OPERATING CHARACTERISTICS OF A HIGH-CURRENT DEMOUNTABLE Cs-Ba TACITRON

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Abstract

Tacitrons[1,2] are triode gas-discharge tubes, similar in construction to thyratrons. The primary functional difference between a tacitron and a thyratron is that the tacitron is designed to be completely grid-controlled, whereas a thyratron has grid control only over ignition. Demountable cesium-barium (Cs-Ba) tacitrons have exhibited very low forward voltage drops in the range of a few volts, hold-off voltages greater than 200 V, and average conduction current densities greater than 10 A/cm^2. These characteristics yield an average power switching density on the order of 10^3 W/cm^2 approaching 95% peak switching efficiency[3]. This parameter regime places the Cs-Ba tacitron in the range of conventional solid-state devices, with the advantage that the tacitron should reliably operate in extremes of temperature and radiation. The high-current tacitron has been designed to modulate average currents in the range of 100 to 200 A, with the intent of demonstrating continuous power conditioning capability in the kilowatt range.

Introduction

A demountable high-current Cs-Ba tacitron (HCT) has recently been designed and fabricated at the Russian Scientific Center, Kurchatov Institute, and tested by the University of New Mexico's Pulsed Power and Plasma Sciences Laboratory. The high-current tacitron has been designed to modulate average currents in the range of 100 to 200 A, with the intent of demonstrating proof-of-principle power conditioning capability for a 6 kWe direct energy conversion space power source. Tacitron technology is particularly suitable for use near high temperature or radioactive power sources, to convert high-current dc source power to low-current ac power prior to transmission to the payload, reducing the mass of the power transmission cabling. A comparison is made between the basic operating characteristics of the high-current tacitron and those of the demountable low-current Cs-Ba tacitrons previously studied at the University of New Mexico's Institute for Space Nuclear Power Studies[4-11]. Preliminary conclusions regarding device scaling are drawn by comparison of performance data between the high-current tacitron and the previously tested low-current tacitrons, as well as a comparison of the differences in construction. The high-current tacitron has a nominal discharge region cross sectional area of 28 cm^2 versus the 2 cm^2 surfaces of the low-current tacitrons, and a similar system of external cesium and barium reservoirs whose temperature (i.e., vapor pressure) is regulated via separate heaters.

Description of High-Current Demountable Cs-Ba Tacitron

Fig. 1 shows a schematic diagram of the high-current tacitron. The emitter heater consists of a wound tungsten filament placed within the molybdenum emitter cup. Two refractory metal heat shields are placed between the heater winding and the top plate. A molybdenum spacer is used between the upper lip of the emitter cup and the boron-alumina nitride (B,Al)N ceramic insulator that isolates the emitter from the grid. The spacer also functions as a heat shield for the emitter cup. The grid is a honey-comb design in 6 quadrants, constructed of 1-mm wide tantalum ribbon with a mean cell diameter of approximately 1 mm. The quadrants are separated by

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14. ABSTRACT

Tacitrons[l,2] are triode gas-discharge tubes, similar in construction to thyratrons. The primary functional difference between a tacitron and a thyratron is that the tacitron is designed to be completely grid-controlled, whereas a thyratron has grid control only over ignition. Demountable cesium-barium (Cs-Ba) tacitrons have exhibited very low forward voltage drops in the range of a few volts, hold-off voltages greater than 200 V, and average conduction current densities greater than 10 A/cm2. These characteristics yield an average power switching density on the order of 103 W/cm2 approaching 95% peak switching efficiencyl31. This parameter regime places the Cs-Ba tacitron in the range of conventional solid-state devices, with the advantage that the tacitron should reliably operate in extremes of temperature and radiation. The high-current tacitron has been designed to modulate average currents in the range of 100 to 200 A, with the intent of demonstrating continuous power conditioning capability in the kilowatt range.

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1 mm thick struts running radially outward from a 1.6-cm diameter hub. A tubular attachment extends downward from the hub of the grid, through an orifice in the collector electrode, into a cool well located in the base flange. The purpose of this tubular attachment is to radiate heat from the grid to the base flange. The collector electrode is isolated from both the base flange and the grid electrode by (B,Al)N insulators.

Emitter and collector planar surface areas are 28 cm^2 and 27 cm^2, respectively. The grid has the same planar area as the emitter, with a transparency of 65%. The grid is located approximately in the center of the emitter-collector gap, with grid-collector and grid-emitter electrode separations of approximately 1.5 mm.

Barium primarily provides enhanced cathode emission, and cesium is used primarily as the ionizing medium. External reservoirs allow cesium and barium pressures to be controlled independently of emitter temperature in the demountable high-current prototype. The Ba reservoir consists of a molybdenum cup mounted on an upright linear feedthrough below the base flange, while the Cs reservoir is placed outside the vacuum chamber.

During device operation, the base flange is maintained at a temperature approximately 30 –80° C higher than the Ba reservoir to prevent Ba and Cs condensation within the flange. The temperature gradient between the emitter and the base flange insures that the internal surfaces of the HCT are hot enough to remain free from excessive Cs or Ba condensation. The Cs orifice plug in the base flange Cs delivery line serves to minimize the diffusion of Ba into the Cs system.

Description of Test Stand

The test stand consists of a vacuum chamber with a base pressure of 10^{-7} Torr and feedthroughs for emitter, base flange, Ba reservoir, and Cs pipeline heater leads. Feedthroughs are also provided for thermocouples, collector and emitter bias power leads, grid control leads, and the Cs pipeline that runs between the external Cs reservoir and the HCT base flange.

The I-V power supply consists of a half-wave rectified transformer energized by a variac. This supply provides a variable amplitude signal that sweeps from zero voltage up to a maximum value and then back to zero. An Electronics Measurement Inc. TCR 120T40 power supply, providing a dc collector bias of up to 120 V at 40 A, is used for modulation tests.

The data acquisition and control system consists of an 80486 PC running a software application written in the National Instruments LabWindows development environment. The acquisition and control application is interfaced to a LeCroy 9304 (4-channel) 175 MHz digital oscilloscope for current and voltage measurements and an ADAC Corp. 5302EN I/O module for thermocouple measurements and I/O control signals. Uncertainty in relative temperature measurements is approximately 5° C for the emitter and 2° C for all others. Current measurements for I-V tests are accomplished through the use of current shunts. Modulation currents are measured through the use of current transformers.

Experimental Results

Voltage Hold-Off

Fig. 2 presents preliminary voltage hold-off measurements of the high-current prototype tacitron taken with the grid electrode grounded to the emitter. The applied collector potential is a half-sine of duration 3.6 msec. Hold-off exceeds 125 V at $T_E = 1070°$ C, $T_{Ba} = 560°$ C, and $T_{Cs} = 135°$ C (4×10^{-3} Torr) at less than 2 A leakage current. The plateau at 93 V in the 125 V pulse of Fig. 2 is caused by saturation of a measurement buffer amplifier in the data acquisition system. Pulse amplitudes greater than about 125 V can not be applied at present due to limitations in the power supply.

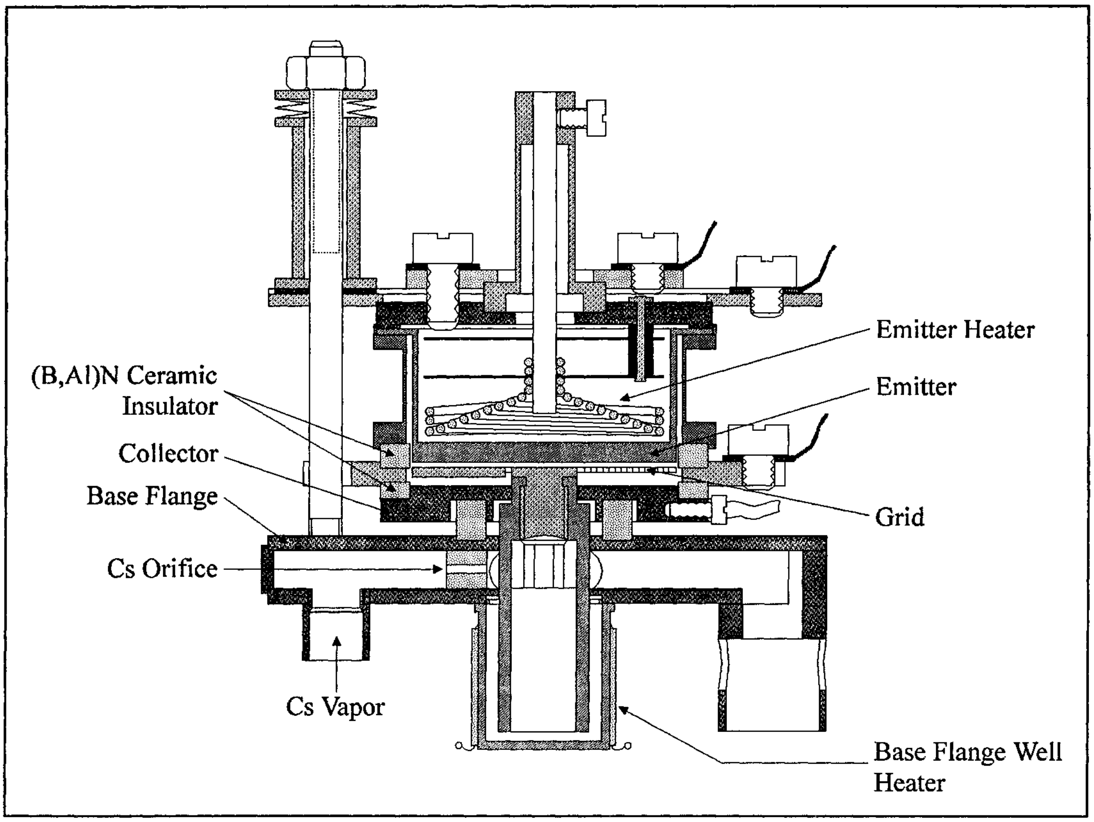

Fig. 1. Schematic illustration of the high-current Cs-Ba tacitron.

When the grid is allowed to float, and T_{Cs} = 146° C (7 x 10^{-3} Torr), ignition occurs at approximately 15 V. This is due in part to the higher Cs pressure and in part to the fact that the insulation resistance between grid and collector is somewhat less than that between emitter and grid, so that collector pulses applied with a floating grid result in a grid potential that is approximately 70% of the applied pulse.

Ref. [4] lists the voltage hold-off of a cylindrical tacitron as 170 V (half-sine duration of approximately 7 msec) at T_{Cs} = 157° C, T_{Ba} = 507° C, $T_E \cong$ 1170° C. Wernsman, et al.,[16] note a planar device with similar grid design at a given $P_{Cs} \cdot d$ product (where P_{Cs} is the cesium pressure in the discharge gap and d is the gap separation) ignites more readily due to edge effects. Since our power supply was unable to provide a sufficiently large pulse to ignite the HCT, the precise hold-off voltage in the region of T_{Cs} = 135° C is presently unknown.

I-V Characteristics

Fig.s 3 and 4 show I-V sweeps of the high-current tacitron. Peak current in Fig. 3 is 249 A at T_{Cs} = 180° C (33 x 10^{-3} Torr), T_E = 1128° C, and T_{Ba} = 558° C. The second I-V sweep in Fig. 3 was taken at similar emitter and Ba reservoir temperatures, but at a lower Cs reservoir temperature (T_{Cs} = 136° C) corresponding to a Cs vapor pressure of 4.2 x10^{-3} Torr. Note that the conduction drop for the latter case is a factor of two higher (2.2 V at 4 A/cm^2) than for the former. The I-V sweep taken at T_{Cs} = 136° C resulted in HCT ignition at 15.7 V, while the high-T_{Cs} I-V sweep resulted in an ignition voltage, V_i = 8.1 V.

Plasma instabilities and increased conduction drops are evident in the return paths of both I-V sweeps of Fig. 3, indicating that the conduction current was of sufficient magnitude to deplete heavy components from the plasma during the time of the discharge. For thick-grid tacitrons with "large" grid apertures, Kaibyshev and

Kuzin[3] attribute the dominant extinguishing mechanism to removal of heavy components from the discharge region. [In this context, a "large" grid aperture is one for which the applied negative grid pulse is insufficient to cause discharge extinction via Langmuir sheath overlap in the aperture.] This implies that current modulation could be achieved in the HCT at currents in excess of 200 A. Note that the low-T_{Cs} I-V sweep of Fig. 3 represents an operating regime that is suitable for stable current modulation[17].

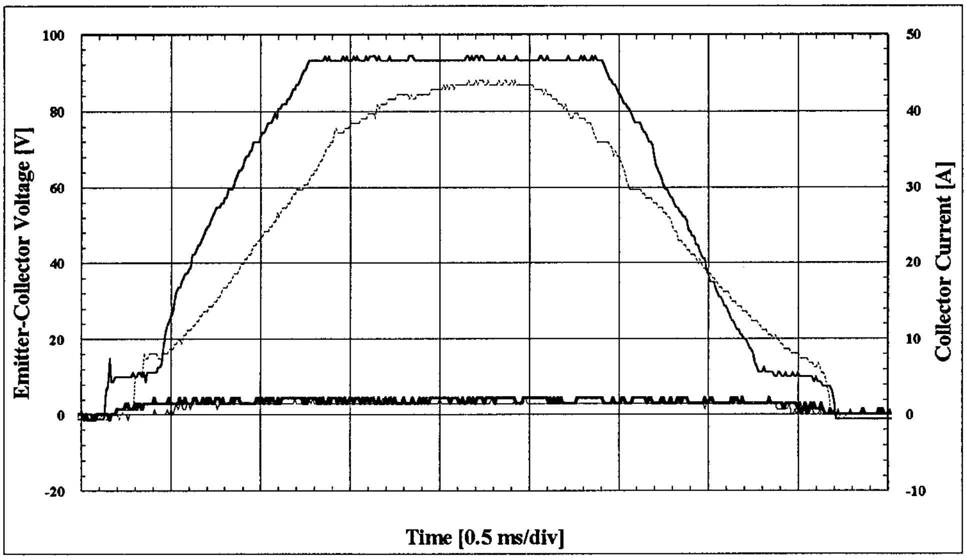

Fig. 2. Preliminary voltage hold-off measurements of the high-current prototype tacitron taken with grounded grid at $T_E = 1070°$ C, $T_{Ba} = 560°$ C, and $T_{Cs} = 135°$ C (4 x 10^{-3} Torr). Applied pulses are 88 V (fine curve) and 125 V (heavy curve) peak amplitude.

Fig. 4 shows two I-V sweeps taken at similar Cs vapor pressures (20 – 25 x 10^{-3} Torr), but under different emission conditions. Note that V_f is approximately 2 V in both cases, but that the "knee" current, I_k, is roughly 80 A for the low-emission case and 160 A for the high-emission case. As anticipated, V_i and V_f are strongly dependent on Cs vapor pressure, while I_k is strongly dependent on emitter temperature and Ba vapor pressure.

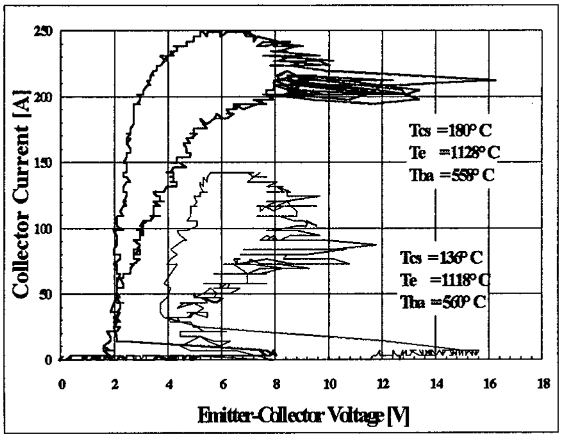

Fig. 3. I-V sweeps of the high-current Cs-Ba tacitron at high and low Cs pressure (sweeps H615-21 and H616-03).

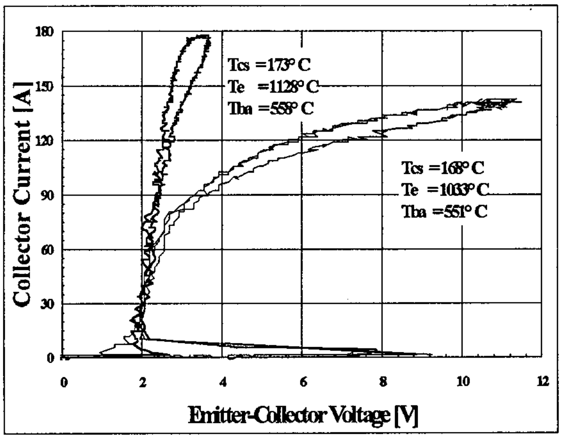

Fig. 4. I-V sweeps of the high-current Cs-Ba tacitron under high and low emission conditions (sweeps H615-15 and H621-05).

Fig. 5 is a scatter plot of ignition voltage and conduction drop versus Cs reservoir temperature. Ignition appears to follow the low $P_{Cs}{\cdot}d$ side of the Paschen breakdown curve, as expected, with increasing ignition voltage required at decreasing Cs vapor pressure. The conduction drop also increases as Cs vapor pressure decreases.

Grid transparency of the HCT (65%) is approximately the same as that reported for a planar Cs-Ba tacitron with triangular grid apertures[11]. The hexagonal aperture honeycomb grid of the HCT is thicker (approximately 1.5 mm versus 0.5 mm) and has larger geometrical aperture area (by roughly a factor of 4) than the triangular aperture grid (TAG) tacitron. Although data for comparison is limited, it appears that the voltage drop of the HCT device is approximately 0.5 V higher than that of the TAG device at equivalent current densities and Cs reservoir temperatures. This may be due to the thicker grid structure in the HCT. Stable current modulation of the TAG device was achieved for Cs reservoir temperatures in the range T_{Cs} = 140 –154° C (5.2 – 10 × 10^{-3} Torr), versus an approximate range of T_{Cs} = 130 –145° C (3.1 – 6.7 × 10^{-3} Torr) for the HCT[17].

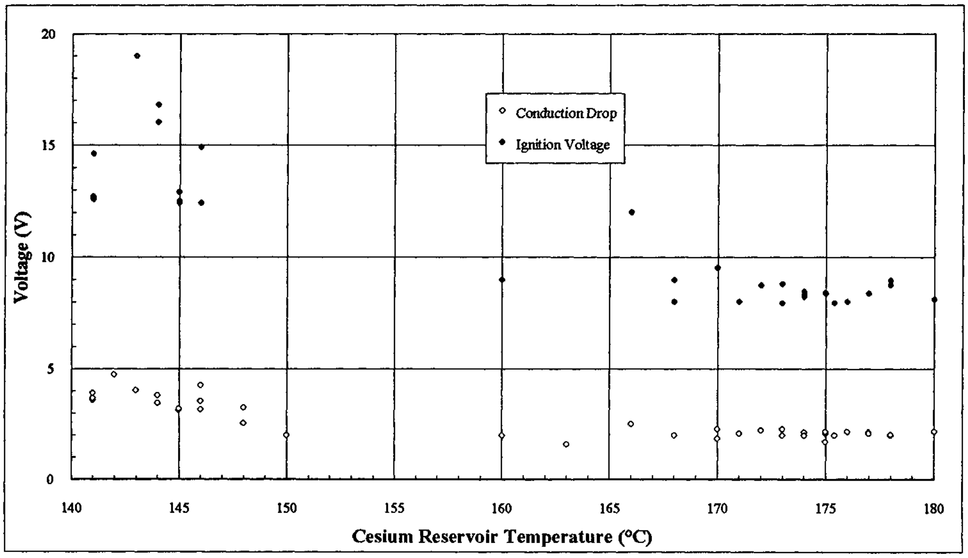

Fig. 5. Ignition voltage and conduction drop versus Cs reservoir temperature.

Discussion and Conclusions

The high-current demountable Cs-Ba tacitron has demonstrated successful conduction of currents up to 249 A. A hold-off voltage of at least 125 V has been achieved, and I-V tests demonstrate a forward voltage drop of 2.2 V at current densities of up to 4 A/cm^2.

A few aspects of the HCT indicate directions for device improvement. The emitter heater is composed of nine turns of 1.2 mm diameter tungsten wire. The outer four turns are supported by insulating stand-offs, but the inner five windings are not supported. After a few tens of hours of operating time, the inner five windings sagged into the emitter electrode and shorted due to insufficient structural support.

During low duty cycle modulation and I-V sweeps, HCT grid temperature is ~700° C at the outer edge when the emitter is at ~1100° C and the base flange is at ~600° C. The large grid area and high grid temperature contributes to a relatively large grid emission current on the order of a few amperes. This is a potential problem in terms of voltage hold-off. It is expected that the grid will dissipate significant power during continuous modulation, raising the grid temperature even higher. It may be necessary to water cool the grid in order to obtain high-power continuous modulation with reasonable voltage hold-off.

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References

[1] V. Z. Kaibyshev, G. A. Kuzin, and M. V. Mel'nikov, "Use of the Thermionic Converter for Regulation of Current in Electric Circuits," *Soviet Physics Technical Physics*, Vol. 17, No. 6, pp. 1006-1009, 1972.

[2] E. O. Johnson, J. Olmstead, and W. M. Webster, "The Tacitron, a Low Noise Thyratron Capable of Current Interruption by Grid Action," *Proceedings of the IRE*, Sep., 1954.

[3] V. Z. Kaibyshev and G. A. Kuzin, "Effect of a Third Electrode on a Low Voltage Arc," *Soviet Physics Technical Physics*, Vol. 45, No. 2, pp. 320-327, 1975.

[4] M. S. El-Genk, C. Murray, and S. Chaudhuri of ISNPS, and V. Kaibyshev, A. Borovskikh, Y. Djashiashvili, and Y. Taldonov of the Kurchatov Institute, "Experimental Evaluation of Cs-Ba Thermionic Switch/Inverter -- 'Tacitron'," *Proceedings of the IECEC*, Boston, MA, Aug. 4-9, 1991.

[5] M. S. El-Genk, C. Murray, and Glen McDuff of ISNPS, and V. Kaibyshev, A. Borovskikh, Y. Djashiashvili, and Y. Taldonov of the Kurchatov Institute of Atomic Energy, "Peculiarities of the Discharge Breakdown of the Cs-Ba Tacitron," *Proceedings of the 2nd Thermionic Specialist Conference of the USSR*, Sukhumi, USSR, Oct. 28 - Nov. 2, 1991.

[6] C. Murray, B. Wernsman, and M. S. El-Genk of ISNPS, and V. Kaibyshev of the Kurchatov Institute of Atomic Energy, "Ignition and Extinguishing Characteristics of Cs-Ba Tacitron," *Journal of Applied Physics*, Vol. 72, No. 10, 15 Nov. 1992.

[7] M. S. El-Genk, V. Kaibyshev, C. Murray, B. Wernsman, and Y. Djashiashvili, "Effect of the Grid Aperture on the Operation of the Cs-Ba Tacitron Inverter," *Proceedings of the IECEC*, San Diego, CA, Aug. 3-7, 1992.

[8] B. Wernsman and M. S. El-Genk, "Experimental Investigation of Current Modulation in a Planar Cs-Ba Tacitron," *IEEE Transactions on Electron Devices*, Apr. 1994.

[9] B. Wernsman, M. S. El-Genk, and V. Z. Kaibyshev, "Experimental Investigation and Analysis of the Operation Characteristics of a Planar Cs-Ba Tacitron," *11th Symposium on Space Nuclear Power and Propulsion*, Jan. 9-13, 1994, Albuquerque, NM.

[10] B. Wernsman and M. S. El-Genk, "Modulation Capabilities of Different Grid Designs for a Cs-Ba Tacitron," *21st International Power Modulation Symposium*, Jun. 28-30, Costa Mesa, CA, 1994.

[11] I. Djachiachvili and M. S. El-Genk, "Investigation of Triangular Aperture Grid for Plasma Switch Devices," *21st International Power Modulation Symposium*, Jun. 28-30, Costa Mesa, CA, 1994.

[12] C. Murray, M. S. El-Genk, B. Wernsman, and V. Kaibyshev, "A Steady-State Model for a Low-Pressure Cs-Ba Diode," *Journal of Applied Physics*, Vol. 74, No. 1, 1 Jul. 1993.

[13] C. Murray, M. S. El-Genk, and V. Kaibyshev, "Steady-State Model of a Low Cs Pressure Discharge in a Triode," *11th Symposium on Space Nuclear Power and Propulsion*, Albuquerque, NM, Jan. 9-13, 1994.

[14] J. Luke and M. S. El-Genk, "A Transient Model of a Cs-Ba Diode," *11th Symposium on Space Nuclear Power and Propulsion*, Albuqurque, NM, Jan. 9-13, 1994.

[15] G. B. Masten, D. Hidinger, I. Djachiachvili, G. Sharp, and J. M. Gahl, "Operating Characteristics of a Sealed-Prototype Cs-Ba Tacitron," *10th IEEE Pulsed Power Conference*, Albuquerque, NM, July 10-13, 1995.

[16] B. Wernsman and M. S. El-Genk of ISNPS, and V. Kaibyshev of the Kurchatov Institute of Atomic Energy, "Operation Characteristics of Planar Cs-Ba Tacitron," *Rev. Sci. Instrum.*, Apr. 1994

[17] G. B. Masten, I. Djachiachvili, D. Brent Morris, and J. M. Gahl, "Preliminary Performance Results of a High-Current Cs-Ba Tacitron in a Simple Two-Switch Inverter," *10th IEEE Pulsed Power Conference*, Albuquerque, NM, July 10-13, 1995.