IEEE Transactions on Nuclear Science, Vol. NS-26, No. 3, June 1979

TWENTY-MILLION WATT VACUUM TUBE AND TEST RESULTS

D. Carter, J. Eshleman and J. Stabley[a]; A. Deitz and R. Winje[b]; and R. Gray[c]

Introduction

The Power Devices group of Electro Optics and Devices, RCA, Lancaster, Pennsylvania, has developed a gridded Tetrode power tube[1] that is capable of switching twenty-two million watts of power at pulse widths of five seconds or more. The tube, designated the RCA S94000E, was developed under funds provided by DOE and contracted through the Plasma Physics Laboratory of Princeton University.

The development of this tube represents an advancement in the state of the art for gridded tubes in terms of plate dissipation, voltage holdoff, and switched power at the pulse widths involved. Prior to this development, switch tube ratings have been limited to approximately 100 kilovolts holdoff voltage with a plate dissipation of several hundred kilowatts. These ratings applied typically to pulse widths of several milliseconds. The S94000E is rated for 200 kilovolts holdoff voltage and a plate dissipation of two million watts at five seconds pulse width. Load or output currents up to 125 amperes are available, with a tube voltage drop during the pulse in regulator use of typically seven to thirty kilovolts.

This tube was developed to[2] switch and regulate the accelerator electrode voltage on Neutral Beam Ion sources that are to be used for plasma heating in the TOKAMAK Fusion Test Reactor[3] (TFTR) being constructed at Princeton, New Jersey.

In order to evaluate the tube, it was necessary to make arrangements for the use of facilities other than those available at RCA's Lancaster location. At this point in time the facility most capable of providing the power requirements at full voltage is located at the Rome Air Development Center in Rome, New York.

RADC Test Facility

The facility at RADC[4] contains within one building six 65 KV, 9 Ampere power supplies, a high power load resistor, a complete demineralized water system, crowbar protection devices and various power supplies, both DC and pulse, that can be incorporated for tube evaluation.

The power supplies can be connected in a number of arrangements, one of which yields 200 KV at 18 Amperes of continuous current. The eighteen ampere rating was increased to 50 Amperes for pulse widths no greater than 0.5 second by RADC engineers. The test conditions therefore reflect the 50 ampere limit at 200 KV.

A dummy load resistor is located on the high side of the power supply, and is comprised of four sections of glass tubing filled with a solution of sodium nitrite or sodium chloride and water. The solution serves as the resistor and is circulated through a water-to-air heat exchanger which is electrically floating at the high voltage level.

Changes in the resistance can be accomplished by varying the salt content of the water. The Crowbar device is a series of 20 triggered air gaps that can be activated by applying a high pulse voltage to each tap.

For detection of tube faults, 80 UDD5 Unitrode diodes immersed in oil are connected between the anode and ground. The diodes are back biased until the plate voltage drops below some pre-set reference voltage which represents a plate arc in the tube. The reference voltage then provides forward bias, allowing the diodes to conduct, which generates a trigger pulse to fire the crowbar. A similar arrangement is used for protection of the screen grid. The tube itself is contained, anode up, in a rectangular lead shielded tank that is filled with transformer oil to prevent arcing across the anode ceramic. The tank is raised from the floor which allows the filament leads and auxiliary water hoses to be attached to the tube.

Long Pulse Operation

Pulsing a tube at long pulses where meters can be read for current and voltage, is somewhat different than the normal pulsing most of us have been used to. The building seems to groan a little, the light blinks, and the Vac-Ion pressure increases during each pulse. As the anode dissipation approaches 2.0 megawatts, and a .5 second pulse is occurring every 12 seconds, an appreciation is obtained for the anode design and its extreme importance to tube reliability under adverse or shorted load conditions that can occur with the Neutral Beam Ion Source.

Tests were concluded on the 16th of November and the tube was shipped to Lawrence Livermore Labs to be used in conjunction with the TFTR Neutral Beam Ion Source testing.

During the testing at RADC an anode dissipation level of 2.15 megawatts was reached. Anode voltages during the .5 second pulse were as high as 62 KV and an anode current of 60 Amperes was achieved. All this was accomplished in the negative grid no. 1 region using an RCA 40582 transistor to change bias during the pulse. Long pulse rise time testing was done in conjunction with TFTR requirements and to establish that the tube was oscillation free and could withstand the higher plate dissipation encountered during the turn on portion of the pulse. Test data highlights are shown in Table I.

An interesting tube/circuit phenomenon was encountered during testing. The tube vacuum pressure increases during the pulse and is pumped down during the interpulse period. At higher peak vacuum pressures during the pulse,

a RCA, Lancaster, Pennsylvania
b Princeton Plasma Physics Laboratory, Princeton, New Jersey
c Rome Air Development Center, Griffis AFB, Rome, New York

0018-9499/79/0600-4069$00.75 © 1979 IEEE

The ion current drawn through the control grid-to-ground external impedance can cause the control grid pulse voltage to increase enough that a measurable increase in plate current results. This effect was eliminated by lowering the control grid-to-ground circuit impedance to approximately 500 ohms.

TABLE I

TEST DATA SUMMARY

Ebb KV	Ep KV	Ib Amps	Eg2 Volts	eg Volts	Power Dissipation in Anode (KW)
With oil across anode ceramic; pulse length .5 second at 3 per minute; and 200 useconds rise time:					
185	62	27.3	520	-30	1690
190	42	47.0	490	-10	1980
193	53	43.0	500	-15	2080
193	50	46.0	600	-25	2150
200	36	50.0	590	-18	1800
400 useconds rise time:					
193	39.5	46.8	565	-18	1848
No oil across output ceramic; pulse length .5 second at 5 per minute; and 400 useconds rise time:					
107	36.0	52.0	590	-14	1872
107	26.0	60.0	740	-14	1560

Test Problems

Actual testing of the tube began the first week in September and what was envisioned to be a three week test, turned into a three month adventure, due to the fact that the RADC equipment was being stressed far beyond its ratings. Very early in the test program a resistance capacitance divider literally exploded. Water was our next enemy as the salt water in the dummy load developed a leak and seeped into the high voltage insulating plenum chamber that supplies cooling air to the load resistor heat exchanger.

However, in the midst of yet another equipment failure, we did inadvertently learn a very important thing about the survivability of the S94000E. It happened during a high voltage tube conditioning process. The 200 KV rectifier was being used with a series 200 K resistor with the crowbar protection dismantled. During this conditioning exercise, the high voltage diodes mentioned earlier, shorted, which caused the 200 KV power supply with only its internal impedance to be connected directly to the tube; which in turn faulted. A #16 wire being used acted as a fuse and probably saved the day. The Vac-Ion pump current exceeded 50 ma. The tube had taken a serious jolt, but it did recover. The RADC power supply also survived when the breakers opened. The tube voltage was processed up from 50 KV to the 200 KV level in a matter of several hours; and amazingly enough, the majority of the tests listed were made after this episode. We believe this is a highly significant event which gives an indication of the ruggedness and survivability of the S94000E.

General Description

The S94000E is constructed primarily from metal and ceramic materials. It is thirty-six inches high with a maximum diameter of 22¼ inches and weighs approximately 320 pounds. The tube is arranged with the plate terminal separated from the cathode terminal and mounting plate by the plate ceramic insulator. The bottom end of the tube has the terminal appendages for the screen grid, control grid, filament and filament ground. In addition, an ion pump and the pinch-off cover are also located on the bottom. The terminal appendages serve the dual purpose of providing an electrical contact as well as the coolant water connectors.

Internal Description

The design of the S94000E utilizes both something "old" and something "new". The input parts of the tube (filaments, control grid and screen grid) are identical to a smaller rf amplifier tube (4648) that has been in production for some years. The support structure of the S94000E was simply scaled up to incorporate more of these units.

The filaments are also used in other large power triode amplifier tubes. Having been produced for over twenty years, they have been proven to provide the long life required by the application. The plate arrangement of the S94000E, however, has been the major advancement in tube technology in terms of both power dissipation and plate holdoff voltage.

The internal arrangement of the tube is a cylindrical array of sixty-six individual electron optical systems surrounding a centrally located plate. Each electron gun in the tube is comprised of a directly heated ribbon filament, a control grid and a screen grid. All the electron guns are connected in an electrically parallel configuration and supply their output current to the plate structure. The plate structure of the S94000E is of a unique design. Just a few years ago, when long pulse service was discussed, it was interpreted to mean pulse lengths of several milliseconds with duty factors up to perhaps 10%. Under such conditions, power tube plate structures have demonstrated good operating life at dissipation levels exceeding ten kilowatts per square centimeter. On the other hand, CW service tubes are generally not successfully operated above about 2-3 kilowatts per square centimeter. The application for the S94000E unfortunately strikes an unhappy compromise between the two types of service, i.e., required plate dissipation of the pulse types, but with pulse widths that will result in the plate temperature reaching the steady-state condition during the pulse.

The plate structure of the S94000E collects the power at an oblique angle to the electron beam axis. In this manner, the collecting area of the plate is effectively enlarged and the power dissipation reduced to below levels normally used for CW tubes. Even with the area enhancement utilized and the high water velocity, local boiling takes place in the coolant channels near the end of a two MW dissipation, one second pulse. Because of this, the S94000E is required to operate with the plate terminal up (water flow up through the plate structure) and the coolant water requirements are necessary in terms of water purity and dissolved gasses. In order to control the boiling condition in the plate structure, a minimum back pressure of 20 psi gauge is required at the plate water exit connector.

Because of the high voltages employed in the use of the S94000E, x-rays are generated. Measurements indicate that at the tube envelope the intensity exceeds one Roentgen per hour. Because of this, x-radiation shielding is required for personnel protection. The maximum ratings for the tube are listed below.

	Maximum Rating
DC Plate Voltage	200 KV
Pulsed DC Plate Current	125 A
DC Grid No. 2 Voltage	1.8 KV
Pulsed DC Grid No. 2 Current	7.5 A
Negative Grid No. 1 Bias Voltage	1000 V
Grid No. 1 Dissipation	10 KW
Grid No. 2 Dissipation	10 KW
Plate Dissipation	2000 KW
DC Filament Current	4700 A

S94000E Maximum Ratings for Switch or Regulator Tube Service at Pulse Widths up to 5 Seconds

The transconductance of the tube is approximately 1.6 Mhos. The screen grid mu of the tube is approximately 9 and the plate mu of the tube is several thousand.

For operation with the TFTR Neutral Beam Source, [2, 5] the S94000E will be required to provide approximately 70 amperes of current at 120 kilovolts. Initial operation will be with one-half second pulse widths at two pulses per minute. For this operation, the S94000E provides a pulse voltage to the accelerating and gradient grids of the Ion Source, with the pulse rise time controlled to coordinate with the rise time of the arc current in the Ion Source. During the flat top portion of the pulse, the switch tube will be required to regulate the voltage. In the event of a flash arc within the Source grid structure, the tube will block the voltage so that the arc will be quenched and the Ion Source structure will not be damaged. After a suitable recovery time, the voltage will again be applied and the operation continued until another arc occurs or the one-half second "on" interval ends. Then the tube again blocks the voltage until the next "on" period occurs.

An electronic crowbar provides protection for the S94000E. In the case of a tube internal arc, the crowbar is fired to quench the arc and a vacuum interrupter opens the primary power to the HV power supply.

Requirements for the TFTR include four Neutral Beam lines with each line containing three Ion Sources. The Electro Optics and Devices activity is presently under a production contract with the Princeton Plasma Physics Laboratory to deliver S94000E tubes for the entire TFTR Neutral Beam Injection System.

Conclusion

During the tube tests on the RCA S94000E, operation was achieved to 200 kilovolts and to 50 amperes of switched current. Plate dissipation was varied, up to 2150 kilowatts at one-half second pulse widths. Tube voltage regulator range was tested up to 62 kilovolts.

Tube testing at one-half second pulse widths and three pulses per minute presents some interesting new aspects, especially when coupled with voltages up to 200 KV and power of multi-megawatts. With the slow repetitive rates, the adjustment of electrode voltages and currents requires delays of up to twenty seconds until the effect can be measured. Memory oscilloscopes were found to be very valuable, especially in the measurement of tube operating parameters.

The use of gridded power tubes for controlling the injected heating power of thermo nuclear reactors is an exciting new application. The performance of the S94000E offers future extended capability in terms of pulse width and voltage holdoff. The plate structure as it now exists offers operation at increased pulse widths and duty factors including continuous or DC operation.

For future experiments with fusion reactors that require more ion energy, the output structure of the tube provides a firm foundation for scaling to the higher voltage that might be required.

1 J. Eshleman, J. Mark: "Recent Developments in High Power Switch Tubes for High Power Radar and Fusion Research", Proceedings International Pulsed Power Conference, 1976, pp. IC 5-1, IC 5-5

2 A. Deitz, H. Murray R. Winje: "The TFTR Neutral Beam Power System", Proceedings of the Seventh Symposium on Engineering Problems of Fusion Research, 1977, Volume II, pp. 1151 - 1155

3 D. Steiner, J. F. Clarke: "The TOKAMAK: Model T Fusion Reactor", SCIENCE, Volume 199, 31 March 1978, pp. 1395 - 1403

4 R. Gray: "Long Pulse Testing of High Power Tetrodes", IEEE-AGED Modulator Symposium, 1976, pp. 172 - 178

5 H. Allen: "Neutral Beam Injection System", Princeton Plasma Physics Laboratory, Princeton, New Jersey, March 1977