OPERATING EXPERIENCE AND RELIABILITY IMPROVEMENTS ON THE 5 KW CW KLYSTRON AT JEFFERSON LAB

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Abstract

With substantial operating hours on the RF system, considerable information on reliability of the 5 kW CW klystrons has been obtained. High early failure rates led to examination of the operating conditions and failure modes. Internal ceramic contamination caused premature failure of gun potting material and ultimate tube demise through arcing or ceramic fracture. A planned course of repotting and reconditioning of approximately 300 klystrons, plus careful attention to operating conditions and periodic analysis of operational data, has substantially reduced the failure rate. It is anticipated that implementation of planned supplemental monitoring systems for the klystrons will allow most catastrophic failures to be avoided. By predicting end of life, tubes can be changed out before they fail, thus minimizing unplanned downtime. Initial tests have also been conducted on this same klystron operated at higher voltages with resultant higher output power. The outcome of these tests will provide information to be considered for future upgrades to the accelerator.

1 BACKGROUND

1.1 Number & Type

An original purchase of 350 klystrons was made over a three year period.

Beam voltage	11.6	kV
Beam current	1.3	Amps
P_{out}	5	kW
P_{in}	2	watts (max)
Frequency	1497	MHz
Bandwidth	6	MHz
Heater voltage	7.3	Volts dc
Heater current	4.3	Amps (typ.)
Magnetics	PM	
Cooling	water (LCW)	35º C

Table 1 - Varian VKL8711W Parameters [1]

The contract was awarded to a single vendor, Varian Associates (now Communications & Power Industries - CPI).

2 KLYSTRON FAILURES

2.1 Failure Rates

As could be expected, klystrons failed. To date, some 83 have died. As tubes failed, the few spares originally purchased dwindled and additional tubes were purchased to supplement the 350 originals. Concurrent with the purchase of spares, a vendor was also selected to repair and rebuild the failed klystrons. Both contracts were the result of a competitive bid process. New tubes would be supplied by Litton Electron Devices, while a startup company, Pendulum Electromagnetics (PendEl) in Raleigh NC, would handle all the repairs and rebuilding.

The spec requested tubes with at least 20-25k hours life. Overall, even with a high number of early failures, the MTBF was around 22k hours by 1994. Currently, the hours/failures ratio shows about 90K hours of filament operation and 67k hours of HV operation average. None of the failures so far has been from normal wear out, that is, cathode depletion. Instead, catastrophic failures have ranged from open heaters to external arcing.

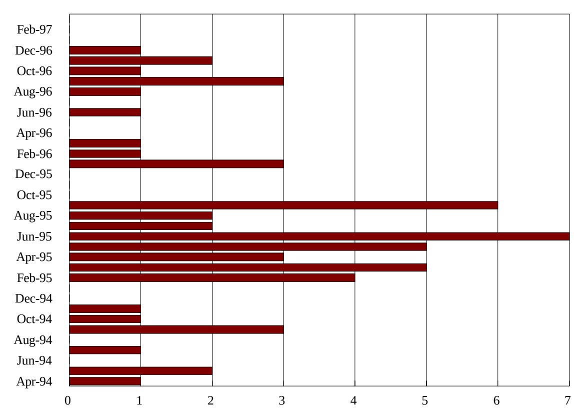

Figure 1 - Klystron Failures by Month

The high voltage power supplies each feed eight klystrons and did not arrive with a crowbar. A crowbar was later added but is not used because of nuisance trips and other issues. Though the power supply turned off when a tube arced, operators usually made several attempts to restart the zone before technicians were called. By that time, if the tube had arced, there was a

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substantial track across the ceramic and the tube would be dead.

Partly because full RF power wouldn't be required for awhile, and partly to try and reduce the rising rate of failures, the klystron's operating voltage was lowered. This seemed to give some relief for a time, but failures continued.

2.2 Failure Modes

The largest number of failures were the result of *external* arcs across the ceramic of the gun assembly. The gun assembly is potted with a silicone RTV to prevent problems with dust and humidity. In many cases, the RTV closest to the gun reverted to either a thick soup of silicone oil and solids or a dry and crumbling material. While the RTV was rated at 250 °C [2] and measured surface temperatures according to data provided were well below that point, silicone supplier GE Silicone felt the material was being exposed to temperatures too high.

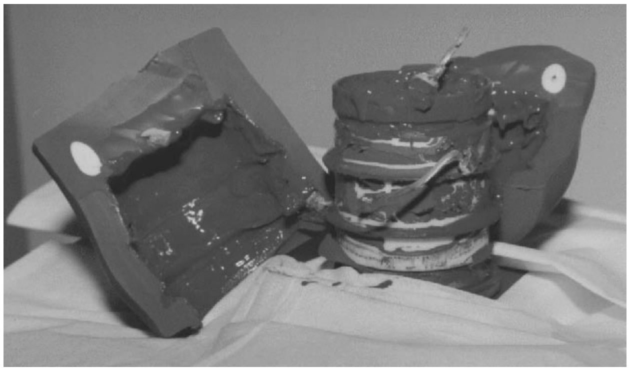

Figure 2 - Gun assembly showing degraded potting

Besides obvious interruptions to machine operation, most of the failures also made repairs more difficult since tubes typically went to air with resultant internal contamination from silicone oil being sucked in. If catastrophic failures couldn't be prevented completely, it seemed prudent to try and remove suspect tubes from service before they took the machine down.

2.3 Locating the Bad Actors

We felt that the decay of the RTV was contributing to the arcing across the ceramic so methods of determining the condition of the potting were examined.

The RTV should have a good bond to the ceramic and metal and be free from voids, so all potting was checked for voids using ultrasound measuring techniques. When a tube failed, the test results of the ultrasound were checked. There didn't seem to be any obvious correlation between the test results and tube failure.

A second *tactile* test was also used, wherein the potting was squeezed and twisted lightly to determine whether it was still solid and well attached. This picked up on some bad RTV but once again didn't reliably allow us to spot potential candidates for failure.

2.4 Repotting

Recognizing that we couldn't consistently spot bad potting or predict failures, a decision was made to repot all the tubes in the machine. This time the RTV was Stycast 5952 from Emerson & Cuming., a product with higher thermal conductivity [3] and one that didn't require stage curing.

Tubes were swapped out with spares and those tubes were then repotted. The old RTV had to be removed first. In many cases it turned out to be still perfectly intact, in which case it was difficult to remove. The material was cut, pried , scraped, and wiped off, and then abrasive blasted with aluminum oxide and liquid washed to insure clean surfaces. New leads were attached and a primer coat was applied to help the RTV bond. A three piece clamshell mold was placed over the gun assembly, the RTV mixed, de-aired, poured, and cured with the aid of a heat tape wrapped around the mold. After the mold was removed the leads were cut and terminated and the tube put on the test stand for a full battery of tests. The results of these tests have been put in a database to allow comparison, both among the group, and against itself in the future if it is retested.

2.5 A Different Failure

Failures continued among tubes with original potting, and eventually, one of the repotted tubes failed. The gun ceramic fractured and took the tube up to air. This time the potting closest to the ceramic appeared dry, gritty and hard. A potting sample submitted to Emerson & Cuming came back with a suggestion that the apparent reason for failure was high temperature. So we looked for other heat sources.

Hipotting the tubes had shown that some tubes had a voltage at which the tube didn't break down completely, but where leakage current started to climb rapidly. These breakpoints, or knees, were determined to be related to field emission. Internal ceramic contamination caused a different, more linear resistance. Again, hipotting didn't reliably predict life or death for all tubes, but it was a good indicator for certain problems. Also, hipotting was done on a cold tube and couldn't be continuously monitored.

3 HEAT SOURCES

3.1 Mod Anode Intercept

Measuring operating temperatures on a potted and operating gun was difficult because of the high voltage on the gun. Thermocouples placed in the potting had measured temperatures with only heater power applied, and those temperatures were satisfactory. We presently monitored and could log, cathode and body currents, but not mod anode current. As a test, a metering panel was assembled on a clear acrylic panel and mounted in spare rack space on the HPA. As predicted, we found that a few tubes had higher than normal mod anode current.

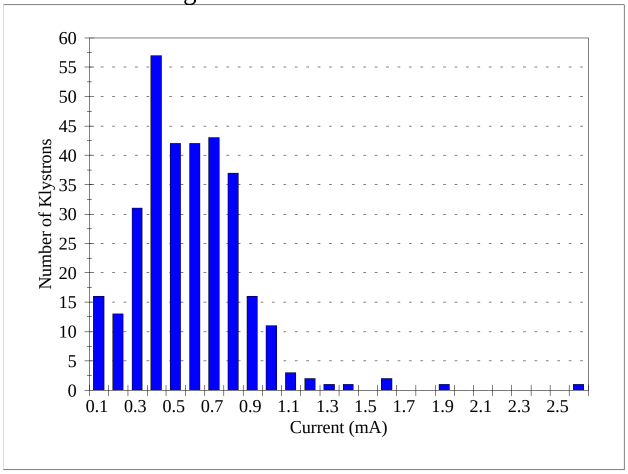

Figure 3 - Mod Anode Current Distribution

Original specs required mod anode intercept to be < 1% of beam current, which equated to <13 mA. Assuming that most of the current intercepted by the modulating anode was dissipated by the metal and ceramic through the potting material, we simulated additional heat on our thermocouple equipped tube by increasing heater power. The temperature reached 250 °C with another 30 watts input. So while 12 mA of intercept would fall within the specs, it would also generate 139 watts of heat. The gun would fracture well before that point. In fact, at least three tubes have suffered that fate, so it's convincing that excessive mod anode current was probably a major contributor to potting failures.

3.2 Controlling Mod Anode Current

We had lowered the cathode voltage but kept the heater setting at the nameplate value. Running a curve of cathode emission vs. filament voltage, we found that most tubes would operate satisfactorily with about 75% of the rated voltage. Running cathodes hot had resulted in excessive barium boil off and internal contamination. Since resetting individual filament voltages based on emission curves, the failure rate has dropped noticeably.

Even though heater power was lowered, those tubes with high mod anode current and a sharp breakdown knee still had problems. We found that the knee could, in most cases, be raised beyond our operating voltage and the tube recovered. Reconditioning was accomplished either with multiple hits from a capacitor discharge setup or by slowly raising cathode voltage while insuring mod anode current didn't exceed about 2.5 mA.

Because mod anode current was found to be a critical measure of the tube's health and an indicator of impending failure, permanent monitoring has been installed on all klystron positions. This parameter is now remotely monitored, and can be logged or trip the power supply if a preset threshold is exceeded.

4 MORE RF POWER

4.1 The Future

While present RF capacity may accommodate a machine upgrade to 6 GeV, more power will be required to reach 8 GeV. A Free Electron Laser project (FEL) presently in the construction phase also requires higher RF power for its superconducting cavities.

4.2 Options

Three options for generating more RF power include replacing the present klystrons and their power supplies, replacing the current klystron with a higher efficiency unit and possibly retaining the existing power supplies, and operating the present klystrons at higher voltage by replacing the present power supplies. The latter will be used to meet short term FEL requirements.

4.3 5 kW Klystrons Running at 8 kW

Increasing the cathode voltage to 14 kV scales the output power to 8 kW. DC input power rises a similar percentage so cooling is increased to maintain tube temperatures at approximately the same point.

Some of our present tubes have been run at various voltages from the nominal 11.6 kV up to 14 kV. The original Varian tube had a robust collector. With increased cooling it has easily accommodated the 60% additional beam power. The primary concerns dealt with body and mod anode currents. Body current can be tweaked if necessary by placement of magnetic shunts inside the bowl magnets.

Tubes from all three sources, Varian, Litton and PendEl have been run at 14 kV and delivered 8 kW. It should be noted, though, that some will require conditioning to run reliably at 14 kV. Some, with excessive leakage due to barium deposits on the ceramic, may not be suitable for 8 kW service at all.

5 ACKNOWLEDGMENTS

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REFERENCES

[1] CEBAF Specification EE0043
[2] `GE Silicone RTV-31 Data Sheet', GE Silicones
[3] `Technical Data Sheet, Stycast 5952', document number 2M793C-J107, Emerson & Cuming