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A 1-MEGAWATT CW RF POWER SOURCE FOR 80 MHz*

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Summary

The Fusion Materials Irradiation Test (FMIT) accelerator requires 13 RF amplifiers at 80 MHz, with a CW output of 600 kW each. The EIMAC 8973 (formerly the X-2170) was chosen as the amplifier tube for this application. Never before had the 8973 been operated at this power level and frequency; therefore a test program was initiated to determine its capabilities. The tube was operated Class B in the grounded-grid, grounded-screen configuration. Maximum CW output power was in excess of 1 MW, with a plate efficiency greater than 60% and a 14-dB gain. Details of the test setup and the results will be presented.

Background

The EIMAC 8973 power tetrode was chosen as the final amplifier tube for the 13 FMIT RF amplifier systems. This choice is the result of a test program that was necessary because there was no information available on the 8973's performance at the power level (600 kW) and frequency (80 MHz) required for the FMIT application.

At high power levels and frequencies greater than 50 MHz, the screen grid is considered to be the most vulnerable tube element. Because of the plate-to-screen capacitance (~140 pF), RF displacement current heating of the screen structure becomes significant at frequencies above 50 MHz. As a result of the very low thermal capacity of the screen structure, its temperature should reach steady state in just a few minutes of operation. Consequently, a screen failure, because of overdissipation, will occur within several minutes after tube operation begins.

Ceramic tube seals are prone to deterioration over a long period of time, but seal integrity depends on the larger dissipations of the filament and the anode, which in all cases were running within, or well below, maximum ratings.

Experimental Test Program

The primary goal of the experimental test program was to demonstrate satisfactory performance of the 8973 at 80-MHz and 600-kW CW output. The secondary goal was to determine the ultimate output capability of the 8973 by driving it to destruction.

The EIMAC 8990 was used as a driver, and the 8973's output was coupled to a temperature-controlled sodium nitrite load. The 8990 could produce 25 kW of power, which was believed to be capable of driving the 8973 to at least 500 kW, but not to its limit. The 8973 was operated Class B in the grounded-grid configuration. After the initial period of adjustment and calibration, the amplifier was operated for approximately 6 hours at power levels between 450 and 525 kW. During this period of sustained high-power operation, there were occasional arcs in the amplifier anode cavity that caused the anode power supply to crowbar. In every instance the high voltage was immediately restored and operation continued, with no change in tube performance. This indicated that the arcs were occurring in a noncritical part of the anode cavity, the most likely place being across the cavity tuning plates. These plates had a spacing of 2-1/2 in. and a capacitance of approximately 25 pF, and therefore had the highest RF voltage of any part of the circuit. The ratio of tuning capacitance to tube capacitance in this cavity structure is about 6 to 1. At 550 kW the tube should have been generating about 7000 V rms, which was stepped up to over 40 kV across the tuning plates, a voltage at which arcing could be expected. The situation was probably aggravated by cooling air that was introduced at this point, and it was most likely an accumulation of dust that triggered the arcs at random intervals. The voltage limit of the cavity was reached at 550 kW and the cavity arced at this power level almost independently of dc anode voltage, which was further proof that the arcs were occurring at a high RF-voltage point.

The operating parameters for different power levels are shown in Table I. Table I has two entries for power output. The first is based on directional couplers built into the output line that were calibrated against a Hewlett Packard Model 431 power meter and Bird Model 43 in-line power meter. The second is based on calculations from temperature rise and flow rate of the coolant to the dummy load. The calorimetric method was consistently 5 or 6% higher than the couplers. The calorimetric method and the equipment used for it is the same as used by EIMAC for tube evaluations.

The data in Table I show close agreement between total dc input and the power dissipated in the dummy load, plus power absorbed by anode cooling water. Actually, the power appearing in the dummy load and the anode cooling circuit should be greater than the total dc input, because a substantial part of the filament heating power (10 kW in this tube) is absorbed by the anode, but because RF drive power in a cathode drive configuration contributes to power output, these factors partially balance out.

Calculated values, shown in the table at 514 kW, agree closely with experimental values at 510 kW, except for drive power. This indicates higher actual gain than the calculations predict. This is not surprising, because the calculations were based on constant-current curves that were derived by manipulating control-grid voltage only. The experimental circuit used cathode drive, which is equivalent to driving both the control grid and the screen grid. This is because when the control grid and screen grid are at RF ground potential, a change in instantaneous cathode voltage makes an equal change in both cathode-to-screen and cathode-to-control-grid voltages. In the 8973, the mutual conductance of screen to plate is about 1/4 that of the control grid to plate, so that driving both grids should substantially increase the tube gain, as compared with the calculated gain. Also, the observed gain is higher than the calculated gain because the calculations assumed a -500 V grid bias whereas the tube was operated at -300 V grid bias.

The data selected for Table I do not reflect conditions for maximum anode efficiency, but indicate conditions favorable to low screen dissipation. The power output goal can be reached at lower plate voltages with an improvement of a few points in efficiency, but

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TABLE I

	Experimental Data				Calculated Data
RF power output (P_o), kW (Directional Coupler)	200	310	425	510	514
Plate voltage, kV	9.6	11.5	14.0	14.5	15
Drive power, kW	12.1	15.5	17.5	20	34
Gain, dB	12.2	13.0	13.9	14.1	11.8
Plate current, A	31.6	40.8	45.6	51	52.4
Screen voltage, V	760	1000	900	910	1000
Screen current, A	1.0	2.0	2.5	2.6	0.5
Screen dissipation (P_{sc}), kW	0.76	2.0	2.25	2.37	0.5
Grid voltage, V	300	310	305	305	500
Grid current, A	0.5	0.9	1.2	1.4	1.3
Grid dissipation (P_{g1}), kW	0.15	0.28	.037	0.42	0.65
dc anode input, kW	303	469	638	740	786
Anode efficiency, %	67	67	67	69	65.2
Total dc input: Anode input + P_{sc} + P_{g1}, kW	303.9	471.5	640.6	772.7	787.8
Anode dissipation: dc anode input - P_o, kW	103	159	215	230	272
Anode cooling water heat, kW	113	146	206	230	
Total anode power dissipation: P_o + anode cooling, kW	313	456	631	740	
P_o(based on calorimeter), kW	210	325	445	540	
Anode efficiency, % (based on calorimeter)	69.3	69.2	69.7	72.9	

with increased screen dissipation. The highest screen dissipation allowed during any 500-kW run was 3100 W, which is less than half the maximum screen-grid dissipation rating. This allows a large margin for RF heating.

The highest sustained operating power was 525 kW (551 kW by the calorimeter) for 45 minutes. This run was with 13.6-kV anode voltage, 53-A anode current, and a 3.06-kW screen dissipation. Anode efficiency was 72.6%. Plate dissipation during this run was 209 kW, as determined from flow and ΔT of anode cooling water; and 196 kW, as determined by subtracting power output from dc-power input. Maximum ratings for the 8973 are 22.5-kV plate voltage, 650-kW plate dissipation, 65-A plate current, and 7.5-kW screen dissipation. Note that at 525-kW output to the dummy load (which does not include losses in the dc blocker, impedance transformer, and a short section of transmission line) the tube is running far below maximum ratings in all respects.

Because of periodic crowbars, we were unable to make a continuous, uninterrupted test run of several hours. There were one-hour periods of uninterrupted operation during which temperatures stabilized. At no time did the 8973 exhibit erratic behavior.

Maximum Power Test

The 8973 plate cavity was dissassembled and reconfigured to increase the spacing between the capacitive tuning plates, thus increasing the voltage breakdown level and permitting testing at higher power levels.

We knew that for this operation most of the active components of the test stand would be above ratings and in some cases at their absolute limit. We planned to increase power rather rapidly until some component other than the 8973 failed, then to improve or reinforce that component and proceed to higher power levels. After several minor setbacks, such as the failure of the dummy load center-conductor insulator and a rather spectacular arc-over in the 9-in. coaxial output line, it became apparent that the limiting factor would be the driver amplifier. In this test stand, a common high-voltage power supply was used for both the final amplifier and the driver.

Test results are shown in Table II. Output power was determined by two independent methods. The EIMAC staff calculated the output power from temperature rise and flow rate of the chemical-salt solution in the dummy load. In all measurements, several thermometer readings were averaged to determine ΔT. Output power also was determined by the output of a directional coupler built into the 50-Ω section of the output transmission line. This coupler was calibrated by the Los Alamos staff at exactly -60 dB. The coupler output was measured with a Hewlett Packard Model 434A calorimeter-type power meter that was calibrated at least twice daily. The very close agreement between the two methods of measurement lends credence to the output measurements.

For 800-kW output, the 8973 required a 17.5-kV anode voltage, which was at least 50% over the maximum rating for the driver tube. Because both tubes used the same anode power supply, the driver had to run at the same voltage as the 8973. At 800 kW,

TABLE II

Tabulation of Test Data at Power Levels Near 650, 800, and 1000 kW.

	650 kW	800 kW	1000 kW	Max Ratings
Plate voltage, kV	16	17.6	20	22.5
Plate current, A	64.2	68.4	78	65
Screen voltage, V	890	910	860	2.5
Screen current, A	4.2	3.3	5	
Screen dissipation, W	3736	3003	4300	7500
Grid voltage, V	310	300	300	
Grid current, A	2.7	1.8	4.2	
dc anode input, kW	1027	1024	1560	
RF drive power, kW	30	28	38	
RF output power, kW (directional coupler)	682	808	1050	
RF output power, kW (dummy load water temperature and flow)	674	770	1035/1055	
Plate dissipation, kW	345	396	510	650
Anode efficiency, %	66.4	67.1	67.3	
Duration of run, min	17	26	1 3/4 min	

the 8973 required about 30 kW of drive, which is a very good 14.3-dB gain. At this drive level, the dc input to the driver was 63.4 kW, for a plate dissipation of 33.4 kW, whereas rated maximum plate dissipation for the driver tube is 20 kW. Driver efficiency could have been improved by reducing output coupling, but this would have increased RF voltages in the driver output cavity, and already there were sporadic cases of arcing. At 800 kW, the 8973 was running at the maximum 69-A plate current, but with only 17.6-kV anode-supply voltage. The rated maximum is 22.5 kV. Plate dissipation was only 450 kW, well below the 650-kW maximum rating. Also, at this power level and plate voltage, the tube appeared to be reaching saturation. Reaching the maximum ratings obviously called for higher anode voltages. Because it appeared that the driver stage was near its absolute limit, approval was requested and received from EIMAC, to continue testing at higher voltages at the risk of sacrificing the driver tube and damaging the driver output cavity.

The final test was begun at 16-kV anode voltage, 30-kW drive and 700-kW output. With tuning and matching optimized, plate voltage was increased to 20 kV. At this voltage with 38 kW of drive power, the output was 1050 kW as measured from output line couplers and 1035 kW and 1055 kW by two measurements from load-cooling-water temperature and flow. Total anode dc input was 1556 kW, and plate dissipation about 500 kW--still below the tube's maximum rating. This power level was maintained slightly less than two minutes, which was long enough for instrumentation and thermometers to stabilize. The run was ended by an arc in the driver cavity.

On a second run, an output of 1061 kW was attained, but the driver cavity arced down in less than one minute. Subsequent trials did not reach the 1-MW level, apparently because of deterioration in the driver and final amplifier cavities. At these very high power levels, approaching 1 MW, the voltage levels in the driver and power-amplifier cavities exceeded the levels for which they were designed; consequently, arcing in either stage would cause the crowbar to shut down the system. The longer we continued, the more frequent the arcdowns, and the lower the plate voltage at which they occurred.

Test Conclusions

In no test was there ever any evidence of performance variation that might be attributed to excessive dissipation in a tube element. A test run usually terminated because of an arc in the driver cavity, the 8973 cavity, or the output circuit. There were several false crowbars in the high-voltage power supply. After each arc or crowbar, the amplifier was immediately brought up to the previous operating condition; in every case, excepting those when some component failed, the 8973 operated exactly as before the shutdown. Even at the 1.05-MW level, there was no change in element currents for the duration of the test. At the 800-kW level, the entire system ran for 26 min with about a ±1% change in output.

It is agreed that the 8973 could operate conservatively into a matched load at 700 kW, with a 1-MW peak capability. These conclusions are based on tests of only one tube of this type. However, our experience with EIMAC tubes is that their performance and parameters are very consistent.

Operation into a resonant load, and the possibility of mismatch conditions (as will be experienced in the FMIT application) should suggest operation at a lower power level; but if the tube used during these tests is representative of the type, routine operation at 600 kW, with 800- or 900-kW short-term peak output, seems well within the capacity of the 8973.

The secondary goal of the test program, which was to determine the ultimate capability of the 8973 by driving it to destruction, was not attained. This was because of limitations in the test-stand equipment such as the driver-cavity voltage-breakdown level, available drive power, output coaxial line, and load.

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