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EXPERIMENTAL AND ANALYTIC STUDIES OF AN RF LOAD RESISTOR[*]

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Abstract

The pulsed output of an 850-MHz klystron was directed into a load assembly containing a water-cooled, 50-ohm resistor. The load was systematically subjected to high peak-power pulses from the klystron. Several thin-film resistors were tested and exhibited various damage patterns for different combinations of peak microwave power (33 kW – 500 kW) and heat input. In order to better understand the phenomena observed, the electromagnetic field distribution inside the resistor housing was studied with WaveSim, a two-dimensional, finite-element scattering code. The conformal mesh of the program allowed accurate representations of the complex assembly geometry.

1 INTRODUCTION

The Low Energy Demonstration Accelerator (LEDA), currently in the construction stage at the Los Alamos National Laboratory (LANL), will provide design confirmation and operational experience toward accelerator production of nuclear isotopes for defense and medical applications. Throughout the LEDA beam acceleration process, RF fields are established in the accelerating cavities using a large number of klystrons as compact, high-power-microwave sources. For this reason, a large number of microwave power-dissipating loads is also required.

LEDA utilizes 200-kW water loads containing thin-film resistors manufactured by Altronics Research, Inc. (ARI) through a proprietary process. Due to the initial rate of failure for these resistors, a study was initiated to test 25-kW water loads of identical design at various power ratings and levels of dissipation, to be supplied by ARI. An extensive information database has been created as the basis for future design improvements. These tests were performed at the University of New Mexico (UNM) using an 850-MHz klystron test stand.

2 EXPERIMENTAL LAYOUT

The UNM klystron uses a modulated anode to generate pulsed microwave bursts up to 2-ms long at a frequency of 850-MHz. The klystron amplifier produces a gain of 55.4 dB and a peak output power of 1.26 MW[1]. The amplified signal is extracted and fed to a test stand or an antenna using a waveguide equipped with an RF isolator to prevent reflected signals from damaging the klystron tube. For these experiments, the test stand consisted of a thin-film resistor and its housing (see Fig. 1), and was connected to the waveguide as a matching load.

Figure 1: Photograph of the type 9725 resistive-load assembly for 850-MHz.

2.1 *Resistor Design*

The type 9725 resistor utilizes the same substrate and resistive film as the LEDA (type 57200) resistors, at approximately 1/10th physical scale. The cylindrical resistor substrate is composed of ground 96% aluminum oxide (cermet) and overcoated with bismuth rutinate, a metallic oxide. There is a single resistive layer (0.001 in thick) deposited on the cermet which is mechanically and chemically bonded through the fabrication process. The oxide is overcoated with glass and processed in air at 850°C. The glass coating was added to protect the film against water erosion.

Although the resistive film is deposited only on the outside surface, the tubular substrate is hollow in order to allow coolant (distilled water) to flow through the inside of the element as well as the outside.

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Loading on the 57200 resistor (2.0x34 in) is about 99 W/in^2 based on a film surface of 202 in^2. In order to obtain a comparable film loading, the 9725 resistor (1.1x10 in), which has a total film surface area of 80 in^2, was initially powered at 30-33 kW. There is a physical difference in the resistor enclosures, which may not allow exact scaling for best possible data. This issue was addressed with the electromagnetic field distribution modeling performed using WaveSim.

2.2 Failure mechanisms

Two distinct mechanisms appear to be involved in observed film failures: thermal stress and dielectric breakdown.

Thermal stress usually occurs due to insufficient coolant flow, air bubble formation caused by pressure drop through the resistor housing, as well as small transients in the flow rate, such as those caused by water supply pressure variations. Heat damage to the resistor is usually caused by either localized boiling of the water coolant, or by differential expansion among several layers of dissimilar materials, both of which can result in the localized shattering of the resistive film.

Dielectric breakdown occurs when the resistor is subjected to a high peak-power microwave pulse, which generates increased power dissipation throughout the resistive film, overloading the resistor. Localized areas are then formed where permanent physical damage has occurred and the resistive properties have changed. This kind of localized damage will continue until enough areas are affected, ultimately resulting in complete failure of the resistor as a load.

3 FIELD DISTRIBUTION ANALYSIS

In order to predict and explain any damage pattern observed during these experiments, the electromagnetic field distribution inside the resistor housing was modeled for both the 9725 and the 57200 elements. The simulation program used was WaveSim[2], a two-dimensional, finite element scattering code with applications in radar, communications and microwave devices. The fine conformal mesh used in the layout of the program allowed an accurate representation of the various layers and the complex assembly geometry involved.

The modeling showed a significant variation of the field magnitude along the length of the resistor, which indicates non-uniform power dissipation (see figure 2). When using water coolant, there is a strong concentration of the field near the downstream end connector. The power dissipation there is over 25 times that at the upstream end of the resistor. This result was consistent with early experimental results, in which the film was damaged circumferentially adjacent to the downstream connector.

Clearly, different input microwave frequencies create uneven power dissipation levels along the axis of the resistor element. At the resistor's test frequency (850 MHz), enhanced fields up to 5.7 kV/m were predicted compared to the approximately uniform field of 2.25 kV/m at a lower frequency (85 Mhz). Failures due to severe dielectric stress in this region were observed experimentally as noted in Section 4.

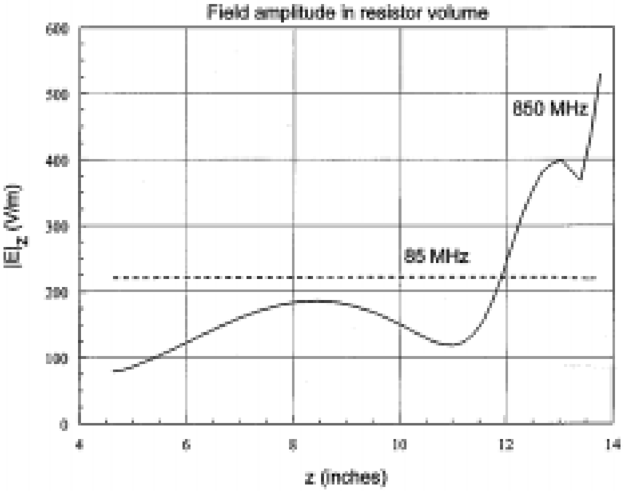

Figure 2: Field amplitude plotted from input end (left) to water downstream end (right) assuming 25W input power.

4 OUTLINE OF TESTS

UNM's klystron was used to first determine the limits of dielectric film strength. Resistor elements manufactured without protective glass coatings were chosen for this test, in order to allow sectional film resistance to be measured. This feature allowed significant thickness variations in the film to be observed both axially and rotationally (probably due to the manufacturing process). These initial tests bounded the film's rating for low power, low duty-cycle operation. No degradation was noted for 30,000 shots of 2 ms/1Hz pulses at 33 kW. Although the sample size was not statistically valid, this test suggested robust film performance is likely at the rated load. Similar tests were applied at peak powers up to 150 kW, eventually causing failure. A characteristic failure pattern was observed near the downstream connector, corroborated by WavSim modeling. ARI modified the contact ring design in response to this failure.

At the end of the first test phase, it was observed that coolant was causing film erosion and unwanted film aging during the experiment. Therefore, all subsequent tests were performed using ARI's coated stock elements. Test goals were also modified to allow data to be taken over a wider range of both temperature and input RF power. In order to standardize the effect of film aging, a fixed pulse sequence was chosen.

LEDA's requirements for resistive loads target 75% availability or 6,570 hrs per year, but at intermittent loading. A valid test for a resistor rated at 50,000 hrs MTBF (Mean-Time Between Failure) requires a simulation of 50/6.57 = 7.5 years of life in order to insure that at least one life-cycle's operation has been tested. Further, each resistor will be required to withstand 20 reflected power events per day in the first year, tapering to 5 per day in three years, then continuing at that rate until failure. Based on these assumptions, a final series of tests were performed to identify the failure curve for this scenario. They are described in Section 5.

5 EXPERIMENTAL RESULTS

5.1 Test Setup

The microwave output of the klystron was fed into the resistor load in pulses about 1-ms long at a repetition rate of 3 Hz. In this way, approximately 13K shots for each data point were obtained in roughly one hour. The input pulse, as well as the reflected pulse, was closely monitored to observe the functioning of the resistor. Since the dissipated thermal energy was low, an independent means of controlling film surface temperature was required. Heat input was varied by use of a thin, 2.5 kW electrical water heater that was inserted into the inlet cooling channel. Due to its geometry, some uneven flow distribution along the inside resistor surface occurred which cannot be easily quantified. The amount of heat rise needed for each test was controlled by varying the flow of the cooling water. A resistor was declared 'failed' as soon as a significant increase in the reflected microwave power became measurable, indicating a change in the load impedance.

5.2 Failure Curve

Three different resistors were used, each at a different amount of heat rise, ΔT, roughly 15 °C, 7 °C, and 3 °C. Each resistor was initially subjected to a relatively low power level, after which peak power was increased in increments of 33 kW. Tests were continued until failure of each resistor occurred.

The results of this extensive series of tests are shown in the graph of Figure 3. All data below 15 °C were obtained through direct measurement, while the remainder was estimated from vendor specifications. Reliable operation is implied in the region to the left of the failure curve. Published ratings are 25 kW continuous dissipation at 20 °C rise.

It should be noted that the failure region cannot be precisely defined with this method since such effects are gradual, i.e., conditioning is a significant factor. If a longer pulse width (50-100 ms) had been chosen, the region would likely be more constrained. Conversely, if a shorter pulse series (less than 13,000) had been applied at each test point, the region may have been less constrained. The ultimate value of performing such tests lies in their general ability to highlight areas of needed design improvement.

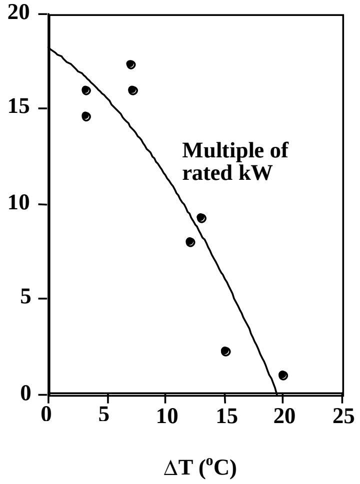

Figure 3: Failure curve for the 9725 resistor (Multiple of Rated Power vs. Heat Rise, ΔT).

6 CONCLUSIONS

A variety of conclusions were drawn from the results of this study, namely:

1. The electromagnetic field distribution inside the resistor housing was modeled accurately using the simulation code WaveSim, resulting in a design change.
2. The combined effect of heat and dielectric stress are causal factors in film breakdown, as summarised above.
3. Manufacturing variability adds an unquantified dimension to the problem of applying film resistors at RF power densities near their ultimate ratings. In this operating regime, further work is needed to insure component reliability.
4. Additional test data for RF film resistors are needed in applications such as LEDA. Specific issues include: scaling to larger elements, continuous versus pulse power ratings, and the impact of water flow instability.

7 ACKNOWLEDGEMENTS

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8 REFERENCES

[1] D. L. Borovina, J. M. Gahl, D. Rees, "Spectral Analysis of Breakdown at or Near RF Windows", presented at the Particle Accelerator Conference PAC'99, New York, April 1999.

[2] WaveSim, authored by Dr. Stan Humphries, Jr. of UNM-EECE, Albuquerque. N.M. Contact: humphrie@ warlock.eece.unm.edu