LIFETIME ISSUE OF A THYRATRON FOR A SMART MODULATOR IN THE C-BAND LINEAR COLLIDER

J. S. Oh, KEK and PAL/POSTECH, Pohang, Kyungbuk 790-784, Korea
W. Namkung, PAL/POSTECH, Pohang, Kyungbuk 790-784, Korea
H. Matsumoto, KEK, Tsukuba, Ibaraki, Japan

Abstract

Long lifetime over 50,000 hours for the thyratron is essential requirement to provide reasonable availability of the C-band e+e- linear collider. The lifetime and reliability of a solid-state device are not well confirmed yet. There are some examples that show long life of a thyratron. Many thyratrons were dead due to several common causes related to circuits and operation environment rather than intrinsic problems of a device itself. The C-band smart modulator uses an inverter charging method and this scheme affects so much the life of a thyratron. Several valuable feedback systems are easily adopted to enhance the lifetime. There are still unidentified questions to be verified in the thyratron. Close collaboration between laboratories and companies is strongly requested in order to improve the lifetime and performance of a thyratron.

INTRODUCTION

The proposed C-band e+e- linear collider is consisted of about 4,000 thyratrons for smart klystron-modulators. In order to provide reasonable availability of the linear collider, long lifetime over 50,000 hours for the thyratron is essential requirement [1].

A solid-state device is emerging device and it seems to have potential to provide such a long life. However, it is catastrophic to the faults. It needs complicated auxiliary system that should be more robust and reliable than the device. The lifetime and reliability of these devices are not well confirmed yet. The cost is very high and difficult to reduce due to the small scale of semiconductor business. Solid state devices such as IGBT or SI thyristor are might be better for the applications that require rather low voltage, high average current, high average power.

The thyratron parameters are well suited to high power pulse applications that require high peak voltage, high peak current, high peak di/dt, and high efficiency. A matching driver circuit is very simple due to the simple structure of the thyratron tube. Many thyratrons were dead due to several common causes that are related to circuits and operation environment rather than intrinsic problems of a device itself. There are some researches to improve the performance and lifetime but those results are not well combined and proved well. Even though the low inverse voltage of the thyratron anode is important, it is not tightly controlled.

POTENTIAL OF THYRATRON TUBES

There are three major development series through the history of SLAC thyratron for about 30 years since 1964. The Wagner model CH191 tubes had been delivered since 1964 and rebuilt as ITT F143, Omniwave 1002. From the beginning of SLC era in 1984, ITT F241 tubes had been used and rebuilt as ITT F310. In the 1992, EEV tubes such as CX1836A and CX2410 had been adopted [2].

About 1600 tubes of Wagner model CH1191 had been used in SLAC for 10 years since 1964. The operational statistics of CH1191 thyratron tubes is shown in the figure 1. This data analysis includes only 35% tubes since 1985. From 1964 to 1984, operational parameters of thyratrons are 46 kV, 4.2 kA, 3.8 μs, 360 pps, 5.7 A. From 1985 to 1994, operational parameters of thyratrons are 46 kV, 6.3 kA, 5.4 μs, 120 pps, 4.1 A. Amazingly 20 tubes are still active in 1994 with ages between 75 ~ 120 hours. We can see the wide distribution of age and lifetime profile from the figure.

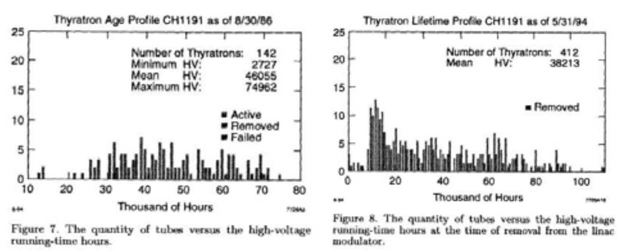

Figure 1: Operational statistics of CH1191 thyratron tubes.

REVIEW OF A THYRATRON

Switching cycle

Figure 2 shows typical Paschen curve related to the operation of a thyratron filled with hydrogen to a pressure of 0.5 Torr. The small inter-electrode spacing of 3 mm between the high voltage electrodes, marked "low pd" in the diagram, provides the high voltage hold-off up to 40 kV. In order to minimize the trigger-voltage requirement, the cathode/trigger-grid spacing, marked pd_{min} in the diagram, is set at about 15 mm. The "high pd" is applied to the insulation design of the envelope of the thyratron, and the electrodes have a spacing of about 75 mm.

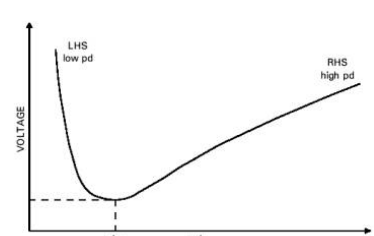

Figure 2: Paschen curve of a thyratron.

Thyratron commutation is achieved by introducing plasma into the grid/anode region via slots in the grid structure. The plasma is created in the cathode/grid region by a fast rising trigger pulse applied to the grid, which then diffuses to the grid slots where it comes under the influence of the anode field. The trigger plasma provides a copious supply of electrons so that anode breakdown proceeds until ionized plasma connects the cathode and anode. When the commutation phase is complete, the thyratron is fully filled with hydrogen plasma. Current is carried between cathode and anode with a potential drop of the order of 100 V per peak current of 1 kA. This low voltage drop is caused by the shielding effect of the positive ions in the plasma that allows the electron current to flow without space-charge limitation.

In order to decay back the plasma to neutral gas, the thyratron needs a recovery period with the anode at a slight negative potential. The plasma decay is dominated by the recombination of ions and electrons on adjacent electrode surfaces. Diffusion processes in the grid/anode region therefore control thyratron recovery. Since the anode/grid gap and grid slots are relatively narrow, the plasma density drops rapidly in this region with a time constant of 2-7 μs. The grid-cathode plasma decays much more slowly because of the wider gaps involved [3].

High voltage structure

The tube is triggered at the cathode end and the high voltage gaps go into conduction. It starts with the gap at the cathode and followed by a delay of around 50 ns before the next gap, and so on. The result is that the last high voltage gap at the anode must withstand the full anode voltage for a period of 50 ns without arcing.

Molybdenum tubes have been operated successfully at up to 160 kV but copper has been observed to suffer arc damage above 60 kV. The generally accepted maximum field strength for D.C. voltages in electron tubes with conditioned surfaces is 10-kV/mm. The peak electric field exceeds this level by a factor of two for a period of 50 nsec during commutation at the anode voltage of 50 kV. The limits for acceptable peak field strength under such transient conditions are not precisely known.

Cathode temperature

The optimum cathode operating temperature is around 750-780°C. It is a balance between sufficient primary electron emission at one extreme and minimizing thermal evaporation at the other. A temperature increase of as little as 25°C may double the rate of coating evaporation. The cathode back heating by ion impact makes a significant contribution to overall cathode power dissipation. The average anode current of 4 A can raise the cathode temperature about 100°C. This is equivalent to the increase of the heater power of 100 W. It is perhaps surprising that the practice of operating thyratron with reduced heater power to compensate for back heating has not been adopted much more widely [4].

Cooling

The dV/dt signal of the anode provides a relative measurement of the gas pressure. The cooling of the anode stem to below 70°C is advisable when the tubes are being used with high forward voltage over 30 kV and inverse voltage. The gas pressure variation as average current is increased can be made small by improving the heat extraction from the surface of the anode using large diameter anode rod. The ceramic envelope near the cathode must not fall below 70°C when operating normally in air. It is possible to overcool the thyratron, which may result in a low cathode temperature and a low gas pressure. Excessive airflows directed at the cathode and reservoir regions can reduce the envelope temperature below optimum levels. The resulting change in radial gas density gradient is equivalent to operating the thyratron at low gas pressure and can reduce the performance and operating life.

Others

In cases where the pulse current exceeds several kilo-amps, it is advisable to ensure symmetrical current flow in the connections around the thyratron. An asymmetrical magnetic field can impose forces on the internal plasma that prevent uniform current density at the cathode and at grid apertures with unpredictable effects on performance and lifetime. Helium will diffuse through the envelope of a glass thyratron if the tube is run hot in a helium-rich atmosphere. It is important that where glass thyratrons are used in an environment that could contain helium (e.g. a TEA CO_2 laser), they are adequately cooled.

CRITICAL ISSUES OF A THYRATRON

Cathode

The thermionic cathode is one of the key features that will determine the life. The oxide cathode is preferred over the smaller BA impregnated cathode simply due to the cost. Operation at a reduced average anode current is believed to be an effective way of increasing the tube lifetime to over 50,000 hours [5].

Reservoir and Ranging

The switching performance of the thyratron is very sensitive to the internal gas pressure. Gas pressure of about 0.5 Torr is maintained by heating titanium hydride TiH_2 in porous nickel capsules, reservoir that is loaded with several hundred tube-volumes of hydrogen. A high capacity reservoir system minimizes gas pressure adjustments throughout tube life. A ranging is a procedure of checking and adjustment of the optimum pressure of the thyratron. Intensive ranging is a time-consuming part of modulator operation and maintenance. Automatic tracking of the optimum pressure against changes in applied reservoir voltage and back-heating conditions is provided in the E2V thyratron, which has a temperature-sensitive regulation circuit (barretter) in the tube base.

Triggering

An additional grid between the control grid and the cathode is adopted to generate pre-ionizing discharges by using either a D.C. or a pulsed current. This tetrode tube has a performance that is satisfactory for a linear collider: very low switching jitter of 1 nsec and drift, faster switching, and a smaller grid spike. The traditional D.C. pre-ionizing current of a few hundred milli-amperes is considered to be insufficient to ionize fully all the cathode area. A thyratron double-trigger system could produce a pulsed current of several tens of amperes to ionize fully the cathode space.

Inverse anode voltage

An inverse voltage level above 5 kV just after a forward conduction causes strong ion bombardment of the anode. It liberates enough anode material that will be deposited on the critical insulating surface. This affects eventually the forward voltage hold-off adversely. An inverter charging power supply provides the command-charging feature that is effective way to turn-off a thyratron without an inverse voltage, which is highly recommended to guarantee a long life. Proper design of the tail clipper and the EOLC circuit is essential to ensure low inverse.

Saturating anode inductor

To reduce the anode heating arising from switch-on losses, and to reduce the voltage appearing across the top gap during thyratron commutation, it is effective to use a saturating anode inductor with a thyratron. A saturating anode inductor with a volt-second product of 1-mVs will give a switch-on delay of about 50ns. It may be necessary to trade off the effect of the added saturated inductance on the current rise time against the protection afforded to the top gap. Saturating anode inductors also afford some protection against the adverse effects of inverse voltages.

R&D OF A THYRATRON SWITCH

Further deep understanding of the thyratron is necessary to enhance the performance and lifetime. First, autopsy of thyratron tubes is necessary to understand the causes of failures and differences of each tube. In addition, we have to study the anode circuit of the thyratron that includes anode temperature measurement, anode dV/dt measurement, anode reactor optimization, etc. Cathode circuit study will include the effect of D.C. heater vs. AC heater, cathode temperature measurement, and auto ranging of cathode heater. Grid circuit R&D is consisted of grid temperature measurement, the comparison of D.C. prime vs. pulse prime, trigger optimization of double pulse trigger. Gas circuit study will include measure of gas condition by dV/dt and/or RF pickup, stabilization of gas condition by auto ranging.

Figure 3 shows the experimental setup for the research of switching characteristics. The voltage at the anode and gradient grid electrode are measured to get dV/dt, anode delay time, and jitter. The anode temperature will be measured by a pyrometer to analyze heat loading of the anode. Variable anode reactor will be optimized to get minimum anode heating. Pulse and D.C. trigger scheme will be compared to find optimum trigger condition. RF pickup coil will amplify signals that will be used as a feedback signal to control reservoir temperature. Heater circuit has a constant resistance control mode to keep constant cathode temperature.

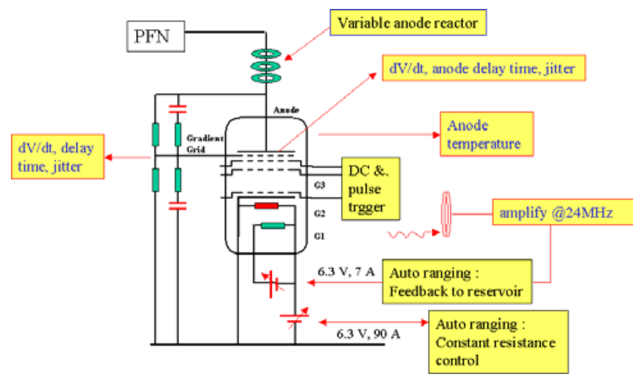

Figure 3: Experimental setup for the thyratron R&D.

SUMMARY

Long lifetime over 50,000 hours for the thyratron is essential requirement to provide reasonable availability in the proposed C-band e+e- linear collider. Many thyratrons were dead due to several common causes related to circuits and operation environment rather than intrinsic problems of a device itself. The C-band smart modulator uses an inverter charging method instead of a traditional resonant charging circuit. Proper design of the tail clipper and the EOLC circuit ensures the low inverse voltage of the thyratron anode. Several valuable feedback systems are easily adopted to enhance the lifetime. There are still unidentified questions to be verified in the thyratron. Close collaboration between laboratories and companies is strongly requested in order to improve the lifetime and performance of a thyratron.

REFERENCES

[1] T. Shintake et al., “C-band Linac RF-system for e+e- Linear Collider,” Proceedings of International Workshop on Pulsed RF Power Sources for Linear Colliders, RF96, Hayama, Kanagawa, Japan, April 8-12, 1996, KEK Preprint 96-27

[2] David B. Ficklin Jr., “A History of Thyratron Lifetimes at the Stanford Linear Accelerator Center,” SLAC-PUB-6543, December 1994

[3] 2000 Marconi Applied Technologies Limited, “A1 A-Hydrogen Thyratrons Preamble,” Issue 2, July 2000

[4] M. Parmenter, et al., “A Thyratron for the NLC Baseline Modulator,” 2001 Klystron-Modulator Workshop, CERN, 2001

[5] C. A. Pirrie et al., “Thyratron and Modulator Design Considerations to Maximize Thyratron Life,” 1998 Klystron-Modulator Workshop, SLAC, Stanford, California, USA, June 29 - July 2, 1998