Performance of and excited state densities in a linear thyratron

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(Received 7 May 1986; accepted for publication 7 July 1986)

A prototype of a new class of thyratrons having a linear geometry is described and measurements of excited state densities in the thyratron plasma using hook method spectroscopy are presented. The linear thyratron is conceptually scalable to high currents by lengthening it in the axial dimension without changing any other critical scaling dimension (such as the cathode-control grid distance). The prototype linear thyratron is a tetrode having a 3 cm$\times$10 cm slotted dispenser cathode with an effective area of 80 cm^2. The thyratron has separately switched 25 kV and 10 kA, with a maximum dI/dt of 1.3×10^{11} A s^{-1}. Using helium as the working gas, maximum excited state densities of 6×10^{12} cm^{-3} were measured for the 2^3P state.

I. INTRODUCTION

Thyratrons are the electrical gas switch of choice for high repetition rate (> 1 kHz), moderate voltage ($\leqslant$45 kV), and moderate current (< 5 kA, $dI/dt < 10^{10}$ A s^{-1}) applications.[1,2] When higher voltages, larger currents, and larger dI/dt are required, spark or rail gap switches are usually used.[3] Thyratrons are traditionally constructed in a cylindrical geometry. Scaling cylindrical thyratrons to higher currents by increasing the diameter of the cathode has had limited success because of the inability to uniformly utilize the entire cathode surface. Scaling cylindrical thyratrons in this manner increases their inductance (thereby decreasing dI/dt) and increases the geometrical mismatch between the switch and stripline modulators.

In an effort to increase the current and dI/dt of thyratrons while avoiding the problems traditionally associated with scaling cylindrical thyratrons, a prototype thyratron having a linear geometry has been built and characterized. The linear geometry is conceptually scalable to arbitrarily large currents by lengthening the thyratron in the axial dimension while not changing the characteristic gap dimensions or the distance between any spot on the cathode and the control grid slot, the critical dimensions which determine the switching properties. This paper describes our prototype device and reports on the density of excited states within the linear thyratron measured with hook method spectroscopy. The purpose of these measurements is to demonstrate simultaneous broad area initiation of the linear thyratron, and to improve our understanding of the operation of the linear thyratron to enable us to scale it to higher voltage and current. These measurements have also provided data with which to compare and validate results from a 2½-dimensional, time-dependent plasma simulation code developed to model the linear thyratron.[4] The code models electron avalanche and commutation in a thyratron operating with helium. It consists of a Monte Carlo particle simulation for electrons and a fluid representation for ions. Results from the model include thyratron voltage, current, and the distribution of excited atomic states, all of which agree well with experiment. Details of the model will be described elsewhere.

The linear thyratron and measurement techniques will be described in Sec. II, followed by specification of its electrical performance in Sec. III. Measurements of excited state densities in helium as the switching gas are discussed in Sec. IV, followed by concluding remarks in Sec. V.

II. DESCRIPTION OF THE LINEAR THYRATRON AND MEASUREMENTS

The present prototype device, shown schematically in Fig. 1, is a tetrode and has a slotted, sintered barium titanate

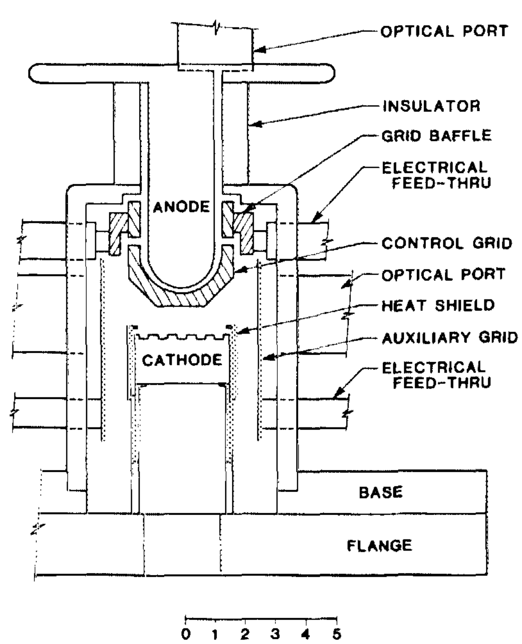

FIG. 1. Schematic cross section of the linear thyratron. The cathode is 10 cm in length.

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dispenser cathode[5] with dimensions 3 cm × 10 cm. The cathode was furnished by Sprectramat, Inc. The effective surface area of the slotted cathode is approximately 80 cm^2. The thyratron body is made of stainless steel and is sealed with fluorocarbon O-rings. An external gas handling system is used (base pressure 5×10^{-8} Torr), thereby enabling the use of a variety of gases at a selection of gas pressures. The high-voltage insulator is made of Pyrex in a racetrack configuration and is 3.4 cm high. The auxiliary grid is made of molybdenum and the control grid and anode are made of stainless steel. The thyratron is equipped with a pair of 2.5-cm-diam optical ports on either side of the cathode looking perpendicularly into the cathode-control grid space, and a pair viewing the control grid-anode gap. There are optical ports on either end of the thyratron with a viewing diameter of 6 cm which provide optical access to the entire cathode-control grid space and through which the interferometer described below was aligned with the linear axis of the thyratron.

Spatially resolved excited state densities as a function of time were measured using hook method interferometry.[6] The thyratron was mounted on an x-y translation stage in one leg of a Michelson interferometer. The interferometer was illuminated by a wide-band ($\Delta\lambda\approx8$ A) nitrogen-pumped dye laser (pulse duration $\approx$2 ns), collimated by a telescope to a spot size of 1 mm. The resulting fringe pattern was dispersed by a 1-m spectrometer equipped with a 1200-l/mm grating and operated in second order. An RCA TC2011 vidicon camera was used as a two-dimensional detector at the output plane of the spectrometer. Fringe patterns were displayed in real time on a television monitor and recorded on videotape for later analysis. The time duration of the dye laser is short compared to the characteristic time over which the density of excited states changes. The interferometer therefore provides a measure of the instantaneous value of the excited state density. A time-resolved measurement is obtained by delaying the dye laser with respect to the current pulse on successive firings of the thyratron. A single measurement was made during each current pulse. Time and spatial resolution is obtained by making measurements at a particular spatial location at many delay times, changing the spatial location, and repeating the process. A two-dimensional map of excited states for a selected time is obtained by interpolating the time-resolved measurements. Some smoothing is required due to system jitter.

III. ELECTRICAL PERFORMANCE

The thyratron is typically operated in either hydrogen or helium. The performance of the thyratron was qualitatively the same when using either of the gases; voltage fall time, maximum cathode current, and dI/dt were similar. The exception was with high-voltage holdoff and maximum switching voltage. At a given gas pressure, the maximum holdoff and switching voltage was higher in helium than in hydrogen, a consequence of the more favorable Paschen curve for helium as compared to hydrogen. Holdoff in the linear thyratron was limited to 25 kV by field emission at a gas-metal-insulator triple point, resulting in insulator flashover. This limiting voltage occurred at 1.5 Torr in He and 0.6 Torr in H_2. The field emission problem was subsequently corrected during a major modification of the linear thyratron. Holdoff and switching at 95 kV were obtained with the modified thyratron.[7] The details of the modification will be reported elsewhere.

We obtained uniform and simultaneous[4] discharge coverage over the entire area of the cathode by operating with a dc simmer current (a few mA cm^{-2} of cathode area) between the cathode and the auxiliary grid. The simultaneity and uniformity of discharge coverage were measured by observing time and spatially resolved emission from the plasma in the cathode-control grid gap. These measurements were made through the side optical ports by concurrently observing emission with a pair of photomultiplier tubes. Simultaneous cathode coverage was correlated with the simultaneity of the pulsed plasma emission from opposite ends of the cathode-control grid gap. In general, the simultaneity of discharge coverage decreased with decreasing gas pressure in the absence of the simmer current, as shown in Fig. 2 for operation in hydrogen. The use of the auxiliary simmer current did not otherwise affect the thyratron switching capabilities. By operating in this manner, we estimate that the cathode can be scaled to many times its present length while maintaining uniform cathode coverage.

Our prototype device has separately switched 25 kV, 10 kA, and a maximum dI/dt of 1.3×10^{11} A s^{-1}. The latter two values were obtained at different pulse lengths, although we did not attempt to optimize all parameters at all pulse lengths. The high current limit was obtained with pulse duration of $\approx$40 μs with a dI/dt of 2×10^{9} A s^{-1} while the high dI/dt limit was obtained with a pulse duration of $\approx$120 ns and a maximum current of 4.8 kA. These parameters equal or exceed those for commercially available thyratrons.[2] The cited current ratings will increase proportionally to an increase in the length of the cathode.

The cathode was typically operated without auxiliary heating. We obtained nearly the same performance when operating the cathode hot (800 °C) or at room temperature.

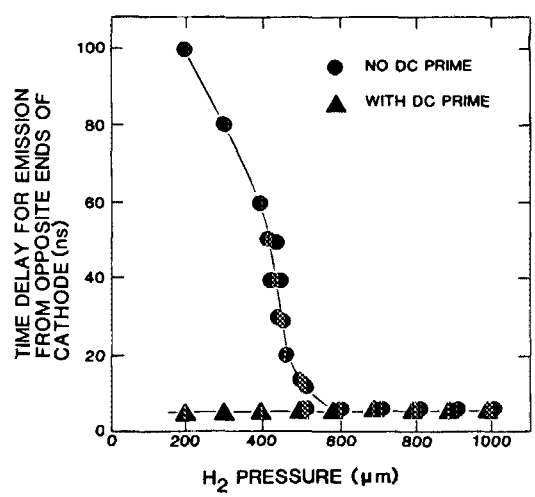

FIG. 2. Time delay for plasma emission from opposite ends of the cathode with and without a dc simmer current as a function of hydrogen pressure. The dc discharge is sustained between the auxiliary grid and the cathode.

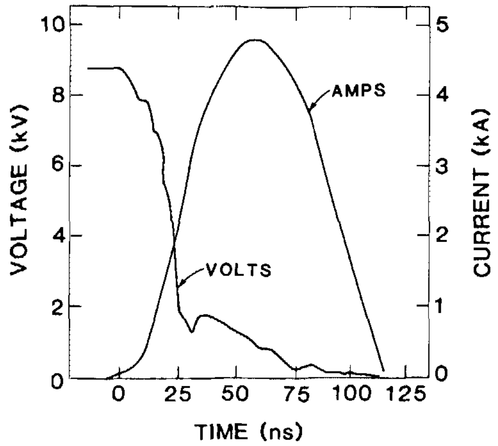

FIG. 3. Current and voltage characteristics for the linear thyratron operating in helium at 1.2 Torr. The inductive component of the voltage has been removed from the trace.

Current densities in excess of 150 A cm^{-2} were obtained with both a hot and cold cathode, indicating that the emission mechanism for this cathode is not dominantly thermal.[8] When operating with a hot cathode, the anode voltage fall time is longer and the jitter is worse than when operating with a cold cathode. The jitter, normally about 5 ns when operating cold, increased to 20–30 ns when operating with a hot cathode.

The current and voltage traces for the thyratron operating in 1.8 Torr of helium appear in Fig. 3. The inductive component of the voltage has been removed by computer processing.[9] The thyratron switched 20 nF charged to 9 kV into a 0.5-Ω load. The cathode was not heated. The peak current was 4.8 kA with a maximum $dI/dt = 1.3\times10^{11}$ A s^{-1}. The thyraton commutation appears to occur in two stages: 0–25 and 25–75 ns. The thyratron resistance at the end of the first stage is 0.2 Ω and after the second stage is 0.025 Ω. These parameters represent the best short pulse performance.

IV. EXCITED STATE DENSITY MEASUREMENTS

Densities of the 2^3P excited state of helium ($\lambda = 5876$ A) as measured with our hook spectrometer for similar conditions ($I_{max} = 3.2$ kA, $dI/dt = 8.0\times10^{10}$ A s^{-1}) to those for Fig. 3 are plotted as a function of position in Fig. 4. The time is at the maximum in the excited state density (approximately 80 ns into the current pulse). Also shown in Fig. 4 is a framing camera photograph of emission from the plasma for the same conditions. The framing width of the photograph overlaps the entire current pulse. The bright patches at the bottom of the photograph are the cathode surface shadowed in the middle by a heat shield. The measured distribution of excited states correlates well with the plasma emission. The maximum excited state density is approximately 6×10^{12} cm^{-3}, and occurs within the baffled region near the control grid slot. The local current density at this time is 900–1000 A cm^{-2}. Excited state densities behind the auxiliary grid were barely at the detection limit ($<10^{11}$ cm^{-3} maximum value). This indicates that there is no significant amount of current flowing between the wall of the linear thyratron (a conductor at the cathode potential) and the auxiliary grid. Excited state densities are small immediately adjacent to both the lower portion of the control grid and near the auxiliary grid. Other than the baffled region near the control grid, the highest density of excited states was observed near the vertex of the control grid, extending down from the baffled region. Results from our plasma simulation model indicate this is a region of locally high space charge.

Immediately above and parallel to the cathode, the density of excited states appears to have a local maximum. This distance approximately corresponds to the negative glow as observed with the framing camera and provides evidence for the existence of a substantial sheath near the surface of the cathode. The evidence would seem to suggest a nonthermal mechanism for electron emission from this dispenser cathode since a cathode supported dominantly by thermal emission would not have a large sheath. This conclusion is reinforced by measurements of the maximum current density that can be supported by this dispenser cathode. By visually observing the transition of the plasma at the surface of the cathode from a glow to an arc, we measured the maximum cathode current density as a function of cathode temperature. Over the temperature range of 300–1300 K, the increase in maximum current density was at most 20%, thereby indicating a small thermal contribution.

The density of the 2S state of atomic hydrogen was also measured with the thyratron operating in 0.275 Torr of H_2.

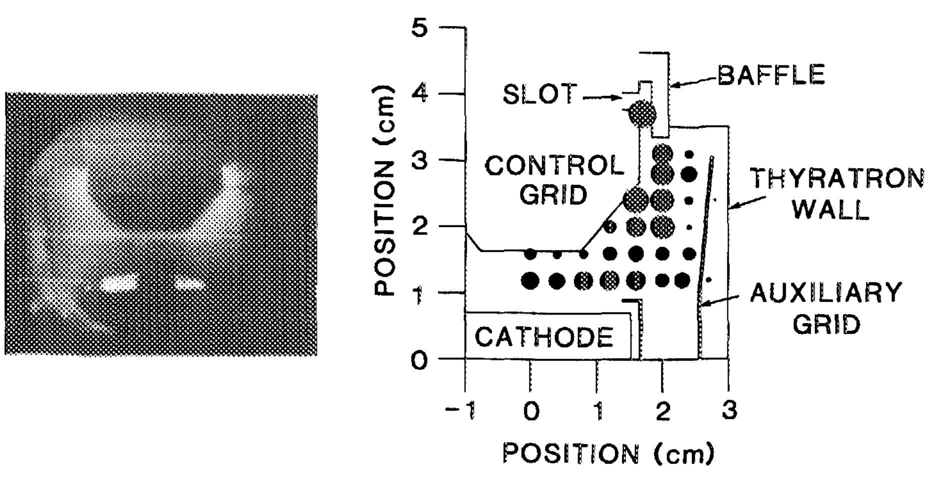

FIG. 4. Density of the He 2^3P excited state 80 ns into the current pulse as measured by hook spectroscopy (right) and a framing camera photograph of emission from the plasma (left). Maximum current of 3.2 kA occurs at 60 ns. The excited state density is proportional to the size of the circles. The highest density is 6×10^{12} cm^{-3} at the entrance to the control grid slot.

The time dependence and spatial distribution of excited states in hydrogen were similar to those measured in helium for the same switching voltage and current. The maximum excited state densities measured in hydrogen in the vicinity of the control grid slot were approximately two thirds those in helium, $\approx 4.5\times 10^{12}$ cm^{-3}. This represents a fractional excitation, based on the initial H_2 density, of 5×10^{-4}. The current density corresponding to this density is ≈ 1 kA cm^{-2}. Penetrante and Kunhardt[10] have calculated the densities of excited states and ions for a steady-state positive-column hydrogen plasma as might be found in a thyratron during the conduction phase of operation. Their calculated fractional excitation of the 2*S* state for similar discharge conditions is 1.3×10^{-4}. Our larger value most likely results from the fact that in the vicinity of the control grid slot, the electron distribution function has a high-energy tail. The high-energy tail is a consequence of the penetration of anode potential through the slot. This condition will result in a higher rate of excitation near the control grid slot than in the positive column.

The delineation between the highly excited region and the relatively low excited region is quite sharp and the time dependence of the excited state densities in the two regions is different. In Fig. 5 excited state densities are plotted as function of time for two locations: adjacent to the control grid and ≈ 0.5 cm away from control grid (in the direction of the auxiliary grid). The excited state density adjacent to the grid has a higher maximum value and has a time dependence similar to the total current. The offset between the extrema of the excited state density and current is due to the finite lifetime of the excited state. The excited state density further from the grid increases only during the first few tens of nanoseconds. We interpret these results as indicating that the current flows nearly uniformly through the region in front of the control grid slot early during the current pulse when the grid voltages are high. Later during the current pulse when the anode and grid voltages are lower, current flows dominantly near the control grid.

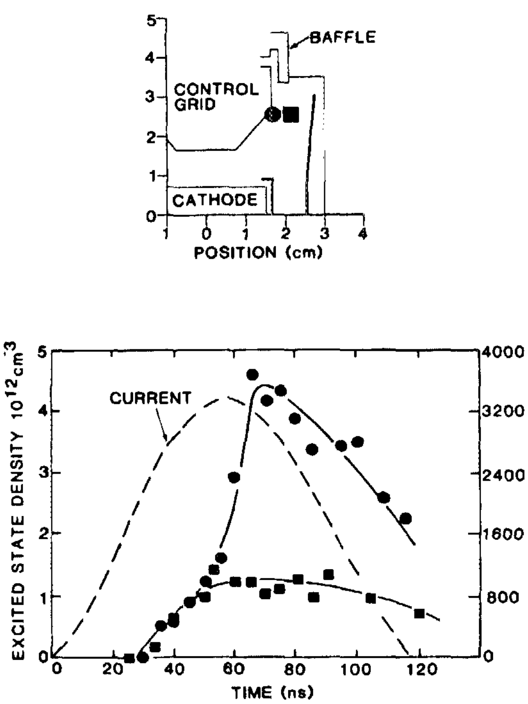

FIG. 5. Density of the He 2^3P excited state as a function of time at two locations near the control grid for conditions similar to that for Fig. 4. The locations are shown in the sketch.

This interpretation is supported by comparison of the effective excited state lifetimes at the different locations. If one assumes that the rate of excitation is proportional to the current, one can show that the effective lifetime of the state is equal to the offset in time between the maximum of the current and the maximum in the density of the excited state. The effective lifetime τ is given by $1/\tau = 1/\tau_r + 1/\tau_c$, where the subscripts denote the radiative and collisional lifetimes. The 2^3P state in He is radiatively coupled only to the 2^3S state with a lifetime of 100 ns. The effective lifetime given by the expression above for the location near the grid is ≈ 20 ns. Since this value is small compared to the radiative lifetime, quenching of the state must therefore be dominantly nonradiative. Away from the grid, the lifetime of the state is ≈ 70 ns, close to the radiative lifetime. Assuming non-radiative quenching is dominated by electron collisions, the longer lifetime and lower maximum excited state density away from the grid implies a lower current density.

V. CONCLUDING REMARKS

A thyratron using a linear geometry has been built and electrically characterized, and has been shown to be a viable option for scaling thyratrons to higher currents than is available with conventional cylindrical thyratrons. Uniform cathode utilization has been demonstrated with a maximum current of 10 kA and a maximum dI/dt of 1.3×10^{11} A s^{-1}. Excited state densities as a function of position and time in the linear thyratron have been measured using hook method spectroscopy. The maximum density measured for the 2^3P state in He is 6×10^{12} cm^{-3}, and 4×10^{12} cm^{-3} for the 2*S* state of atomic hydrogen when operating with H_2. The flow of current, as implied from the excited state densities, is nonuniform. Improvements in the grid design have resulted from these and similar measurements, lending credence to the use of such spectroscopic measurements as a tool in the design of thyratrons.

ACKNOWLEDGMENTS

We would like to thank Dr. David Turnquist of Impulse Engineering for building the prototype linear thyratron. This work was supported by Air Force Systems Command (Wright Patterson Air Force Base) Contract Nos. F33615-82-C-2244 and F33615-84-C-2474.

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