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d Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE 9-30-92	3. REPORT TYPE AND DATES COVERED Final Technical Report (5/1/89-7/31/92)
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4. TITLE AND SUBTITLE High Power Switching and Other High Power Devices	5. FUNDING NUMBERS DAAL03-89-K-0097
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6. AUTHOR(S) Martin Gundersen	DTIC S E L E C T O C T 2 2 1 9 9 2 C D
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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) University of Southern California Dept. of Electrical Engineering-Electrophysics Los Angeles, CA 90089-0484	PERFORMING ORGANIZATION REPORT NUMBER OCT 22 1992
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9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) U. S. Army Research Office P. O. Box 12211 Research Triangle Park, NC 27709-2211	10. SPONSORING/MONITORING AGENCY REPORT NUMBER ARO 26257.33-PH
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11. SUPPLEMENTARY NOTES
The view, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy, or decision, unless so designated by other documentation.

12a. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited.	12b. DISTRIBUTION CODE
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13. ABSTRACT (Maximum 200 words)
High power thyratrons and devices such as high power microwave sources have cathode-related performance limits. The report describes research of a simple, robust "super-emissive" cathode that produces $>10,000$ A/cm² from a macroscopic area (≈ 1 cm²), and operates with a low pressure (≈ 0.1 torr), spatially-uniform glow plasma (density $\geq 10^{15}$ cm⁻³). The cathode also can operate as a hollow cathode, and is at the heart of the operation of the pseudospark and back-lighted thyratron. The physics of this hollow and super-emissive cathode is very rich. The hollow cathode geometry traps electrons in the hollow cathode backspace. The lifetime of these electrons enables them to ionize a spatially homogeneous high density glow, and this hollow cathode mode of operation is responsible for certain types of electron and ion beam behavior. A plasma cathode sheath that is formed during this phase leads to super-emissive behavior, which is responsible for high current emission. Super-emissive cathode thyratron-type switches (with higher peak current, voltage, di/dt) being developed for pulsed power switching of lasers, accelerators, high current and high coulomb transfer, Marx bank operation, transfer of technology to commercial applications, high current electron beams, and millimeter wave generation (1-100 GHz) are described.

14. SUBJECT TERMS High power switching, thyratrons, super-emissive cathode, hollow cathode, high current electron beams, ion beams, plasma cathode high current emission	15. NUMBER OF PAGES 20
	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT UNCLASSIFIED	18. SECURITY CLASSIFICATION OF THIS PAGE UNCLASSIFIED	19. SECURITY CLASSIFICATION OF ABSTRACT UNCLASSIFIED	20. LIMITATION OF ABSTRACT UL
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92-27676
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HIGH POWER SWITCHING AND OTHER HIGH POWER DEVICES

FINAL REPORT

MARTIN A. GUNDERSEN

SEPTEMBER 4, 1992

U.S. ARMY RESEARCH OFFICE

CONTRACT NUMBER: DAAL03-89-K-0097

**UNIVERSITY OF SOUTHERN CALIFORNIA
DEPT. OF ELECTRICAL ENGINEERING-ELECTROPHYSICS
LOS ANGELES, CA 90089-0484**

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SUMMARY OF RESEARCH FINDINGS

The results impact ARO goals for development of small, robust, orientation-independent high current switches, and in other areas. It is our opinion that the most important single result of the prior support is the delineation of the cathode emission mechanism in the pseudospark and back-lighted thyatron (BLT) – the super-emissive cathode.

Back-Lighted Thyatron

A typical BLT is shown in Figure 1. The BLT and the pseudospark are switches that conduct high currents (1 to >100 kA per aperture), stand off high voltages (≈ 70 kV per gap), and have other useful properties. These devices are significant new pulsed power switches, and the BLT is a direct result of ARO support.

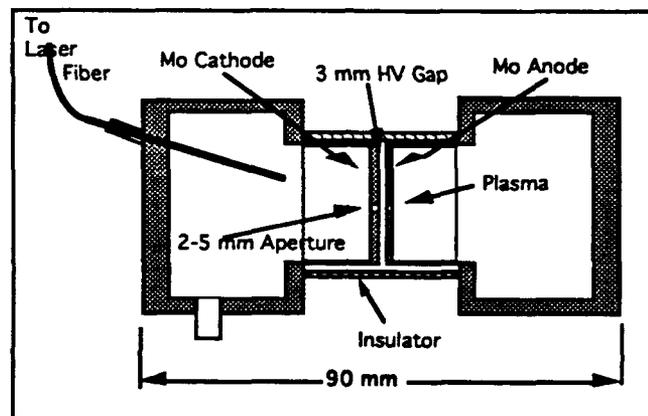


Figure 1. Structure of a BLT switch with optical triggering through an optical fiber. The switch is filled with low pressure gas and is triggered by unfocused UV light incident on the back of the cathode surface.

The principles of these devices have been discussed in detail in the literature, and representative publications are attached as appendices. In a simple and representative configuration, two cylindrical cap electrodes face one another end-on and hold off the applied voltage across a narrow (typical 3 mm) gap. The device contains a low pressure (<0.5 torr) gas, such as hydrogen, nitrogen or argon. Electrons are generated by a trigger pulse – optical or electrical – and pass through the small aperture in the cathode and initiate a discharge which closes the switch^{1,2}.

The switch plasma is initiated with a Townsend avalanche discharge in a low pressure gas (typically 0.1-0.5 torr) that develops on axis due to the focusing effect of the electric field³. A positive space charge builds up inside the hollow cathode region as a result of low mobility of the ions produced by electron-neutral collisions. The release of a sufficient number of starting electrons inside the hollow cathode initiates a transient Hollow Cathode Discharge (HCD).

During this growth phase of the discharge, before the plasma is fully formed, a transient high voltage remains across the electrodes, and an electron beam is produced that passes through the anode aperture. These HCD beams are reported to have kA peak currents and very good

¹M. A. Gundersen and G. Schaefer, Eds., "The Physics and Applications of Pseudosparks," NATO ASI Series B 219, Plenum Press (1990).

²"High power pseudospark and BLT switches," K. Frank, E. Boggasch, J. Christiansen, A. Goertler, W. Hartmann, C. Kozlik, G. Kirkman, C. G. Braun, V. Dominic, M.A. Gundersen, H. Riege and G. Mechttersheimer, IEEE Trans. Plasma Science, Vol. 16 (2), 317 (1988).

³H. Pak and M.J. Kushner, "Simulation of the switching performance of an optically triggered pseudospark thyatron," J. Appl. Phys. 66, 2325 (1989).

emittance and brightness properties ($55 \text{ mm}\cdot\text{mrad}$ and $2 \cdot 10^{11} \text{ Am}^{-2}\text{rad}^{-2}$, respectively at 20 kV with 1 kA beam current). The electron beam will propagate and hence interact with the discharge plasma. The plasma density can be $\approx 10^{12} \text{ cm}^{-3}$ to $> 10^{15} \text{ cm}^{-3}$.

If the plasma density is allowed to increase to $> \approx 10^{14} \text{ cm}^{-3}$, the electric field will be shielded from penetrating into the hollow cathode and terminate the HCD. The cathode then makes a transition to a different phase, the super-emissive phase. This phase has extraordinary emission properties, including production of current densities 10^4 to 10^5 A/cm^2 , generated over a macroscopic area $\approx 1 \text{ cm}^2$.

Super-emissive Cathode

A super-emissive cathode is defined (loosely) as one which produces uniform current emission $\geq 10,000 \text{ A/cm}^2$ from a macroscopic area ($\approx 1 \text{ cm}^2$). A drawing of the switch structure for a pseudospark or BLT is shown in Fig. 2. The current emission characteristics are very large in comparison with conventional heated thermionic cathodes.

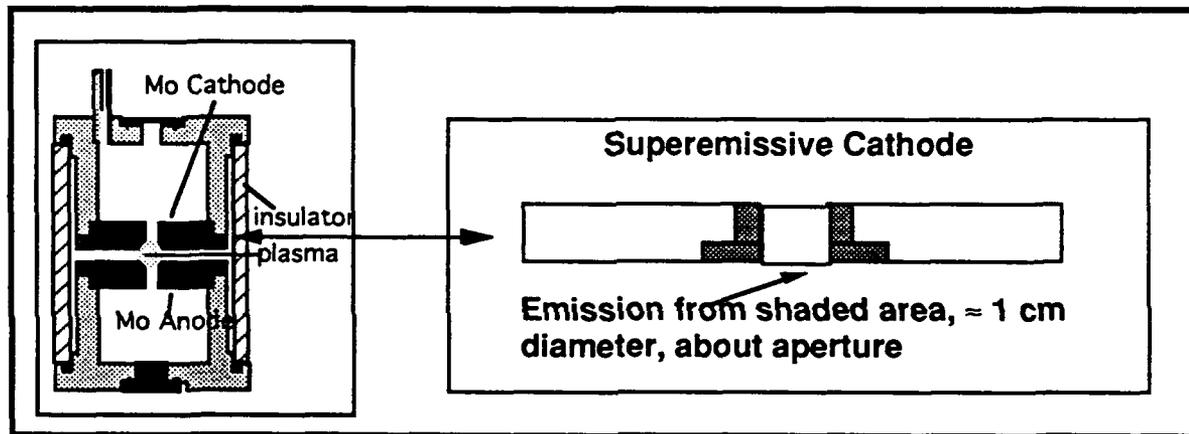


Figure 2. Structure of a pseudospark or BLT. The switch is filled with low pressure (0.01-0.3 Torr typical) gas. Right. Detail of super-emissive cathode electrode structure indicating the region that is highly emissive. This super-emissive area is approximately 1 cm^2 , and is the surface indicated in and around the cathode aperture.

The BLT and pseudospark have been shown to operate with a super emissive cathode (SEC) producing electron emission current densities $> 10 \text{ kA/cm}^2$. The high cathode emission (\gg externally heated cathodes) and current densities obtained in a non-arcing mode and with a simple, robust structure, strongly encourage consideration of new applications. The emission occurs over a surface area $\approx 1 \text{ cm}^2$, and the cathode operates without forming a constricted arc. This is in contrast to the high current densities achieved over very small areas in field emission devices and the high, yet rather disruptive, currents achieved in arc discharges. Although in the past comparable but localized current densities have been achieved through the formation of filamentary arcs, devices used for applications (e.g. spark gaps, felt cathodes, and field emission devices) tend to be life-limited. Problems associated with arc discharges include the melting, sputtering and cratering of electrode material, and addition of electrode material to the arc plasma. This new cathode supports currents that formerly required arc-type devices, such as spark gaps. It appears feasible to extend performance to devices requiring peak currents over 100,000 A, and these results suggest that high brightness cathode design may be significantly improved.

The cathode produces this emission as a result of heating by an ion beam that is present during the formation of the plasma. This mechanism for producing the super-emission was

discovered under ARO support. It is discussed below, and has been reported in detail in the literature⁴.

The SEC switch is thus substantially different in operation from externally heated cathode switches, such as previous thyratrons, hollow cathode switches, and spark gaps. As discussed above, this mode is to be distinguished from the HCD behavior which also occurs in these switches. It is specifically the super-emissive behavior that makes possible the improved high current operating characteristics of the switch.

Reviewed below are results of development of the BLT as a pulsed power switch. These include high voltage, high current, low inductance and compact size for pulsed power applications. In addition, a summary of some of the related fundamental physical processes is presented. Some new applications are discussed, including electron beam production. In addition, a summary of results of an active technology transfer program are presented.

FUNDAMENTAL PHYSICAL PROCESSES IN THE BLT

Super-emissive Cathode Mechanisms

As discussed above, the pseudo-spark and back lighted thyatron operate with a large-area ($\sim 1\text{cm}^2$) superemissive cathode ($\sim 10^4\text{ A/cm}^2$). The discharge is a superdense glow with a cross-section of the order of 1cm^2 , rather than a *constricted* arc. Data obtained under previous support includes the following: Streak camera recordings show that the plasma extends radially outward from the center aperture and is homogeneous. Studies of the cathode with a scanning electron microscope indicate that the discharge produces a uniform surface melting. The data supports the mechanism wherein the cathode surface is heated to the melting point by an intense ion beam present during the avalanche phase of discharge. This high temperature, together with the high field across the cathode sheath, is responsible for the extremely large and uniform field-enhanced thermionic emission over a large area. Cathodes studied with a scanning electron microscope following operation at 6-8KA, $\sim 1\text{msec}$ pulse length, 10^5 pulses in a low-pressure ($\sim 27\text{Pa}$) H_2 discharge show evidence of melting of a thin surface layer within a radius of $\sim 4\text{mm}$. Previous studies show that a mechanism, wherein the cathode surface is heated by an intense ion beam present during the avalanche phase of a discharge, is partially responsible for the cathode emission⁵. In the avalanche phase this ion beam will have an energy related to the initial voltage of the electrode gap, while during the steady-state phase the beam will have a lower energy related to the cathode fall voltage. An ion beam with $10\text{-}20\text{MW/cm}^2$ lasting $\sim 100\text{ nsec}$ was shown to be sufficient to heat a thin surface layer (several μm deep) to a temperature near the melting point of Mo. A high field exists at the surface in the plasma sheath. The combination of high temperature and field suggest extremely large field-enhanced thermionic emission after the initial cathode surface heating. However, this is a somewhat phenomenological explanation, and the actual heating process has not been demonstrated to produce sufficient temperature for thermionic emission to occur uniformly over a large area. Thus thermionic emission is possible, and likely occurs in certain situations, but other mechanisms must also be considered.

⁴"A super-emissive self-heated cathode for high-power applications," W. Hartmann, G. F. Kirkman, V. Dominic, and M.A. Gundersen, IEEE Trans. Elect. Dev. 36 (4), 825 (1989).

⁵W. Hartmann and M.A. Gundersen, "Origin of anomalous emission in superdense glow discharge," Phys. Rev. Lett. 60, (23), 2371 (1988), "Evidence for large-area superemission into a high current glow discharge," W. Hartmann, V. Dominic, G.F. Kirkman, and M.A. Gundersen, App. Phys. Lett. 53 (18), 1699 (1988), and "Cathode-related processes in high-current density, low pressure glow discharges," W. Hartmann and M. A. Gundersen, in "The Physics and Applications of Pseudosparks," M. Gundersen and G. Schaefer, Ed., Plenum Press, 1990.

Part of the process leading to high current is related to the hollow cathode emission that occurs as the plasma is being formed. Beouf and Pitchford have shown that the hollow cathode transition can be very sudden, and will lead to a high current⁶. This current will be limited by the cathode electrode emission properties. The hollow cathode phase provides another important factor in the operation of the pseudospark. Simulations by Pak and Kushner⁷, Penetrante and Bardsley⁸, and Beouf and Pitchford have shown that as the hollow cathode and corresponding plasma is formed, a virtual anode is translated to close proximity with the cathode electrode. Thus, prior to high current, there exists in effect an anode that is very close (a few tens of microns) to the cathode, with a 'bulk' plasma providing a highly conductive path to the real anode. During the transition to the super-emissive phase, the switch needs to somehow activate the real cathode to provide high current. Several mechanisms are possible, including spark-gap (vacuum-gap) like processes, the formation of microstreamers, and thermionic emission. The complex cathode emission processes occurring during the super-emissive phase are to be investigated in more detail, and research will be undertaken to determine the microscopic processes responsible for the extraordinarily high emission.

Modeling of the BLT plasma

Part of the research has been directed towards understanding fundamental plasma properties, so that fundamental limitations and new applications can be understood and developed⁹. Temperature, energy, and densities of two electron distribution function components, including an isotropic "bulk" part and an anisotropic beam, have been analyzed for a hydrogen pseudospark and/or back-lighted thyatron SEC switch plasma with peak electron density of $1-3 \times 10^{15} \text{ cm}^{-3}$ and peak current density of 10^4 A/cm^2 . Estimates of a very small cathode fall width during the conduction phase and high electric field strengths lead to injection of an electron beam with energies $\geq 100 \text{ eV}$ and density of $10^{13}-10^{14} \text{ cm}^{-3}$ into a Maxwellian "bulk" plasma. Collisional and radiative processes of monoenergetic beam electrons, "bulk" plasma electrons and ions, and atomic hydrogen are modeled by a set of rate equations and line intensity ratios are compared with measurements. Under these high current conditions, for an initial density $n_{\text{H}_2} \approx 10^{16} \text{ cm}^{-3}$ the evaluated "bulk" plasma parameters are electron density of $1-3 \times 10^{15} \text{ cm}^{-3}$ and electron temperature of 0.8-1 eV, the estimated "beam" density is $\approx 10^{13} - 10^{14} \text{ cm}^{-3}$.

The model thus consists of two electron groups: a monoenergetic electron beam, which penetrates a Maxwellian "bulk" plasma, directly excites and ionizes atomic hydrogen, and a 'background' Maxwellian "bulk" plasma. Collisional processes of both electron-groups with hydrogen ions and atoms and radiative transitions were considered. The solution of the appropriate set of rate equations yields the population of atomic levels and the "bulk" electron density as a function of electron beam density and energy and electron temperature of the "bulk" plasma. It is shown that a steady state assumption fails for the process of impact-ionization due to a pulse beam electrons with a pulse duration of 100-300 ns. Once the beam disappears the relaxation of excited states occurs immediately and a steady state condition is applied to the remaining "bulk" plasma. Comparison of calculated and measured line intensity ratios of H_α and H_β lines yields the "bulk" electron temperature and electron density.

⁶J.P. Beouf and L.C. Pitchford, "Pseudospark discharges via computer simulation", IEEE Trans. Plasma Sci. 19, (2), 286 (1991).

⁷H. Pak and M.J. Kushner, "Breakdown characteristics in nonplanar geometries", Proc. Fourth SDIO/ONR Pulse Power Meeting 1991, to be published, available through the Office of Naval Research, Arlington VA.

⁸B.M. Penetrante and J.N. Bardsley, "Nonequilibrium simulation of the commutation phase in a back-lit thyatron," Proc. 1991 Intl. Conf. on the Physics of Ionized Gases.

⁹H. Bauer and M.A. Gundersen, "High current plasma based electron source", Appl. Phys. Lett. 57 (5), 434 (1990).

A result of this is the prediction of a new electron beam source. These results suggest the possibility of producing in a simple way a very high density electron beam. Consideration of the current density and electric field strength lead to the assumption of a cathode fall produced electron beam. Electron densities of $1-5 \times 10^{15} \text{ cm}^{-3}$ and an estimated electron temperature of about 1 eV cause a very small cathode fall width of several μm during the conduction phase which results in a high electric field inside the cathode fall which is estimated to about 10^6 V/cm . Hence, because the device geometry is confined and the cathode fall is close to the "bulk" conducting region, it is necessary to consider a strong anisotropic electron component, e.g. an electron beam. Considering only electron-electron encounters the mean free path of electrons with initial energies of 100 eV is estimated to be $\approx 1-5 \text{ cm}$ for ionization degrees of 0.1 - 0.5. Because the gap spacing is much smaller than this mean free path, injected electrons will not become thermalized during the gap penetration, i.e., their distribution function becomes not too broadened and is therefore assumed to be a Dirac delta function in energy. The beam is estimated to traverse the device without thermalization if the plasma density is $\leq 2.5 \times 10^{15} \text{ cm}^{-3}$. High brightness electron sources are necessary for various new plasma based devices, and these results encourage consideration of this electron beam as a new candidate for applications including microwave generation sources, electron sources for accelerators and plasma based accelerators which require improved cathodes.

We think that the super-emissive cathode, which is responsible for the high current in the back-lighted thyratron, will have important applications. The cathode is for high power applications, such as high current thyratrons, and also suggest that high brightness cathode design for other applications may be significantly improved. An analysis of the physical processes responsible for the anomalous high current cathode emission was reported in *J. Appl. Phys.* **65** (11), 4388 (1989). Several new applications are discussed in the references, including an electron source, and an application to microwave and millimeter wave emission. An experiment is now underway to test a concept for generating radiation in the range 10 - 100 GHz, based on the back-lighted thyratron electron beam and plasma.

High voltage, and corresponding very high power operation of BLT-related devices is reported in "Studies of multigap BLTs for high voltage applications," Proceedings, Seventh IEEE Pulsed Power Conference, Monterey, California, June 11-14, 1989. and "A Marx generator using back lighted switches", Proceedings, 1989 High Voltage Workshop, Myrtle Beach SC, October 17-19, 1989. A three stage Marx generator employing fiber-optically triggered BLT switches was successfully operated at 105kV with an erection time of $<50\text{nsec}$. The optically triggered switches have the advantage of complete electrical isolation allowing precision triggering of all switches in the back. The BLT switch allows for the possibility of high repetition rate operation with a long lifetime and simple switch structure.

In addition, the BLT can be 'stacked' to increase the standoff voltage as the gap number increases. An alternating stack of insulating plates and specially shaped electrodes has been designed and fabricated for high voltages ($\geq 100 \text{ kv}$). Recent results include operation at 100 kV stand-off, and 70 kA switched.

An analysis of the distribution function was made and is presented in "A two component model for the electron distribution function in a high current pseudospark or back-lighted thyratron," H. Bauer, G. Kirkman, and M. A. Gundersen, *IEEE Trans. Plasma Sci.* **18** (2), 237, (1990). Temperature, energy, and densities of two electron distribution function components, including an isotropic "bulk" part and an anisotropic beam, are analyzed for a hydrogen pseudospark and/or back-lighted thyratron switch plasma with peak electron density of $1-3 \times 10^{15} \text{ cm}^{-3}$ and peak current density of 10^4 A/cm^2 . Estimates of a very small cathode fall width during

the conduction phase and high electric field strengths lead to injection of an electron beam with energies ≥ 100 eV and density of 10^{13} - 10^{14} cm^{-3} into a Maxwellian "bulk" plasma. Collisional and radiative processes of monoenergetic beam electrons, "bulk" plasma electrons and ions, and atomic hydrogen are modeled by a set of rate equations and line intensity ratios are compared with measurements. Under these high current conditions, for an initial density $n_{\text{H}_2} \approx 10^{16}$ cm^{-3} the evaluated "bulk" plasma parameters are electron density of 1 - 3×10^{15} cm^{-3} and electron temperature of 0.8 - 1 eV, the estimated "beam" density is $\approx 10^{13}$ - 10^{14} cm^{-3} . These results suggest the possibility of producing in a simple way a very high density electron beam.

Summarizing, the USC project has demonstrated several new applications of the BLT device which appeared in print during this period. These include:

- **Marx bank operation**

This is important because it is a proof of principal experiment that demonstrates a method of optical control that is potentially very important for high power modulators. If modulators controlled through optical fibers can be used for large systems with many modulators, the methodology for design will see the most significant change since the modulator development undertaken at the MIT radiation laboratory during the war.

- **Modeling of the BLT plasma**

Analysis and understanding of the fundamental processes.

- **High current and high voltage operation**

BLT operation at 100 kV and 80 kA – very large numbers.

- **Millimeter wave generation**

Experimental demonstration of 100 GHz radiation from BLT.

- **Transition of technology**

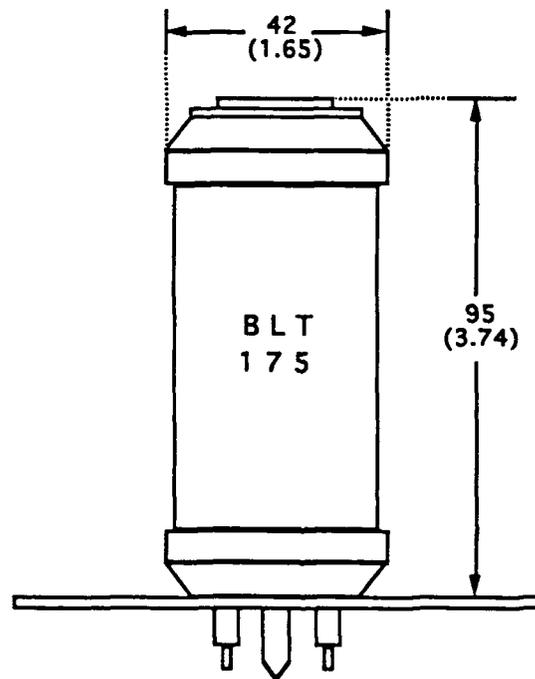
BLT devices are being fabricated by ITT and Integrated Applied Physics inc. as well as by laboratories in Europe and Japan. Testing being undertaken at University of Texas at Arlington, Naval Surface Warfare Center Dahlgren VA, and in Europe and Japan. Additional information about this can be provided.

The USC project has continued work on the super-emissive cathode. Important results include preliminary measurements of the properties of electron beams produced by this cathode. We report a study of the superemissive cathode as an electron beam source.

The cathode has been demonstrated to be a high current electrode in back-lighted thyratron (BLT) and pseudospark switches, which operate in a low pressure glow discharge mode and produce a high current density of ≥ 10 kA/cm² over an electrode area of ~ 1 cm². A temperature rise of the cathode surface caused by ion bombardment during the current build up is responsible for this high electrode emission property. In this work a BLT is operated in the superemissive mode, and a cathode-produced electron beam is extracted through the anode aperture of the BLT and transported to a Faraday cup.

Preliminary results include the following: At argon pressure of 55 mTorr and applied voltage of 15 kV, an electron beam of 120 A maximum current and 120 ns duration was observed 7 cm downstream. An electron energy of less than 4 keV was estimated by a method of magnetic field deflection. The beam energy, as well as the beam current, can be increased by a post-accelerating voltage. Adding differential pumping to reduce the gas pressure in the drift tube to 10 mTorr resulted in an increase in beam current to 260 A.

BLT devices are being fabricated by ITT and Integrated Applied Physics inc. as well as by laboratories in Europe and Japan. Testing being undertaken at University of Texas at Arlington, Naval Surface Warfare Center Dahlgren VA, and in Europe and Japan. A Workshop was conducted by Lawrence Livermore Laboratory in October to consider future directions for developing pulsed power switches for accelerators and other applications. A talk was presented ("Super-emissive cathode switches", M.A. Gundersen, High Average Power Switching Workshop, Lawrence Livermore National Laboratory, Livermore, CA, October 10-11 1990., and Proceedings were prepared. These proceedings are available from either Wayne Hofer (415-422-1636) or Marco DiCapua (415-423-5080). It is my clear impression that the super-emissive cathode switch (e.g. the BLT) is considered a leading candidate for a new generation of pulsed power switches for these applications.

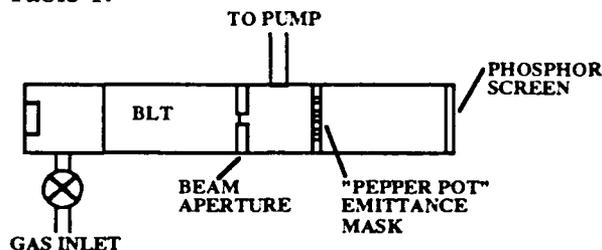


Electron Beams:

Electron beams are often cathode-limited for applications including high power microwaves and as sources for accelerators and particle beams. The BLT structure, a rugged, simple device, is also an electron beam source, as is the pseudospark. Interesting properties include very good beam emittance and brightness. A BLT electron beam device has been studied at USC. Electron beam measurements including time resolved beam current, current density, gap voltage, beam energy, emittance, brightness, beam profile, and dependence of these values on applied voltage, gas pressure and external circuit have been made.

An electron beam current of 105A peak current is observed at 25kV when discharging a total current of 3.5kA. The $\approx 3\%$ efficiency of beam production agrees with the modeling results. The beam current pulse begins before the discharge current and has a shorter pulse length. The highest current and voltage obtained has been 230A and 70kV respectively. Further increases are expected. A beam current of 350A and beam fraction of $>6\%$ is expected at 100kV.

A preliminary measurement of the beam density in phase space was made using the pepperpot emittance diagnostic. In our implementation of this method the beam passes through a pepper pot mask with an array of $300\mu\text{m}$ diameter holes each separated by 1mm, then drifts freely 18.7cm to a phosphor screen where it is photographed. The raw data is used to generate a plot of $x' = v_x/v_z$ against x . The emittance ϵ_0 is defined as $1/\pi$ times the area of the ellipse in $x'-x$ space that encloses $>90\%$ of the beam electrons. The normalized emittance $\epsilon_n = \beta\gamma\epsilon_0$ is about $20\pi \cdot \text{mm} \cdot \text{mrad}$. The normalized beam brightness defined as $B_n = 2I/(\pi\epsilon_n)^2$ is estimated using our measured beam current of 50 - 70A to be $\approx 1.5 \times 10^{10} \text{ A/m}^2 \cdot \text{rad}^2$. This brightness value verifies that the BLT discharge is a source of high brightness electron beams and agrees with the previous measurement in a demountable multiple gap structure by Rhee et. al. verifying that a single gap structure can produce similar low emittance beams as multiple gap structures operated at the same voltage. An $x'-x$ plot are shown in Fig. 1. The electron beam parameters measured at USC are summarized in Table 1.



Normalized Emittance = $20 \pi \text{ mm mRad}$

Normalized Brightness = $1.5 \times 10^{10} \text{ A/m}^2 \text{Rad}^2$

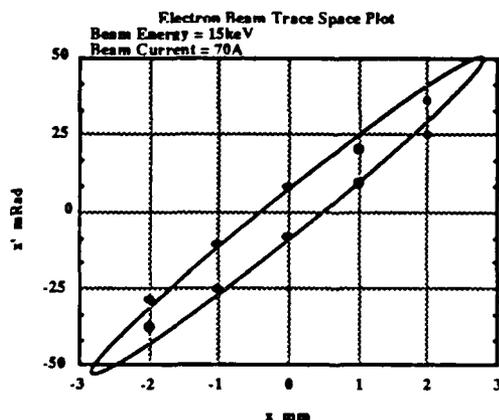


Figure 1. Emittance measurement. The ellipse has been drawn to enclose all the measured points. (top) Experimental schematic for emittance measurement.

Peak Current	$\approx 100\text{A}$
Diameter	$< 0.3\text{cm}$
Current Density	$> 1\text{kA/cm}^2$
Pulse Length	$\approx 100\text{nsec}$
Energy	$10\text{-}70\text{keV}$

Emittance rms	80π mm mrad
Normalized Emittance	20π mm mrad
Normalized Brightness	10^{10} A/m ² Rad ²
Repetition Rate	5kHz
Lifetime Estimate	$>10^{10}$ pulses

TABLE I. HIGH BRIGHTNESS ELECTRON BEAM RESULTS

These results indicate that the BLT is a practical source of high brightness electron beams. The present value of brightness, $>10^{10}$ A/m²rad², is directly applicable for an electron injector for a high power induction linac. The value of brightness exceeds the requirements for the induction linac based MTX microwave experiment at LLNL. The current required for the MTX experiment is over 1kA and the repetition rate over 1kHz. The BLT is expected to produce those values of current and repetition rate. The value of beam brightness achieved in the BLT is possibly sufficient for use in a LLNL experiment at infrared wavelengths (10 μ m). Further development of the BLT as an electron injector could lead to improved performance of linac-based free electron lasers at visible to microwave wavelengths.

PUBLICATIONS

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PARTICIPATING SCIENTIFIC PERSONNEL:

Prof. M. Gundersen, Principal Investigator

H. Figueroa

G. Kirkman - Ph.D., August 1990

P. Hadizad - Ph.D., August 1992

T. Y. Hsu - Ph.D., August 1992

J. H. Hur - Ph.D., May 1992

R. L. Liou

H. Zhao