ensure that the thyratron is working on a stable position of the hydrogen Paschen curve [1]. Because a certain amount of hydrogen molecules will be lost in the glass or ceramic housing, referred as hydrogen cleanup [1], a hydrogen reservoir is within a thyratron to replenish the hydrogen. A supplementary power supply will control the hydrogen release rate from the reservoir. Thyratrons often fail from hydrogen depletion, which is a function of the applied peak power, repetition rate.

II. Life Review of Thyratron

A. Thyratron Operational Parameters

In LCLS, the thyratron typical working parameters are in Table I [2]. In the early period of LCLS, the pulse repetition rate was 30 Hz.

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Table I. Typical Thyratron Operational Parameters in LCLS

Parameter	**Value**
Peak Anode Voltage	48 kV
Peak Current	6 kA
Pulse Repetitive Rate	120 Hz
Pulse Width (FWHM)	5 µs
Time Jitter	3-5 ns

B. Thyratron Models and Life

Historically a high voltage running time (HVRT) meter was used for the measurement for thyratron life. As long as the modulator was on high voltage and the thyratron triggers were on, the HVRT would count the thyratron life time [3][4]. A thyratron life time will vary when operating under different working parameters. For example, we know through experience that the lower anode voltage, the longer thyratron life time will be. Similarly, the lower repetition rate, the longer thyratron HVRT life time will be. To compare thyratron life in different repetition rate modulators, in this report, pulse shots' number will be used to measure the thyratron life [5].

In SLAC thyratron history database, we have over 720 thyratron records served in the 3 kilometer Linac after 1990s. Table II shows the life summary. The typical thyratron four models are F241, F310, L4888 and L4798. The overall average life of these 720 thyratrons is 5.24×10^9 pulse shots.

In Table II, we can see that the thyratron lives of all models are distributed over large ranges. The minimum F241 thyratron life is 40% of its average life and the minimum F310 life is 20% of its average life; while the minimum L4888 life is 30% of its average life and the minimum L4978 life is 10% of its average life. The life standard deviation of F241 and F310 are about 50% their average lives, respectively; while the life standard deviation of L4888 and L4978 are about 80% of their average lives, respectively. These data remind us that thyratron life is not very determined. It is noticeable that L4888 is with lowest average life among four models. It should be pointed that the average life is not only concern in SLAC procurement, the unit price and the source reliability are other important considerations.

Table II. Linac Thyratron Life Information (Unit: 1x10^9 Pulse Shots)*

Model	NO	MIN	MAX	AVE	STD
F241	162	0.24	19.07	6.03	2.78
F310	113	0.14	20.25	6.25	3.03
L4888	430	0.14	34.77	4.74	3.78
L4978	17	0.74	25.35	7.49	5.79

*Note: NO, MIN, MAX, AVE and STD represent thyratron number, minimum life, maximum life, average life and life standard deviation, respectively.

The thyratron models that have been used in LCLS are F241, F310, L4888 and L4978. A total 337 thyratrons were used in 84 klystron-modulator combinations (i.e. rf stations). The average life of these thyratrons is 4.75x10^9 shots. Of the 337 thyratrons, 302 are L4888, 14 are F241, 7 are F310, and 7 are L4978. Because most thyratrons in LCLS are L4888, we will focus on them. They has a minimum life of 0.14x10^9 shots, a maximum life of 34.77x10^9 shots, an average life of 4.41x10^9 shots with a life standard deviation of 3.49x10^9. Comparing with data in Table II, it can be seen that the L4888 average life in LCLS is about 9.3% shorter than the L4888 average life in Linac. Three possible reasons may explain this difference. One is that the design of the L4888 has changed. The old design has a bigger heat sink than the new design, which may reduce the thyratron anode temperature and extend the life. Another reason is that the method of thyratron ranging was changed in 2012 which diminished thyratron lifetime. This process change was abandoned, but the reduced thyratron lifetime over that period has skewed the overall LCLS thyratron lifetime data. One final reason for a reduced lifetime is that the LCLS modulators were upgraded in 2010 to 2015 [2], and those changes may have had an adverse effect on thyratron life.

Fig. 3 shows life time data from the 302 L4888 thyratrons used thus far in LCLS. Typical L4888 thyratron life ranges from 1.0x10^9 pulse shots to 8.0x10^9 pulse shots, which corresponds to 2315 to 18519 hours HVRT at 120 Hz repetition rate.

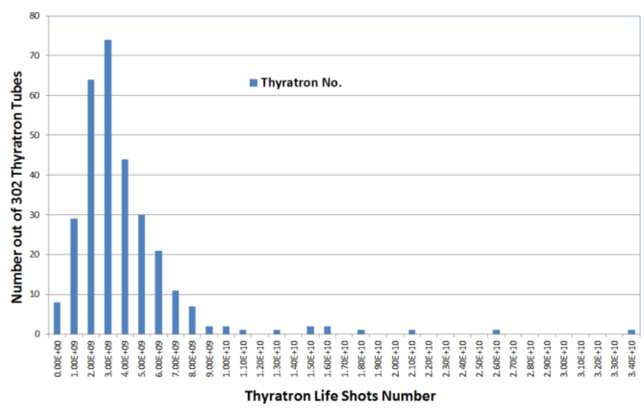

Fig. 3. 302 L4888 Thyratron Life Distributions in LCLS

C. LCLS Thyratron Replacement Chronicle

Fig. 4 shows the number of thyratron replacement in LCLS per calendar year. The horizontal axis represents the calendar year, although it is marked as January. 2009 calendar year is from April 1st, 2009 to December 31st, 2009 because LCLS started to run on April 1st, 2009. The other calendar years are from January 1st to December 31st. The left vertical axis is the number of removed thyratron from the 84 stations in LCLS. The blue line connects all removed thyratron number. The right vertical axis in Fig. 4 is the normalized thyratron replacement number per 1x10^9 pulse shots in LCLS 84 stations (all pulse shots in 84 stations are added together for the calendar year). The green line connects all normalized replacement thyratron points. The blue line points ranges from tens to 70s The green line points range from 0.08 to 0.31 per 1E+9 shots, which corresponds to a range of thyratron average life of 12.5x10^9 to 3.23x10^9 pulse shots. It can been seen that the thyratron replacement rate per year or per 1x10^9 shots changes dramatically in early several years of LCLS.

In 2009, only ten thyratrons failed, but its normalized thyratron replacement rate is about 0.23 thyratron per 1x10^9 pulse shots, not far from average thyratron life of 4.75x10^9 pulse shots mentioned in section II. In 2010 and 2011, both removed thyratron numbers and normalized thyratron replacement rates are at a minimum, but in 2012, the removed thyratron numbers and normalized thyratron rates peak. This peak was from a change in the thyratron ranging process which was later abandoned. The black line in Fig. 4 is a linear fitting for the green line. The black line shows that the thyratron failure rate is slowly increasing.

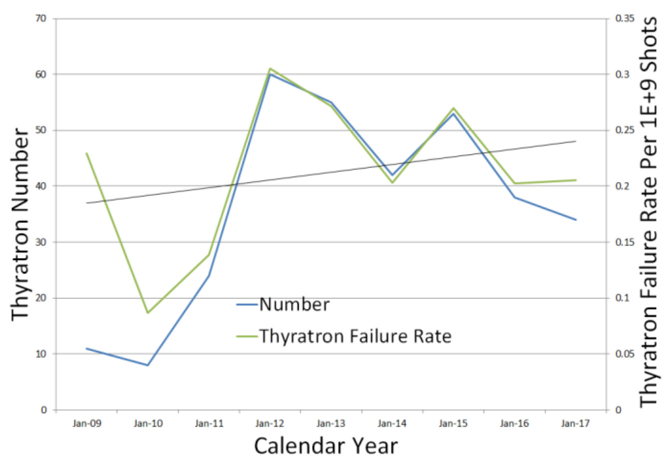

Fig. 4. LCLS Thyratron Removed Chronicle

D. L4888 Thyratron Failure Reasons

Thyratron life relates to a lot of factors, such as working parameters, trigger signal quality, environmental conditions, working electronic circuits, et. al. In LCLS line type modulators, a saturable reactor is installed to prevent the thyratron anode exposing to high energy collection [6][7][8][9]. An EOLC (end of line clipper) is installed at the end of PFN to improve the thyratron recovery [2].

Figure 5 shows the cause of failure of the L4888 thyratrons from LCLS. Here are the top two thyratron failure reasons:

Hydrogen Depletion" and Open Reservoir". These failure mechanisms account for 81% of the failed thyratrons. Generally, the thyratron performs unstably when the hydrogen pressure get lower than the "workable pressure", which means that the reservoir cannot replenish enough hydrogen molecules to compensate hydrogen cleanup before the next pulse.

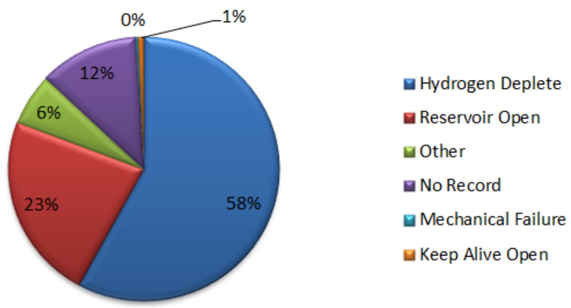

Fig. 5. 302 L4888 Thyratron Failure Reasons in LCLS

Based on the discussion above, the "reservoir" is a key to extend the thyratron life.

III. Life Development of Thyratron

The thyratron will lose a certain amount of hydrogen molecules in each conduction period, depending on operational parameters, and the reservoir will release some hydrogen molecules to replenish the loss. L4888 is a two-gap hydrogen-filled thyratron suitable for line type modulator applications, utilizing titanium-hydride as a reservoir material. A reversible chemical process in equation (1) occurs in thyratron operation as a function of temperature [10][11][12][13].

$$TiH_x \leftrightarrow Ti + \frac{x}{2}H_2 \qquad (1)$$

If the hydrogen pressure can be maintained at a "workable" level before the firing starts, the thyratron is good to operate. Once the operational parameters are set, the thyratron gas pressure achieves a relative stable equilibrium state, the thyratron can work stably for a period. If any parameters change, like the repetition frequency is increased, then the hydrogen cleanup rate gets higher. Over time the hydrogen replenishment gets slower because of reservoir aging resulting in un-equilibrium state. When this occurs, the thyratron needs to be ranged to a new equilibrium state for stable performance. Generally this is accomplished by raising the thyratron reservoir power supply voltage to increase the rate of hydrogen released from the reservoir. As the thyratron continues to age, the reservoir can no longer release enough hydrogen to compensate for the hydrogen cleanup, and the thyratron will need to be replaced. Alternatively, if the modulator operational parameters are adjusted, like lowering the repetitive rate or lowering the high voltage on the thyratron anode, then the thyratron lifetime can be extended. This is why some thyratrons retired from LCLS at 120 Hz repetitive rate can be commissioned to work in FACET at 30 Hz repetitive rate at SLAC.

To extend the thyratron life, eighteen modified L4888 were manufactured and installed in LCLS modulators since 2012 with more hydrogen storage in reservoir. Four different options are utilized.

Option 1: With 5 titanium reservoir capsules, titanium reservoir temperature in a thyratron is reduced to increase hydrogen storage;

Option 2: With 7 titanium reservoir capsules, titanium reservoir temperature in a thyratron is NOT reduced to increase hydrogen storage;

Option 3: With 7 titanium reservoir capsules, titanium reservoir temperature in a thyratron is reduced to increase hydrogen storage;

Option 4: A single large capacity reservoir capsule is utilized in a thyratron;

In Option 1 and Option 3, the reservoir working temperature is reduced to increase the hydrogen storage [1]. In option 2, the reservoir working temperature is not reduced but the reservoir capsules number is increased from 5 to 7. In option 1, 2 and 3, the hydrogen reservoir has been increased with different ways. These thyratrons had been installed in different modulators and life data is shown in Table III, IV, V and VI.

Table III. Life Data of L4888 with Option 1 in LCLS

Serial No	**Beam Volt (kV)**	**Life (Hours)**	**Life (Shots)**
100914	350	23040	9.88E+09
100918	350	12936	5.58E+09
100926	345	15504	6.70E+09
100933	335	8424	3.64E+09
100934	339	16152	6.91E+09
100937	330	10080	4.35E+09
100938	350	8088	3.49E+09
Average		**13140**	**5.65E+09**

Table IV. Life Data of L4888 with Option 2 in LCLS

Serial No	**Beam Volt (kV)**	**Life (Hours)**	**Life (Shots)**
100920	300	15960	6.89E+09
100923	350	16584	7.14E+09
100924	340	13608	5.87E+09
100925	350	9840	4.25E+09
100928	350	7440	3.21E+09
Average		**12686**	**5.47E+09**

Table V. Life Data of L4888 with Option 3 in LCLS

Serial No	**Beam Volt (kV)**	**Life (Hours)**	**Life (Shots)**
100921	324	21642	9.34E+09
100930	350	12528	5.41E+09
100932	350	15576	6.55E+09

100936	350	14736	6.37E+09
Average		**16116**	**6.92E+09**

Table VI. Life Data of L4888 with Option 4 in LCLS

Serial No	**Beam Volt (kV)**	**Life (Hours)**	**Life (Shots)**
100929	340	19848	8.44E+09

Comparing the data in table III-VI with L4888 average life in Fig. 1, it can be seen that all L4888 with options gain more life shots: the average life shots of the thyratrons with option 1, option 2, option 3, and option 4 gain 28.6%, 24.3%, 57.3% and 91.8%, respectively. The result shows that increasing the hydrogen storage in the reservoir with the four options effectively extend the thyratron life. Because option 3 s a combination of option 1 and option 2, the thyratrons with option 3 gain more life than option 1, or option 2, separately. Although the thyratron with option 4 gains 8.44×10^{9} life shots, we cannot conclude that it has maximum average life than other options because only one tube is involved. A conclusion can be reached that the life performance of a thyratron with option 4, a single large capacity reservoir capsule, is not worse than a thyratron with several small reservoir capsules.

In summary, all four options extend the L4888 life to different degrees. The thyratrons with the combination of option 1 and option 2 extend the thyratron life more than the thyratrons with option 1 or option 2 only. Because SLAC does not hold detailed manufacturing information, it is not proper to do the quantitative technical analysis for the life data.

IV. Summary

The different model thyratron life information are collected and analyzed. Pulse shots are used to evaluate the thyratron life in SLAC, replacing the high voltage running time (HVRT). Reservoir related thyratron failures take more than 81 percent account for all thyratron failures. To extend the thyratron life, L4888 hydrogen thyratrons have been modified with four different options and are installed in LCLS modulators. All thyratrons with options gain more life shots to different degrees. The life performance of a thyratron with a single large capacity reservoir capsule is not worse than a thyratron with several small reservoir capsules.

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References

[1] S. Goldberg and J. Rothstein, Research Study on Hydrogen Thyratrons. Edgerton, Germeshausen & Grier, Inc, Boston, MA, 1956.

[2] M. N. Nguyen, et al., “Recent Upgrade of the Klystron Modulator at SLAC”, SLAC-PUB-14486.

[3] D. B. Ficklin, “A Hsitory of Thyratron Lifetimes at the Stanford Linear Accelerator Center”, Proceedings of the IEEE 21st Power Modulator Symposium, Costa Mesa, California, 1994, pp. 264-267.

[4] D. B. Ficklin, “An Update History of the Thyratron Lifetimes at the Syanford Linear Accelerator Center”, IEEE Conference Record of the 23rd Internation Power Modulator Symposium, Rancho Mirage, California, 1998, pp. 70-73.

[5] G. D. Wait and M. J. Barnes, “Thyratron Lifetimes, a Brief Review”, 1995 Second Modulator-Klystron Workshop, Stanford, CA, 1995 pp. 258-263, 1995.

[6] A. R. Donaldson, “A Hybrid Anode Reactor for the SLAC Modulator”, Proceedings of the IEEE 21st Power Modulator Symposium, Costa Mesa, California, 1994, pp. 136-139.

[7] J. S. Oh, W. Namkung and H. Matsumoto, “Lifetime Issue of a Thyratron for a Smart Modulator in the C-band Linear Collider”, Proceedings of APAC, 2004, Gyeongju, Korea, pp. 767-769.

[8] C. A. Pirrie, C. A. Roberts, P. W. Robinson and K. G. Cook, “Thyratron Design & Circuit Techniques to Overcome the Adverse Effects of High Inverse Voltages”, Proceedings of the IEEE 21st Power Modulator Symposium, Costa Mesa, California, 1994, pp. 272-276.

[9] I. Smilanski, “Reducing Thyratron Losses in CVL Modulator”, IEEE Conference Record of 19th Power Modulator Symposium, San Diego, CA, 1990, pp. 287-289.

[10] C. A. Pirrie and H. Menown, “The Evolution of the Hydrogen Thyratron”, IEEE Conference Record of the 24th International Power Modulator Symposium, Norfolk, Virginia, 2000, pp. 9-16.

[11] J. A. Kunc, S. Guha, and M. A. Gundersen, “A fundamental theory of high power thyratrons I: The electron temperature,” Laser and Particle Beams, vol. 1, no. 4, pp. 395–405, 1983.

[12] J. A. Kunc and M. A. Gundersen, “A fundamental theory of high power thyratrons II: The production of atomic hydrogen and positive ions,” Laser and Particle Beams, vol. 1, no. 4, pp. 407–425, 1983.

[13] J. A. Kunc, D. E. Shemansky, and M. A. Gundersen, “A fundamental theory of high power thyratrons for high power laser and beam applications III: the production of radiation,” Laser and Particle Beams, vol. 2, no. 2, pp. 129–140, 1984.