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Author(s): Floyd R. Gallegos
Michael J. Hall

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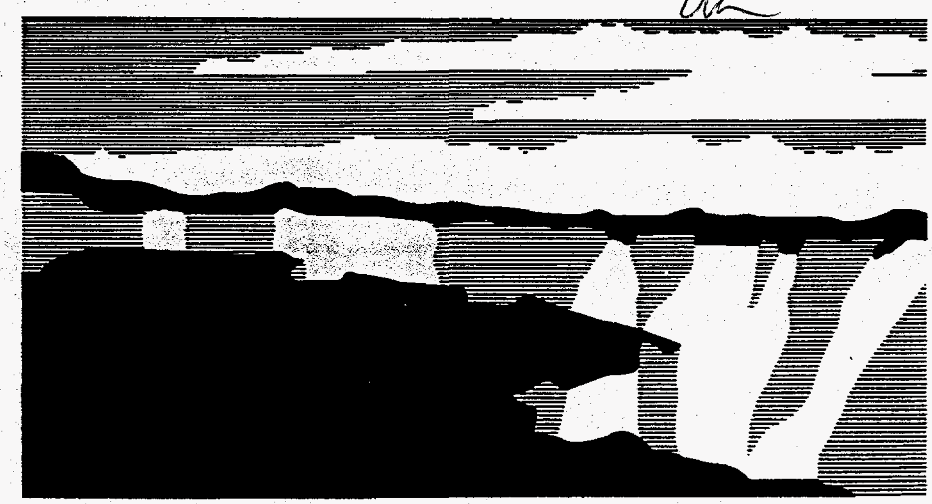

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LANSCE Beam Current Limiter (XL) *

Floyd R. Gallegos, Michael J. Hall
Los Alamos Neutron Science Center,
Los Alamos National Laboratory,
Los Alamos, NM 87545 USA

Abstract

The Radiation Security System (RSS) at the Los Alamos Neutron Science Center (LANSCE) is an engineered safety system that provides personnel protection from prompt radiation due to accelerated proton beams.

The Beam Current Limiter (XL), as an active component of the RSS, limits the maximum average current in a beamline, thus minimizing the current available for a beam spill accident. Exceeding the pre-set limit initiates action by the RSS to mitigate the hazard (insertion of beam stoppers in the low energy beam transport).

The beam limiter is an electrically isolated, toroidal transformer and associated electronics. The device was designed to continuously monitor beamline currents independent of any external timing. Fail-safe operation was a prime consideration in its development. Fail-safe operation is defined as functioning as intended (due to redundant circuitry), functioning with a more sensitive fault threshold, or generating a fault condition.

This report describes the design philosophy, hardware implementation, operation, and limitations of the device.

Introduction

The Los Alamos Neutron Scattering Center (LANSCE) operates two pulsed beam injectors and a linear accelerator, generating H+ and H- ion beams (typically 1 mA and 70 μA average respectively) over energy ranges of 113 to 800 MeV. Each injector is capable of variable pulse widths (typically 800 us) and repetition rates (maximum frequency of 120 Hz). Beam duty factors are limited to approximately 10%, but can be varied according to the needs of the experimental programs. Accelerated ion beams are delivered to four experimental areas.

The Beam Current Limiter (XL) was designed to be an integral part of an instrumentation-based, engineered personnel protection system at LANSCE. Other components of the Radiation Security System (RSS) include the personnel access control systems (PACS), fail-safe ion chamber systems (GD), safety system logic and wiring, and safety system beam transmission mitigation devices (beam plugs or stoppers). Testing, verification, and configuration control of these systems are essential requirements for safe accelerator facility operation.

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As part of a limited-scope probabilistic safety analysis of selected safety systems at LANSCE, the device underwent a reliability analysis by an experienced team of Los Alamos National Laboratory safety analysts. The analysis provided estimates of system unavailability (ratio of average downtime to uptime in the interval between testing) of 3.7×10^{-3} with an estimated error factor of 2.2. Annual testing and operation for half a year per year were assumed (1, 2).

Design Philosophy

The XL provides fail-safe beam current limiting protection. "Fail-safe" is defined as functioning as specified, or if a single failure occurs the device will 1) function as intended (due to the redundant circuitry), 2) function with a more sensitive fault threshold, or 3) generate a fault condition.

The device specifications and design requirements are listed below. Refer to Fig. 1 for functional block information.

Specifications

Current detection must be non-intercepting and bipolar. The device is a current transformer with a signal winding, self-test winding, and calibrate winding. The calibrate winding provides the ability to inject test signals to verify the trip level settings without removing the XL cover plates. Since the device is located in the accelerator beam tunnel, the calibrate winding provides the ability to remotely test the device to verify proper operation. This allows more frequent testing with minor interruption of ion beam availability.

The XL must detect average current with an input peak beam current up to 20 mA. The circuitry is designed such that an input of 20 mA peak current will not saturate the input amplifiers (10 volts) and they will respond linearly. Higher peak currents are attainable by adjusting the gain of the current to voltage amplifier circuitry. The maximum detectable peak current is limited by the magnetic saturation of the toroid.

The trip setpoint must be adjustable to address the maximum beam spill concerns of various experimental areas. Average current trip level setpoint adjustment (1, 3, 10, 30, 100, 150, 300 μA) is made by physically changing the filter rectifier and amplifier setpoint printed circuit boards. An interlock chain is incorporated to prevent insertion of the incorrect printed circuit board combination. The cards and connectors are physically keyed to ensure insertion into the proper connector slot.

The device must trip within 10% of the desired setpoint. To achieve required trip tolerances, grounding of the device is critical. An internal electrical isolation joint is incorporated to prevent signal interference by currents which would flow through the XL via the beam pipe. Multiple layers of EM shielding are incorporated into the XL design to reduce the effect of noise.

The time to initiate a 3 μA trip with an average beam current of 1.2 mA must be equal or less than 25 msec. The overall circuit time constant is approximately five seconds. The circuit time constant equation can be approximated by (assuming the current to voltage conversion is linear):

$$i_{trip} = i_{final}(1-e^{-\text{trip time/time constant}})$$

$$\text{trip time} = -\ln[1-(i_{trip}/i_{final})]*\text{time constant}$$

It has been demonstrated that two 10 mA peak, 1 msec pulses 8.33 msec apart (120 Hz, 1.2 mA average) will cause a fault condition (3 μA trip) within 22 msec. Therefore three beam pulses will pass prior to the initiation of a fault condition. Experimental operations required that the circuitry be designed to permit a single 10 mA peak, 1 msec wide pulse to pass without causing a fault condition.

The XL must be self-contained and essentially isolated. The device is only dependent on incoming AC power for its operation. Trip information supplied by the unit is electrically isolated from internal circuitry and power supply. The introduction of external effects such as electrical loading or problems due to operator error are minimized. External cabling consists of the AC power cable, two armored cables which transmit the XL fault state to the RSS logic, and a remote test calibrate cable.

It must be active at all times (no dead-time). The XL is an AC-coupled device with full-wave rectification. As such it does not require a means of DC restoration to determine average current levels. Monitoring is active at all times and will provide protection regardless of the beam timing. External timing gates are not required for proper operation.

Fail-safe operation is critical. The XL was designed to be as fail-safe as practical (limited by information available on component failure modes). In the design of the XL, an attempt was made to ensure that the unit would fail in a condition that would not compromise the safe operation of the accelerator. Certain parameters are monitored within the unit such that if an out-of-tolerance condition is detected, the XL will fault. The various design schemes used are as follows:

a) Asynchronous test signal generation for self checking of circuitry and toroid connectivity --- Self checking pulses are generated in the XL. These pulses are directed along two paths. One set of pulses is sent directly through circuitry on the filter-rectifier card. The other set of pulses goes through the toroid via a test winding. Current due to the pulses is induced on the signal winding and processed in the filter-rectifier card. The voltages due to the currents from these two paths are filtered and compared. If they are identical, the effect is canceled. If they are different in magnitude or phase, an output is generated and rectified. This output is an error signal. If the signal wiring or test wiring was disconnected, the error would be sufficient to cause a fault of the unit. Thus, the unit fails safe. If there was a problem with the gains of the signal path or the test path, the error generated would effectively reduce the trip setpoint since the error would manifest itself as a current level that is always present.

b) Full-wave rectification --- By full-wave rectifying, an absolute error is generated thus eliminating the possibility of cancellation of error signals due to opposite polarities. For example if bipolar noise is introduced into the system both polarity components would manifest themselves (additive) as a current offset level that is always present.

c) Self-test signal --- To ensure that the self-test signal is present, the signal is full-wave rectified and used to generate a reference level that is summed with the error signal output. If the reference level is not present, the XL will fault since it is outside the trip band.

d) Power Monitoring --- The power supply voltages are monitored by self-check circuitry. The power supply voltages (±15 volts) are used to generate the current pulses directed to the test winding. The voltages used to generate the current pulses sent to the self-check circuitry are derived from ±2.5 volt reference diodes. If the power supply voltages drift from their required values, an error signal is generated since cancellation is not achieved in the filter-rectifier card. The components used by the XL are commercial. The reliability of their electrical characteristics is decreased if stated absolute maximum ratings are exceeded or if values fall below minimum ratings. The power supply voltages are internally monitored by additional circuitry to ensure that maintenance personnel are aware that the voltages remain greater than 12 volts and less than 18 volts; otherwise the XL will fault.

e) Redundant circuitry --- Certain sections of the XL circuitry are not easily checked using a self-test method. Where self checking of the circuitry cannot be performed, redundant fault channel circuitry has been added. Redundant fault outputs (relay contacts) are supplied to the RSS.

f) Complete loss of power --- On a complete loss of power, the two redundant fault contacts will open.

g) Interlocking --- The system has been designed with an interlock chain incorporated on the printed circuit board. If the proper combination of printed circuit cards is not inserted in the correct card locations, the unit will fault. The printed circuit cards are also keyed to prevent insertion into the incorrect slot.

Device Description

The XL is 18 in. high by 17.5 in. wide and 14 in. long (beam axis). The current transformer consists of a 2 mil tape-wound supermalloy toroid, 10 in. O.D., 5 in. I.D., and 1 in. length. It is wound with a 100 turn copper signal winding and two single turn (calibrate and self-check) windings. The beam pipe is electrically broken internal to the device to prevent return currents from flowing through the toroid.

The device and power supply are designed to minimize electronic and acoustic noise pickup. The processing and fault generating electronics are contained within the unit chassis to minimize noise introduction. The power supply is externally mounted. Single point grounding concepts in circuit and shielding implementation are used to reduce introduction of noise. See Fig. 2 and Fig. 3.

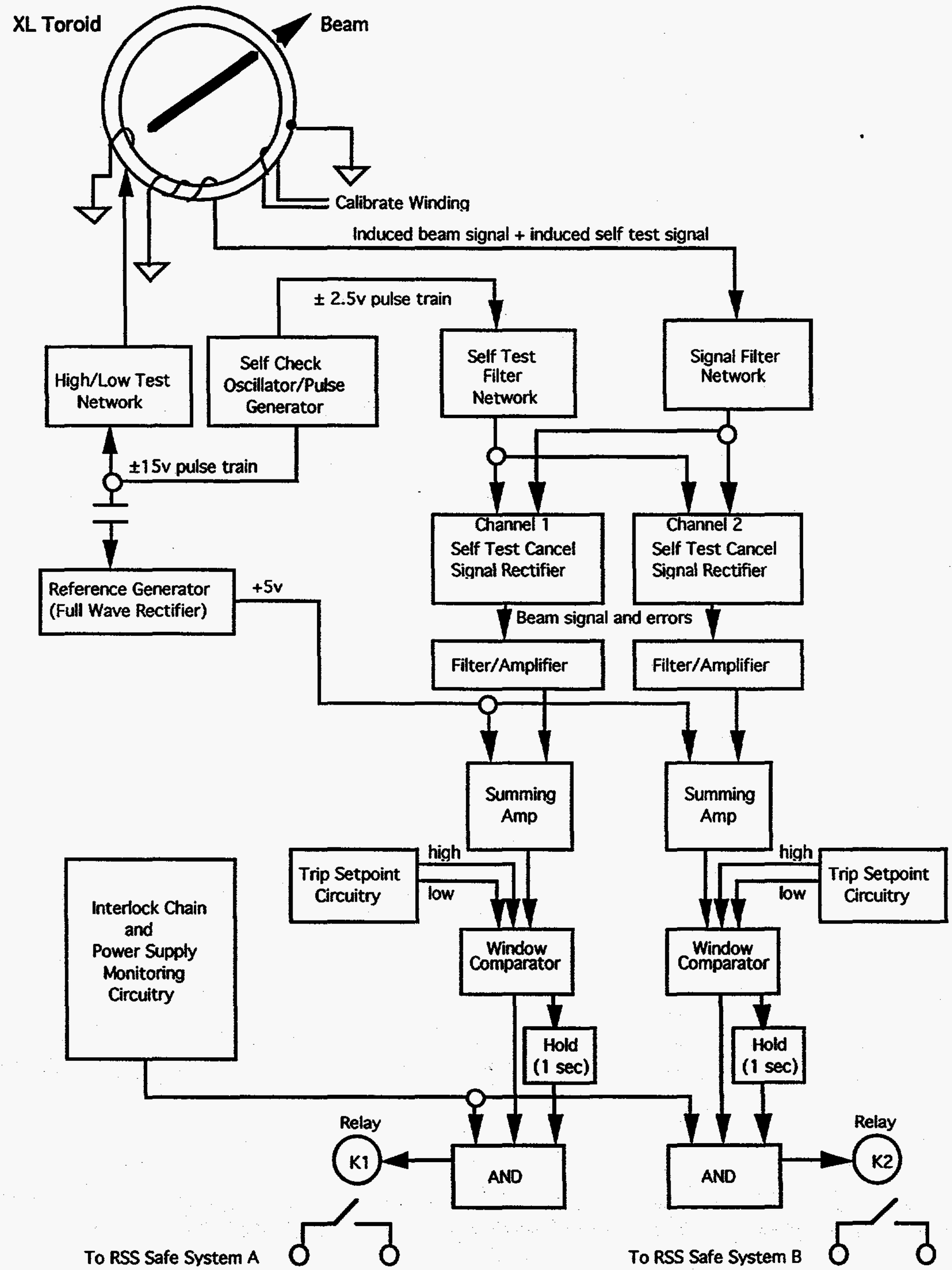

FIGURE 1. Functional Block Diagram of the LANSCE Beam Current Limiter (XL).

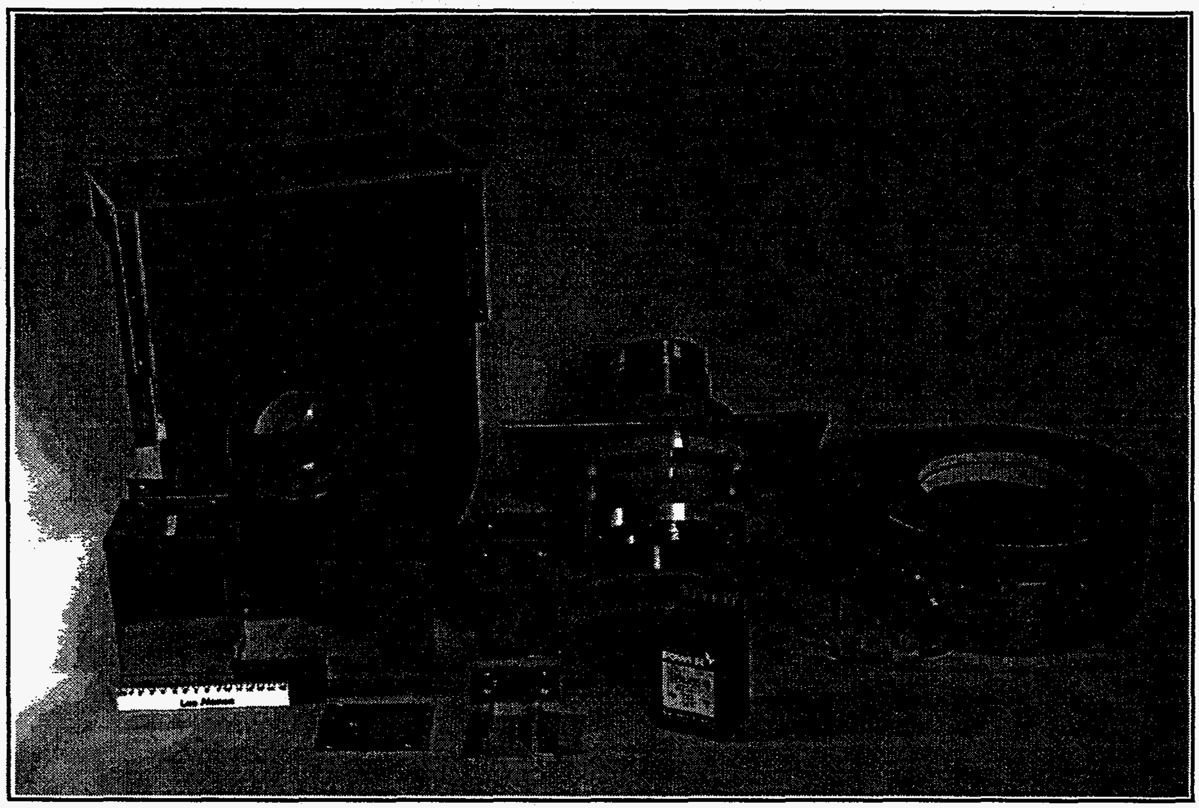

FIGURE 2. Unassembled Current Limiter hardware: Clockwise from top left of photo; outer casing and beam pipe, current transformer with multiple layers of shielding, and power supply and multiple shielding casings.

Operation

The XL requires periodic checkout and operational verification. Procedures for checkout, maintenance, and configuration control are strictly followed. Formal review by the LANSCE Operations Safety Committee is required for system modification.

The unit will trip and remain faulted only as long as the fault condition exists. Latching of the fault is accomplished in the external RSS logic. Since it is located in the beam line, access to the XL during beam operations is restricted. Diagnostic indication, test points, and switches are located on the top panel of the XL. Light emitting diodes are illuminated to indicate the fault condition, the trip level setpoint, and the condition of the DC power. To verify proper fault operation of the unit, two test switches (high/low) are used to increase or reduce the magnitude of the pulses directed to the self-test winding. The test points can be used to determine the power supply voltage levels.

Remote test signal injection capability via the calibrate winding has recently been added. This allows frequent testing of the fault capability without requiring access to the beam line. A documented check of XL and RSS operability is performed weekly during accelerator beam production.

There are six installed units and one test unit. Four provide protection for the neutron spallation target areas. Two additional units are installed on the beam line to another LANSCE experimental area.

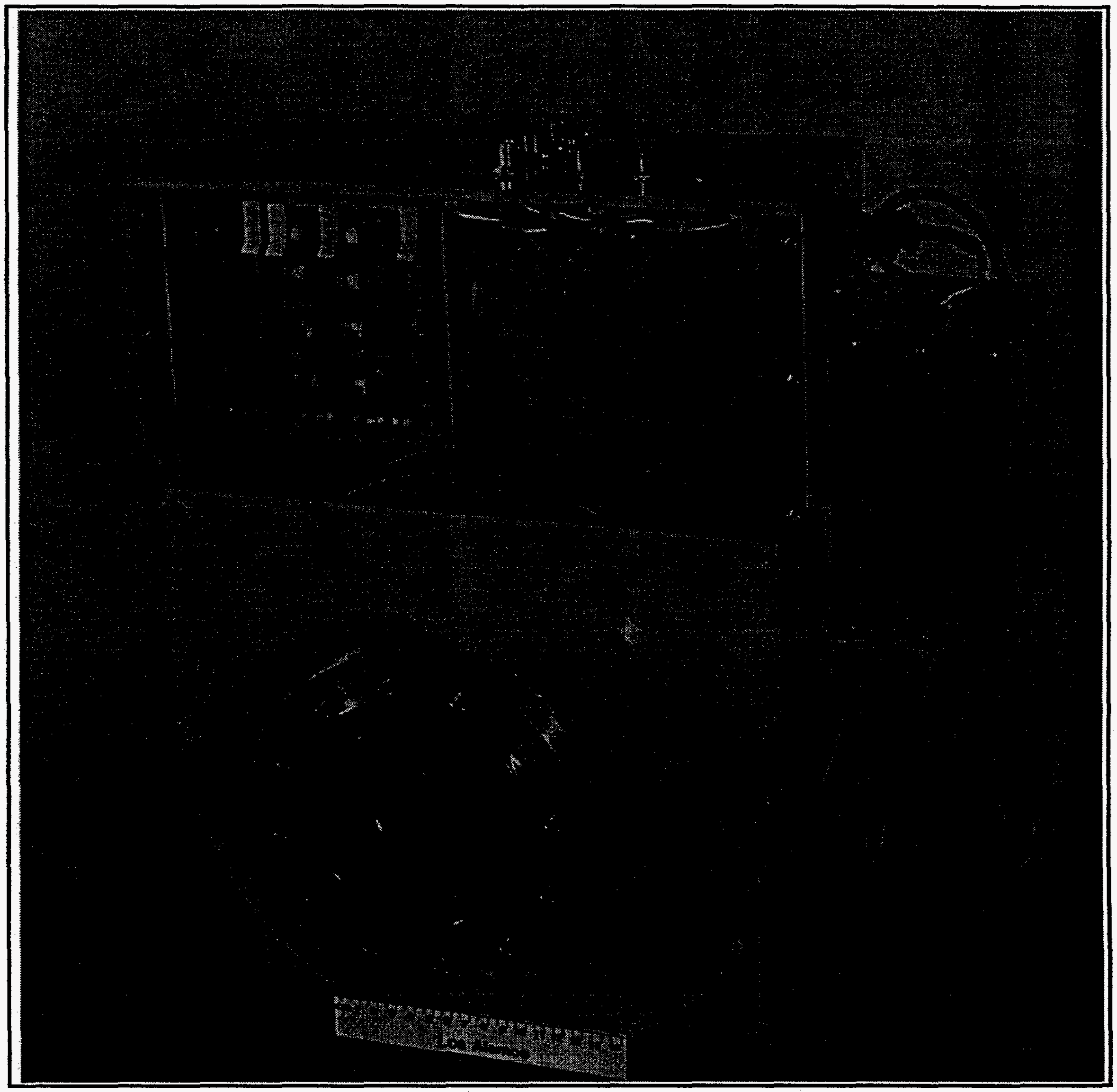

FIGURE 3. Front view of Current Limiter with cover plates removed: Card cage with associated printed circuit boards, mounted power supply, and outer hardware casing.

Vulnerabilities

The XL is an AC device. The location of the XL must be selected such that pulsed beams of opposite polarity are not simultaneously present or signal cancellation will occur. The XL is also ineffective with neutral beams.

Internal electronics are susceptible to radiation damage. Since the electronics must be located as close as possible to the current transformer to minimize noise effects, they are exposed to ionizing radiation fields. This may cause the XL to fail due to radiation damage to the solid-state electronics. Location of the XL with this constraint in mind is critical.

Recently we have experienced a number of failures due to what is believed to be radiation damage of an FET and the subsequent increase in its leakage current. The component has been replaced with a bipolar junction transistor which is less susceptible to damage. The circuitry is presently undergoing in-situ testing.

Investigation will continue into locating the electronics in a more accessible area (low radiation). This is not a simple task. Background electronic noise levels add to the trip setpoint offset and thus affect the accuracy of the device.

Signal levels induced by prompt radiation. During the 1990 operating period the average current delivered to the primary neutron scattering target was significantly increased. An XL which was located on a beam line adjacent to the Proton Storage Ring (beam compressor) extraction line faulted when exposed to a large radiation pulse produced by beam spill from the occasional misfiring of the ring extraction kickers. An identical device placed upstream, shielded from the extraction line, did not exhibit the coupling phenomena.

Summary

Current Limiters have been in service since 1989 with satisfactory results. All failures (seven) were fail-safe in nature. The first failure was due to radiation damage to the XL electronics since the device was located in immediate proximity to a beam stop. The components were highly activated and post-mortem analysis was not possible. One failure was due to failure of a integrated circuit comparator. The other five failures (single leg of redundant circuitry) were due to component failure of a FET controlled relay. The FET developed leakage current that was sufficient to maintain an energized relay regardless of the FET input state. This failure has been addressed by redesigning the circuitry with robust components.

XL's have demonstrated high reliability and exhibited their ability, as part of the safety system, to provide effective protection from exceeding the operating envelope.

Acknowledgments

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