A STATUS REPORT ON THE ADVANCED PHOTON SOURCE 2-MW DC RESISTIVE LOAD

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Abstract

The redesign, construction, and high-power testing of a 95-kV, 2-MW DC resistive load has been completed. The load was built and installed for testing of the 352-MHz high-voltage klystron power supplies at the Advanced Photon Source (APS). The original resistive load [1, 2] has been modified to enhance the load performance and operating power range. In this paper we describe the redesign of the DC load, report on recent test results, and discuss performance improvements.

INTRODUCTION

A high-power water-cooled DC resistive load was built and operated at the APS in order to commission power supplies for use with 1-MW klystrons. The power supplies were designed to provide 95 kV with 20-A current, resulting in a full-load power output approaching 2 MW.

The original DC load had been successfully used during initial commissioning of the 2-MW klystron power supplies at the APS. It consisted of a 10-foot-long, 65-inch-diameter cylindrical containment vessel. Twenty-five ceramic composite wire-wound resistors were connected in series where each resistor extended nearly the entire length of the vessel. Each resistor was located within a 6-inch-diameter, NEMA grade, G11 glass-cloth reinforced epoxy tube that was cooled using deionized water. The entire resistor assembly was supported by a framework of G11.

Due to leakage current into the deionized cooling water, the effective impedance of the resistive network was reduced below its design specification. Due to the klystron power supply current limitation of 20 A, the initial commissioning achieved a maximum voltage of 70 kV. During testing, some evidence of electrical breakdown was noted at voltages greater than 60 kV. Physical inspection showed signs of arcing at the input junction into the resistor network and between resistor elements. Heat build-up was found at locations around the resistive elements and most predominantly at the cooling-water return holes.

Design changes were implemented to increase the performance and reliability of the original load. The voltage across the load was increased to 95 kV at 20 A by reducing leakage current and adjusting the effective impedance. Peak field gradients were minimized by a redesign of the layout of the resistive elements. Substantial improvements were made to the construction and material selection for the resistive elements and the dielectric structures.

* Work supported by the U.S. Department of Energy, Office of Science, Office of Basic Energy Sciences, under Contract No. DE-AC02-06CH11357.

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ELECTROSTATIC SIMULATIONS

The layout of the resistive network for the original design was found to suffer from high electric field gradients and subsequent electrical breakdown during high-power operation. Electric field gradient levels were simulated using the 2-d electrostatic Poisson solver [3]. A simplified geometry of the load was used in the simulation model where the resistive loads were modeled as 2-inch-diameter copper cylinders. Each resistor was assigned a constant potential relative to ground with a 4 kV voltage difference between successive cylinders.

The arrangement of resistive loads is shown schematically in Fig. 1(a) for the original DC load. In the

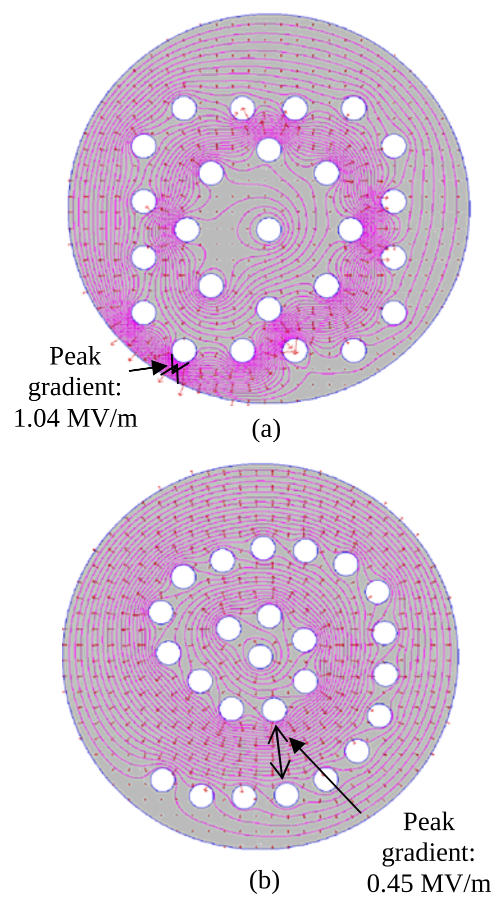

Figure 1: Electrical field contours of the (a) original and (b) redesigned load geometries using Poisson solver. The peak voltage level is 100 kV and is located in the center of each of the designs. A 4-kV voltage drop exists across each resistor, and the outer radius of the containment vessel is assumed to be grounded. A path along which the peak gradient exists is shown for each of the load designs.

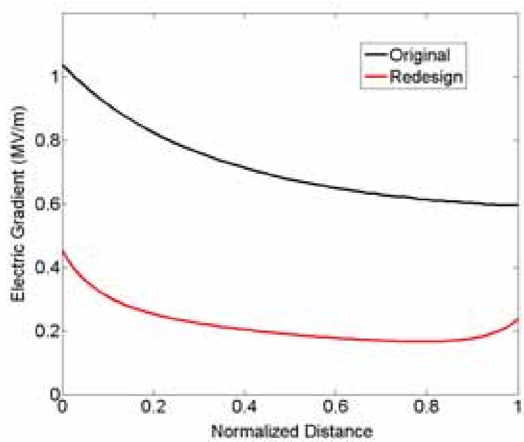

Figure 2: Electric field gradient through the peak electric field paths of the original and redesigned loads shown in Fig. 1.

figure, the electric field gradient magnitude is proportional to the density of the field contour lines as well as the arrow size. As shown in Fig. 1(a), the peak gradient is located near the wall of the containment vessel. High-field regions are also evident between a number of the resistors.

An alternate arrangement of resistive elements is shown in Fig. 1(b) where the electric field contour lines show more uniform field gradients. A logarithmic spiral, to which the radius path grows exponentially with the angle, was used to locate each resistor since the greatest voltage potential difference exists between resistors in successive loops of the resistive elements (assuming all resistors remain sufficiently distant from the grounded containment vessel). To minimize field gradients, the logarithmic spiral arrangement was optimized by maximizing the distance between each resistor element on the logarithmic spiral path within the containment vessel.

Figure 2 shows the electric field gradient along a path (shown in Fig. 1) through the peak gradient for the original and the redesigned DC loads. The peak gradient for the original and redesigned loads in the simplified 2-d models was 1.04 MV/m and 0.45 MV/m, respectively. These results from the Poisson solver provided the basis for the redesign of the layout of the resistor network.

REDESIGNED LOAD CONSTRUCTION

The redesigned load with resistive network, dielectric structures, and containment vessel is shown in Fig. 3. Based on simulation results, the peak gradient in the load was reduced by a factor of 2.3 due solely to a rearrangement of the resistors. Other modifications concerning the construction process and material selection were also critical in maintaining a reduced gradient and improving performance.

NEMA-grade G10 glass-cloth reinforced epoxy and GPO-3 glass-mat reinforced polyester dielectric material were chosen because of their improved dielectric and mechanical strength as compared with G11 used in the original design. During construction, the mechanical assembly was evaluated in order to prevent or reduce field enhancement and poor mating surfaces in high-field regions.

Figure 3: Internal view of the redesigned load with the resistor network and dielectric structures.

Figure 4 shows details of the resistor assembly including a resistor core support and an end-core support. The resistor wire was wrapped around the resistor core, which was supported within the cooling tubes at each end and at the center of the resistor span by G-10 core supports. The resistor core was composed of three layers of 1/8-inch-thick GPO-3 plate bonded together using an aluminum oxide hydrate epoxy. The cooling tubes were constructed of G10 with a 6-inch outer diameter and 0.75-inch-thick wall. They were supported with three 0.75-inch-thich sheets of G10 at each end.

In order to account for approximately 15% leakage current through the water to the grounded containment vessel, the total series resistance of the 25 resistor network was increased from 4.75 kΩ in the original design to 5.5 kΩ. Each resistor was built as a single wire-wound element with an impedance of 220 Ω using 25 AWG iron-chromium-aluminum alloy wire with a unit resistance of 2.24 Ω/ft. The resistors were installed with

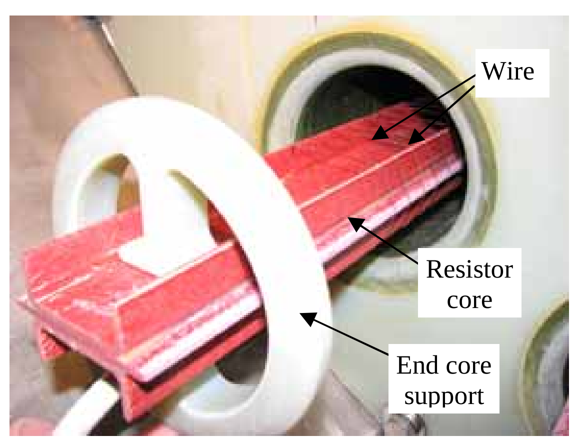

Figure 4: Resistor assembly with GPO-3 resistor core and G10 end core support.

alternating reversed windings to minimize the effects of undesirable inductance.

TEST SETUP

A deionized water test chamber was constructed to ensure that the current handling capability of the 25 AWG iron-chromium-aluminum alloy resistor wire was in excess of 20 A. To demonstrate this capability, a length of wire was wrapped around the resistor core material with an additional length suspended at the connection junction in a similar arrangement to the actual resistors. With 25 gpm of deionized cooling water, the wire was successfully tested up to 22 A.

For the high-power DC load test, a PLC-based safety interlock and data acquisition system was used for personnel and machine protection and for data monitoring. Standard metering was used including the monitoring of the resistivity of the deionized water in order to detect excessive leakage current through the water. Interlock protection included the arcing of internal components and over-temperature conditions.

TEST RESULTS

The total measured resistance of the installed 25 series resistors was 5515 Ohms or within 0.3% of specifications. Initial measurements of the deionized water produced a resistivity of approximately 9.5 MΩ/cm at 22.5^{o}C.

No internal arcing was recorded during testing; however, the testing was limited to 88 kV at 18.7 A due to a water flow limitation of 460 gpm. The water flow was progressively increased to 460 gpm as the input DC power was increased in order to ensure that the exiting deionized water resistivity did not fall below 7 MΩ/cm. Calorimetric power readings verified that the resistive load dissipated approximately 1.65 MW at peak power conditions. The klystron power supply operated the redesigned load in excess of 30 hours until the output de-ionized water resistivity became entropic. The supply current versus return-line current showed that 15.2% of the load current was shunted past the resistive load into the ground, as expected.

After testing, the pressure vessel was disassembled and inspected for electrical breakdown and heating damage. The load performed well, with limited signs of stress on its internal components. There was some visual evidence of electrical damage on the insulation of the silicone lead wires connecting individual resistors; see Figure 5. This was not entirely unexpected since it was rated for a maximum operating voltage of 60 kV, while the actual operating voltage reached 85 kV. Other signs of stress were evident along the dielectric-to-dielectric interfaces where small areas of imperfect contact could result in areas of large field gradient.

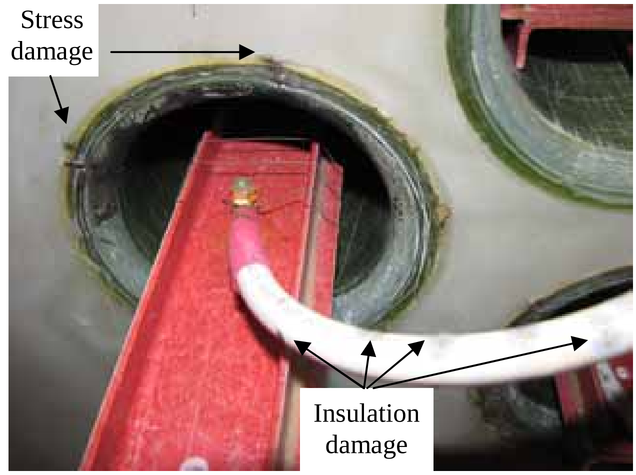

Figure 5: Electrical damage on silicone-insulated lead and stress damage at dielectric-to-dielectric interface.

CONCLUSION

A 2-MW high-power DC load has been redesigned and tested at the APS. A modified layout, material selection, and assembly process have been shown to substantially improve the performance of the DC load. The layout of the 25-resistor network was designed with a logarithmic spiral and has reduced the peak electric field gradients within the load by more than a factor of two based on simulation results. The internal construction and material selection of the resistive elements and dielectric supporting and cooling structures have been modified to reduce regions of field enhancement, reduce the local thermal load, and improve the high-voltage performance of the load.

ACKNOWLEDGMENTS

We would like to thank the RF Group and Mechanical Operations and Maintenance Group technician support personnel for their efforts in prototype testing and construction of the load, including M. Drackley, D. Meyer, and M. Moser for their efforts in the load operation.

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[3] Poisson / Superfish group of codes c/o Los Alamos National Laboratory.