A High Power Water Cooled Resistor For the High Voltage Power Supply in the TRIUMF RF System

K. Jensen, G. Blaker, R. Kuramoto
TRIUMF, Vancouver, B.C., Canada V6T 2A3

Abstract

The Triumf RF system high voltage power supply requires 0.5 ohm current limiting resistors to protect amplifier components during transients and crowbar operations. The crowbar typically causes a 16,000 amp transient pulse, followed by a 4,000 amp current for 55 ms until the circuit breaker opens. The resulting stresses produced catastrophic failure of the original design within 100 crowbar cycles. A new resistor design has been developed to improve heat transfer characteristics and reduce current densities. Design changes were evaluated during extensive testing of a full scale model. The test results are reported with the resulting design described in detail.

I. INTRODUCTION

Continental Electronics supplied the high voltage power supply for the main cyclotron RF system with four water-cooled resistors in its circuit. The resistors are used as current limiting devices, and serve to protect other power supply components and the power amplifiers from current transients. This circuit is shown in Figure 1. R10 limits the current that charges the capacitor banks after the initial charging period when energizing the power supply. R58 and R59 act as current limiting devices for the amplifiers, as well as limiting the crowbar current through the ignitron tube. R60 does not see any crowbar current, and simply limits current to the amplifiers.

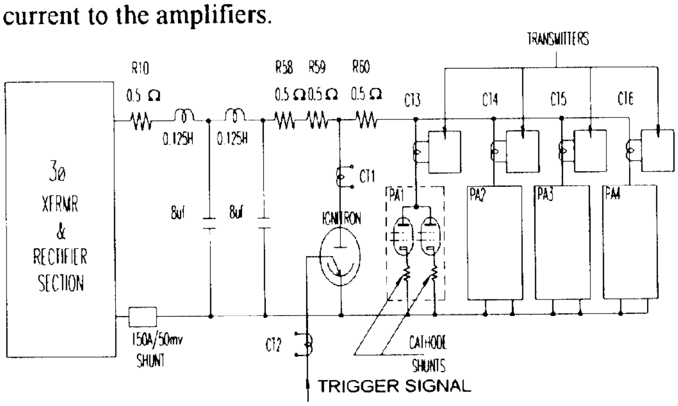

Figure 1. Simplified Schematic of Power Supply

The resistors were supplied as Nichrome wire wound on an epoxy glass G10 core. Bifilar winding was used to reduce the inductance of the 200 in. long wire used. The wound core measures 22.75 in. long and is housed inside a 3.0 in. dia. pipe. Water was supplied to the resistors via 1 inch flexible plastic hoses at 17 USG PM and 55 psig, with the water connections in series.

The power supply operates at a nominal 20 kV. and draws 65 amps. In this state each resistor must dissipate 2.1 kW continuously. During a crowbar event the power dissipation spikes to 128 MW per resistor, then settles back to 8 MW for 55 ms. before ramping down. Figure 2 shows an oscilloscope trace of the peak output current during a crowbar. Figure 3 shows the output current for the duration of the 55 ms until the circuit breaker opens. This type of operation puts extreme stress on the power supply components and has resulted in numerous failures. Crowbars occur on an average of ten per month with resistor failure recorded in as little as two crowbars.

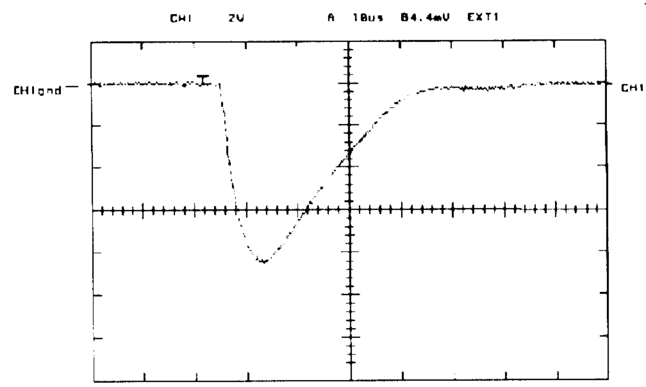

Figure 2. Peak current during a crowbar.
Calibration is -0.00052 V/A

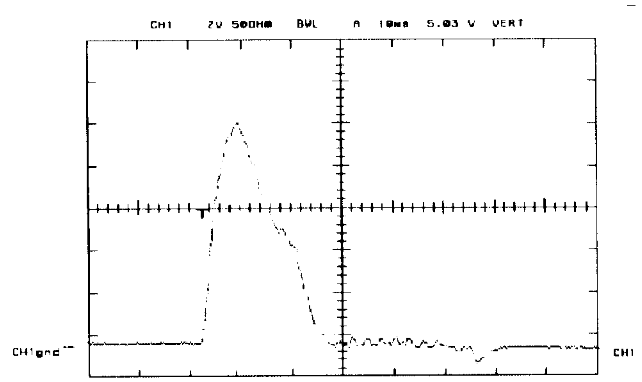

Figure 3. Power supply current for duration of crowbar.
Calibration is 0.005 V/A

There are no cases of resistor failure not associated with a crowbar event. However, the crowbar current limiting resistors were not the only ones to fail. The resistor limiting current to the capacitor banks, R10, often failed in dramatic fashion.

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II. HISTORY

There were two distinctly different forms of resistor failure exhibited, passive failure where the winding simply melted to produce an open circuit, and catastrophic failure where the resistor exploded. The passive failure could be attributed to overloading of the resistive wire or insufficient cooling. There is no evidence to indicate if the effect developed gradually or rapidly.

The catastrophic failure was clearly a case of instantaneous pressure surge. The one inch thick PVC flange would often shatter while the flexible line 4 inches away would remain intact. The pressure relief valve located 12 inches away and set to 125 psi. never tripped yet the force to break the PVC flange required an internal pressure of 2000 psi. Thus the event that would cause the resistor housing to explode must have been a dynamic blast, possibly caused by instantaneous boiling of cooling water into superheated steam. The effects of this blast were absorbed within a very localized area. This would account for explosive failure of stronger materials while adjacent, weaker materials did not even yield.

In the 12 month period before the new design was implemented there were seven resistor failures recorded. This accounted for approximately 22 hours of lost beam time which was 13% of the RF total for the year.

III. HEAT GENERATION

Investigation of the failures included a reconstruction of a shattered housing to determine the location of the center of the explosion. This confirmed our suspicions that the source of the problem was the termination point where the core winding was connected to the terminal plate. The joint consists of two sections of Nichrome wire, approximately .080" dia. , wrapped under the head of a bolt which compresses the wire against a copper conductor. The conductor is attached to the terminal plate by a small copper angle . The terminal plate consists of a 0.250" thick copper plate with cutouts for coolant flow.

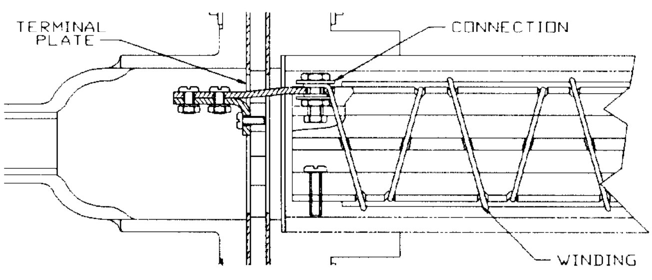

Figure 4. Original Resistor Design

The connection problems are related to current density. With peak currents reaching 16,000 amp. the contact area proved to be insufficient. The maximum contact area with a single wrap of wire under the head of a 1/4-20 NC bolt is estimated to be .100 to .150 square inches. The corresponding peak current distribution is 160,000 amps per square inch, assuming maximum contact has been achieved.

The exact effect these conditions produce is difficult if not impossible to predict. However, what is clear to see is the wire melted at the connections and the core scorched where the wire has been burned away when a resistor fails. A new connection method was required. Previous efforts to form a fused connection with various soldering techniques had met with failure. This combined with concerns about altering the wire's characteristics with the application of heat and a desire to keep assembly and repair as simple as possible produced a design requirement that the connection maintain a clamped configuration.

Several different connection techniques were evaluated with consideration given to area of contact, ease of manufacture and assembly. The new design is referred to as the connection pod. It resembles a one inch diameter copper bullet with two inches of each wire inlaid at the center. This provides four to five times more surface area for electrical contact and a more predictable path of current flow. In the old design there was a potential for one wire to carry the current of both, resulting in overload and failure.

IV. HEAT TRANSFER

In the heat generation analysis we found the nut and bolt connection to be the main problem source. The method provided inconsistent electrical contact area at the bolt, but its major drawback was the poor coolant flow around the joint. Figure 5 shows how the flow is divided into six passages by the core fins. Entrance to these passages is impeded by the stems of the copper terminal plate.

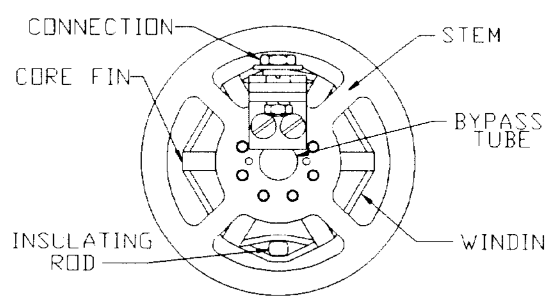

Figure 5. Coolant Passages in old design

The critical passage contains the wire connections which produce the highest temperatures. It also is one of two passages where the bifilar windings cross. This not only concentrates the heat sources but the windings are separated with an insulating rod which further restricts coolant flow.

Another complication comes in the form of stand offs which center the core within the housing. Two of these are located in the critical passage. Thus we have a design with the major sources of heat combined in a passage with all of the restrictions to flow.

One last complication comes from the fact that the center of the winding core was designed to provide a bypass tube to allow some of the coolant to miss the resistor windings. This was done because the resistor's coolant flows in series and the designers presumably were trying to ensure a good supply of fresh coolant reached the downstream resistors. This bypass may work too well at providing a low resistance route for the water. It is estimated that a mere eight percent of the coolant actually passes through the critical passage. That translates into less than 1.5 USG PM. flow of a fluid corrupted by cavitation and stagnant sections. The best flow occurs in the passages that only have to cool the windings, not the connections. These three passages receive 16 USG PM.

Connector designs were evaluated for restriction to flow, generation of turbulence, cavitation and even distribution of coolant in an effort to maximize heat transfer capability. Since there is a connection at both ends of the resistor the design must flow well in both directions. The result was a series of design changes including;

- Removing the connection from within the resistor body.
- Blocking the central bypass tube.
- Reducing winding support fins from 1/4" to 1/8" thick.
- Eliminating the winding separator rods.
- Eliminating the core stand offs.
- Reducing the number of stems on the copper terminal plate from six to two.
- Aligning the remaining stems with the core fins.
- Reducing the winding diameter to increase the clearance from resistor wall.

The final design is shown in figures 6 and 7.

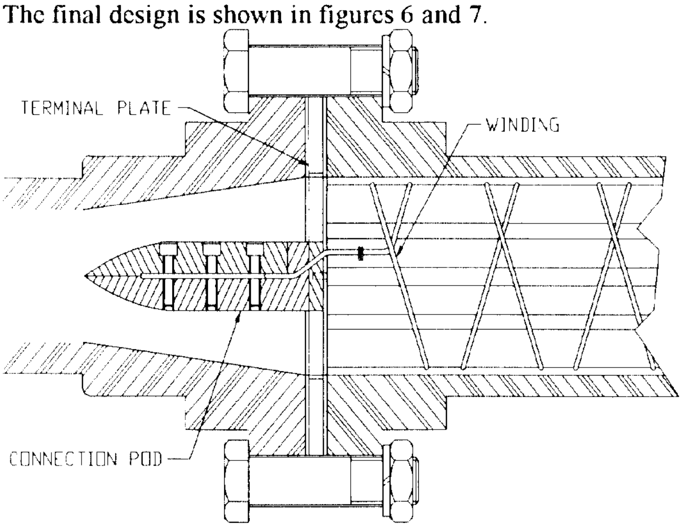

Figure 6. New Resistor Design

The final bullet shape of the connecting pod was found to produce the least disturbance in the coolant flow, resulting in an even flow with no stagnant sections. It provides a substantial thermal mass to absorb surges and distribute the heat flux, thereby reducing surface temperatures. The resulting large surface area greatly improves heat transfer to the coolant, further reducing temperatures.

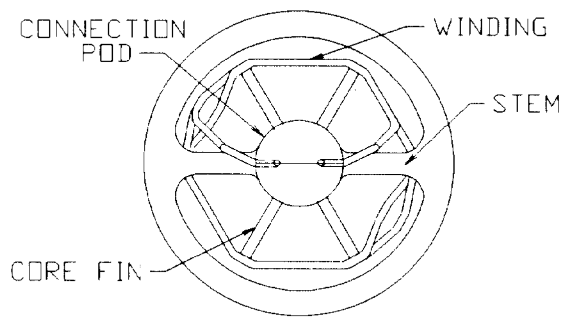

Figure 7. Coolant Passages in new design

The pod is split at the centerline and clamped with three fasteners. This provides simple removal and reassembly without solder. The top pod half encloses half of the wire while the remainder is laid in the bottom pod. A great deal of care is required to fit the wires into the pod halves. We were able to limit the pod center gap to a maximum of .0015 inch on assembly. Several techniques to eliminate the gap were tested including using a displaceable soft metal filler such as Indium. We found that the small improvement they offered did not justify the additional complication. The carefully fitted wire and pod connector suits the design requirements of good contact and ease of reassembly.

With these changes we eliminated the resistor as the limiting factor in the heat transfer equation. The resistors will now flow all of the water that the system can supply. The one inch supply line was upgraded to two inches which, when limited to 10 ft/sec to avoid cavitation, offers a supply potential of 98 USG PM. The flow to the resistors is regulated to 90 USG PM. at 65 psi.

The new resistor is capable of absorbing large power surges by distributing the effects over a large volume and removing the resulting heat with high efficiency and capacity. Under steady state conditions the cooling system keeps the resistor at the water supply temperature. When a crowbar occurs local temperatures will rise but they will be kept below destructive levels and quickly returned to the supply temperature. The oversized cooling capacity will also eliminate the possibility of gradual overheating and resultant deterioration of the nichrome wire during steady state operation. We have also virtually eliminated air pockets, bubbles and cavitation in the resistors to remove the explosive potential .

In the seven months since the new resistors were installed there have been approximately 90 crowbars with no resistor failures or related RF down time.

V. ACKNOWLEDGMENT

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