RAPID START, HIGH AVERAGE POWER BLT SWITCH FOR ANTI-MISSILE RADAR

N. Reinhardt, G. Kirkman, J. Hur, B. Jiang
Integrated Applied Physics, Inc., 50 Thayer Road, Waltham, MA 02154
Thomas Reinhardt
Nimbus Optics, Inc., Williamstown, MA 01267

Abstract: The Back Lighted Thyratron with a Super-Emissive Cathode (BLT-SEC) has unique advantages of high peak current, small size, very low heater power, and prompt warm-up compared to conventional hydrogen thyratrons. These characteristics make it suitable for many modern applications such as anti-missile radar, space borne weapons systems, pollution control pulse generators, and industrial lasers.[1]

We report advances made in the understanding of electrode erosion and average power heating, and describe "rotary firing," a novel method for improving tube life and average power ratings.

Introduction

Despite significant progress by ourselves and others, BLT-SEC tube life expectancy and power handling ability is still regarded as less than adequate for many modern applications. Industrial and electric-utility users in particular want the tube to be capable of continuous, unattended, rep-rate operation for periods of at least one year, a requirement that usually translates into reliable lifetimes of least 10^9 pulses. This demand is now being only poorly met by large and very expensive thyratrons (and not at all by spark gaps). User consensus is that the BLT-SEC will be an extremely worthwhile improvement over present switching technology when we can demonstrate lifetimes at least comparable to those of conventional thyratrons.[2]

Recently, we have undertaken a Phase I SBIR program aimed at improving the tube for high average power operation, and have obtained the promising results reported here. Even though many long months of confirmatory life- and design-tests lie ahead, we believe the improvements in prospect are accessible and real.

Improvement of Life Limited by Electrode Erosion

Operation of the BLT-SEC is accompanied by certain amount of electrode erosion due to the high peak current. Tests have shown the erosion rate to be intermediate between that of thyratrons and spark gaps.[3] Both cathode and anode erode, the anode often more rapidly than the cathode. Over time, the result is enlargement of critical hole diameters and electrode spacings to where long-path discharges can occur, spoiling tube holdoff and ending the life of the tube. This electrode wear currently limits tube life to the neighborhood of 10^8 shots at rated conditions, a limit currently being encountered by all investigators and developers of the device.[4] For some time, the need for at least an order-of-magnitude improvement has been recognized.

Simple calculations show that, unfortunately, little can be done to minimize erosion during the pulse itself. Since heat penetrates only a few microns into the metal during the pulse, there is no conceivable way to absorb or disperse it contemporaneously with its generation. Fig. 1 shows the heat penetration into tungsten at the end of a single 500 ns pulse of 10^7 W/cm^2.

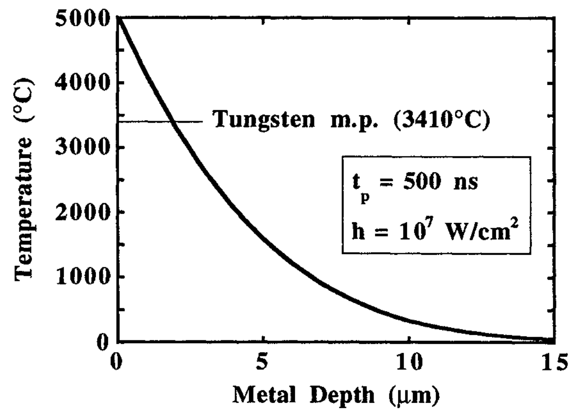

Fig. 1 Heat penetration in tungsten.

One question, however, was whether the heat deposited by repetitive pulsing was increasing the depth to which the surface layer melted or evaporated during the pulse. Perhaps, we thought, better electrode cooling could minimize melting, vaporization, or the flinging of droplets.

Further calculation, however, showed that while the heat collected during repetitive pulsing can very well raise electrode surface temperatures high enough to cause the various troubles associated with high average power, the temperatures reached would have virtually no effect on the amount of material eroded on succeeding pulses. The extreme pulse heat responsible for erosion does not linger at the discharge site from one shot to the next. It diffuses away into the electrodes surprisingly rapidly during the interpulse interval, driven by enormous temperature gradients which die out very quickly, leaving the electrode material at an average temperature too low to have any real effect, one way or the other, on temperature or penetration depth of the next pulse. For typical BLT-SEC opertaing conditions, there seemed to be no way to lower the electrode erosion rate by gross cooling of the electrodes.

We did note, however, that the eroded material itself is not the problem: for the most part, it redeposits itself harmlessly. The real problem was loss of small amounts of material from places where it was critically needed. One semi-facetious idea was to feed "Yule logs" of tungsten into these places in order to maintain critical dimensions, but doing this mechanically was dismissed as hopelessly impractical. Yet, we did find a way to accomplish approximately the same thing electrically by means of rotary firing, a mode of operation to be described below. As a result, we expect to be able to ameliorate the principal cause of short life in the BLT-SEC switch.

Report Documentation Page

Form Approved
OMB No. 0704-0188

Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.

1. REPORT DATE **JUN 1993**	2. REPORT TYPE **N/A**	3. DATES COVERED **-**
4. TITLE AND SUBTITLE **Rapid Start, High Average Power Blt Switch For Anti-Missile Radar**		5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Integrated Applied Physics, Inc., 50 Thayer Road, Waltham, MA 02154**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
See also ADM002371. 2013 IEEE Pulsed Power Conference, Digest of Technical Papers 1976-2013, and Abstracts of the 2013 IEEE International Conference on Plasma Science. Held in San Francisco, CA on 16-21 June 2013. U.S. Government or Federal Purpose Rights License.

14. ABSTRACT
The Back Lighted Thyratron with a Super- the pulse, there is no conceivable way to absorb or disperse Emissive Cathode (BLT-SEC) has unique advantages of it contemporaneously with its generation. Fig. 1 shows the high peak current, small size, very low heater power, and heat penetration into tungsten at the end of a single 500 ns prompt warm-up compared to conventional hydrogen pulse of 107 W 1 cm2. thyratrons. These characteristics make it suitable for many modern applications such as anti-missile radar, space borne weapons systems, pollution control pulse generators, and industriallasers.1 We report advances made in the understanding of electrode erosion and average power heating, and describe "rotary firing," a novel method for improving tube life and average power ratings.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**SAR**	**4**	

<u>Improvement of Average Power Capability by Avoiding Heat Concentration</u>

Average power problems often manifest themselves as "thermal latchup," a refusal of the tube to operate some seconds or minutes into a run. Early in the tube's development, some of this behavior had been encountered, and now, with an attempt to increase ratings, it could be expected once again. Thermal latchups can get started in any of several ways, such as loss of control of hydrogen pressure, unwanted electron emission during the interpulse interval, severe outgassing, or in extreme cases, melting of the electrodes and destruction of the tube, but the common feature is overheating of the critical surfaces of the tube by average power dissipations concentrated at the discharge site. With no immediate prospects of reducing the tube drop and electrode heating responsible for the dissipations, we were left with the need to improve the removal of the resulting heat.

Radial heat flow from the central discharge site of the BLT-SEC implies a logarithmic temperature rise across the face of the electrodes and the existence of a central hot spot. This, a mathematical consequence of the source-to-sink diameter ratio, is a well-known problem in electron device work: there is no simple way to defeat it. (Fig. 2) Neither aggressive cooling of the electrode rim, nor choice of materials has much effect: for the source-to-sink diameter ratio in the BLT-SEC, a 40-fold concentration of heat at the central singularity was implied!

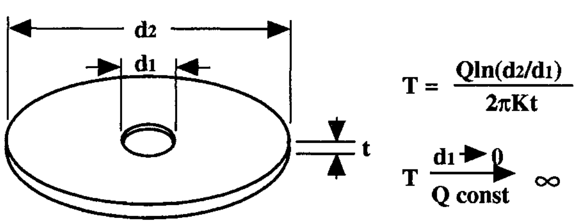

Fig. 2 Relation of temperature (T) and diameters (d_1, d_2). Q is heat and t is the thickness of the metal.

The usual answers, discharge-spreading by means of the multiple grid holes or discharge sites (an answer used in all large thyratrons), and the bringing of water-cooling up inside the tube had not been implemented in the BLT-SEC. Multiple discharge sites were out due to the pronounced tendency of the discharge to "hog" one or another of the discharge sites preferentially and wear it out (a tendency seen in grounded-grid thyratrons as well). Moreover, the superemissive cathode requires high peak currents for stable, efficient operation. Severe jitter, high tube drop, low di/dt, and other effects of discharge starvation appear when operation is attempted at low or unequally-distributed peak currents, and therefore multiple path operation was out. Water cooling of the usual sort was known to improve total heat removal in thyratrons, certainly, but was also known to not necessarily solve the hot-spot problem (in addition to being cumbersome and expensive to incorporate), and unless we absolutely had to use it, it too was out.

Our first approach was to examine closely what happens during repetitive pulsing to temperature rise vs. time and distance, immediately adjacent to the heat deposit sites. Iterative heat pulse calculations based on expressions in Carslaw and Jaeger[5] for the temperature rise vs. distance and time in force-cooled slabs showed that, for heat sinks right up close to the heat deposit site, the intermittent high temperature rise due to pulsing could actually drive much more heat into the sink than the average temperature rise associated with a steady heat flux of the same value. Fig. 3 shows the calculation results.

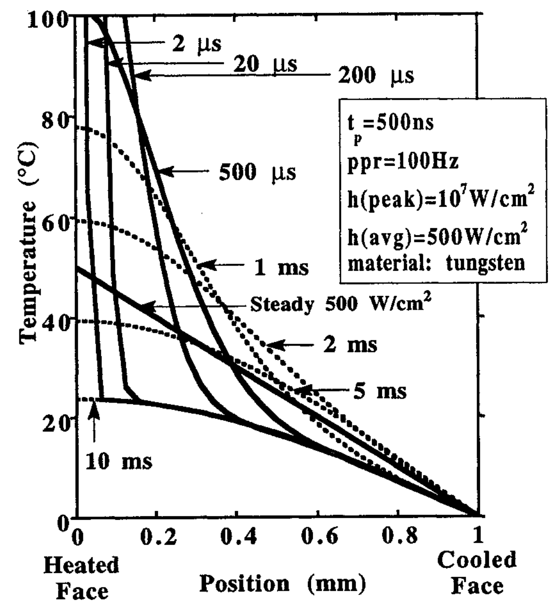

Fig. 3 Temperature vs. time and penetration depth.

Therefore, if tightly-coupled heat sink could be installed right next to the discharge site, not only would the source to sink diameter ratio be as high as possible, but the equilibrium electrode temperature reached during the interpulse cooling period, immediately prior to the next pulse, could be held down and made much <u>lower</u> than that associated with the average, steady-state flow of the same amount of heat! We hoped by this improved understanding of pulsed heat conduction we could remove more heat during the interpulse period. To get anywhere, we would have to use water cooling to absorb the heat and sweep it out of the tube faster than it could be conducted out. Inspired by a recollection of the phenomenal resistance of a thin-walled water-cooled piece of tubing to damage from being hit by a pulsed electron beam, an experience encountered many years ago in other work,[6] we contemplated installing a very tightly coupled, thin wall, microchannel heat exchanger right at the discharge site in the BLT-SEC.[7]

Further calculation showed, however, that in the BLT-SEC, effective extraction of the pulse heat during the interpulse period could only be accomplished by using impractically thin cooling walls and impractically high rates of heat transfer. Though not wrong in principle, the effort would be doomed by the thick walls needed to accommodate electrode erosion. Thick walls would also be needed to avoid metal breakup from fatigue associated with rapid repetitive thermal pulsing, and to withstand the necessary high pressure of the coolant. At length, the hoped-for pulse-related heat flow improvement was recognized to be a mirage: under actual operating conditions an expensive thin-wall, microchannel heat exchanger would soon be destroyed, and the whole idea had to be abandoned as impractical.

"Rotary Firing" A Workable Concept for Increasing Average Power Ratings and Minimizing the Effects of Electrode Erosion

Stymied by these failures in direct approaches to tube improvement, we turned to the well-known rotary-anode technique for cooling X-ray tubes, which solves the hot-spot problem at the cost of considerable mechanical, electrical, and plumbing complexity. Inverting the concept, we arrived at the possibility of "rotary firing," a deliberate step-wise or random shifting of the main discharge from place to place in order to force the spreading of dissipation and wear across the face of the electrodes. An initial large improvement could be obtained without water cooling, since the massive electrode structures had plenty of conductivity for well-distributed heat flow. Within a single SEC-BLT envelope, discharges would be initiated from a number of single superemissive cathodes in sequence, using our recently-developed ability to trigger such cathodes independently without crosstalk or skipping. Each successive discharge would then carry the entire pulse current, thus avoiding the problems of operating individual multi-path cathodes at low peak current and uneven degrees of utilization. Thermal piggybacking at any given discharge site would be inhibited by effective subdivision of the repetition rate there. Best of all, since more electrode area could be involved in tube operation in a controlled and predictable way, electrode erosion in any one spot would be minimized, thus slowing down the dimension changes presently responsible for short tube life.

Construction and Test of an Experimental Tube

Calculation and analog modelling showed that rotary firing of three sites could reduce electrode temperatures by a factor of 2.5, a change we knew would show up as improved behavior at test. Accordingly, standard tube parts were modified to provide three trigger sites on a 2.5 cm bolt circle. A window was installed in the anode to allow firing to be observed (Fig. 4).

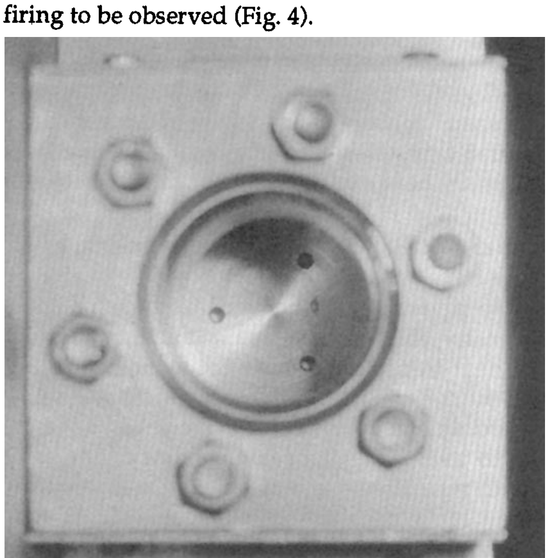

Fig. 4 The anode side view of the 3-hole BLT-SEC switch.

Three sets of trigger electrodes were mounted in the cathode space behind the triggering holes. The tube was given a normal bakeout, processing, filling, and preliminary test before mounting on the test stand.

The test circuit was the one used so far in all our BLT-SEC development work, with pulse conditions of t_p=500 nsec, i_k=12.5 kA, e_{py}=25 kV. Due to power supply limitations, it could not reach high average power except briefly. We therefore had to compare behavior during short runs at high repetition rates with the behavior of standard tubes under the same conditions. Admittedly, the delayed onset (or complete absence) of thermal latchup is only a derivative indication of average power handling improvement, but it is convincing.

Triggering was accomplished by a simple brute-force method employing three separate drivers and bias supplies. Each driver was triggered in sequence by a 4 channel EG&G/PAR pulse generator. Low repetition rate firing was observed visually and recorded with a Sony video camera (Fig. 5). High rep rate firing was observed visually and recorded with an HP digital oscilloscope.

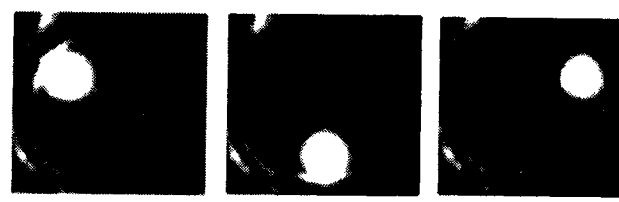

Fig. 5 "Rotary firing" observed by video camera.

Results

Controlled firing was demonstrated in both single-shot and repetitive-pulse modes. Briefly sustained rotary firing was accomplished at high repetition rates (Fig. 6). Several runs were made at a repetition rate of 1 kHz, a rate about three times higher than that obtainable under the same conditions in a standard single hole switch. In longer runs at more typical repetition rates (100 – 200 Hz) thermal latchups and other signs of tube distress were avoided entirely. Crosstalk, loping, and skipping were not encountered in the tube.

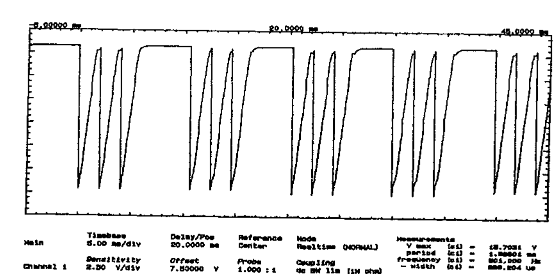

Fig. 6 Anode voltage (~ 15 kV) of the 3-hole BLT-SEC at 100 Hz rep rate and 500 Hz rotary firing frequency.

Conclusions

In BLT-SEC operation, in a situation where careful review and calculation reveals a paucity of options for improvement, "rotary firing" can be used to defeat the effects of heat concentration and electrode wear. We can predict order-of-magnitude improvements in both life and average power ratings within the format of our standard tubes, without resort to water cooling. Tube operation has been demonstrated at a significant multiple of the repetition rates we have been able to run standard tubes. Sequential triggering of multiple discharge sites is not overly difficult to accomplish.

Observations and Recommendations

Before rotary firing can be incorporated in standard tubes, the present cumbersome multiple-driver trigger distribution system used for experiments will need to be simplified. Even though low-pressure gas switch development is never simple, we believe that this can be accomplished inexpensively by means of changes to both tube and driver. Water cooling will be somewhat expensive to implement, and it will have no effect on electrode life due to peak current erosion, but it can be used to increase average power capability still further at modest cost. On the other hand, months or even years of expensive life-test will be required to prove tube reliability at the 10^9 shot level. Such testing has to be done, for there are no reliable ways to accelerate the various slow degradation processes that determine life in thyratrons. With the confirmed prospect of new improvements in hand, however, we look forward to establishing the BLT-SEC as a fully competitive long-life product, ready for modern military, industrial, and scientific applications.

Acknowledgement

This work is sponsored by SDIO Innovative Science & Technology Office through Phase I SBIR program, managed by the Office of Naval Research.

References

[1] Gas discharge closing switches, Advances in pulsed power technology Volume 2, edited by G. Schaefer, M. Kristiansen and A. Guenther, Plenum Press, NY, 1990. Physics and Applications of Pseuosparks, edited by M. A. Gundersen and G. Schaefer, NATO ASI Series B: Physics Vol. 219, Plenum Press, NY, 1990.

[2] A. L. Donaldson, "Lifetime Consideration," in Gas Discharge Closing Switch, G. Schaefer, Ed., Plenum Press, New York, 1990, pp. 325-344.

[3] G. Kirkman, N. Reinhardt, B. Jiang and J. Hur, "High Power Evaluation of Hermetically Sealed BLT Switches," in Preceedings of 1992 Twentieth Power Modulator Symposium, 1992, pp. 369-371.

[4] D. W. Branston, W. Hartmann, G. Lins, H. D. Rphde, J. Stroh and H. Kippenberg, "Switches for Gas Discharge Lasers and a Spark Gap Replacement," presented at the 9th IEEE Pulsed Power Conference, Albuquerque, New Mexico, June 21-23, 1993.

[5] H. S. Carslaw and J. C. Jaeger, Conduction of Heat in Solids, 2nd Ed., Oxford U. Press, 1959, Chs. II, III and X.

[6] R. Kiesling, private communication.

[7] D. B. Tuckerman and R. F. W. Pease, " High performance Heat Sinking for VLSI," IEEE Electron Device Letters, Vol. EDL-2, No. 5, pp. 126-129, 1981.