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Use of Fusible Beam Plugs for Accident Mitigation at the LANSCE Complex

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Abstract

The LANSCE accelerator relies on a Radiation Security System to provide personnel protection from prompt beam-induced radiation. System faults inhibit beam generation in ion sources until areas are made safe by the automatic insertion of beam plugs (stoppers) for the affected area. Should system failures occur, final protection is provided by reliably-engineered, redundant fusible beam plugs which can intercept the beam at the accelerator injection energy of 0.750 MeV. These plugs auto-insert on faults of the Radiation Security System, and remain in until the fault clears. They are normally protected by systems designed to shut off or intercept the full-power beam. In the event of failure of these systems, the beam incident on the stainless-steel surface of the plug will cause the layer of steel to vaporize and open the beam-line to an atmospheric air passage that results in a portion of the accelerator losing vacuum. The low energy beam cannot propagate through air, thus ensuring personnel safety.

Introduction

Personnel protection from prompt radiation hazards at the LANSCE complex is provided by a Radiation Security System (RSS). This system comprises interlocked access control systems as well as active instrumentation such as current limiters which fault on detection of excess current and ion chambers which fault on detection of excess beam loss. This relay logic system is fully redundant and each redundant leg controls the insertion of one of two fusible beam plugs in the Low Energy Beam Transport (LEBT) where the beam energy is 0.750 MeV. The RSS provides inputs to other protective systems; the Run Permit system (RP) which defines equipment configuration and status, and the Fast Protect system (FP) which provides rapid beam shut-off (on the order of tens of microseconds) without operator intervention. These latter systems are not rated for the protection of personnel. Should the RSS fault, beam shut-off in the LEBT is accomplished by the RP and FP systems. It is therefore necessary that the RSS provide a safety-rated barrier which would prevent beam acceleration should the beam shut-off systems fail. This safety-rated barrier is provided by the fusible plugs.

Design Considerations

Several factors specific to the LANSCE complex play a role in the selection of the location for the fusible plugs. There are three locations where the proton or H^- beams may be stopped; the LEBT (0.750 MeV), an intermediate beam stop at 211 MeV, and in the beam switchyard after full acceleration to 800 MeV. Ranges in typical intermediate-mass material at these energies are 4.5×10^{-3}, 40, and 350 gm cm^{-2} respectively. Higher energy plugs are necessarily more massive. Actuation of these beam plugs must be as rapid as possible to minimize potential accident consequences. It is therefore desirable to make the plug as light as possible to facilitate rapid actuation. The concept of the "fuse" relies on the introduction of air into the beam transport. The air then prevents propagation of the beam. Air is an effective barrier at 0.750 MeV given the low areal density required to stop the proton beam at this energy; this is not true at the higher energies. As a final consideration, a beam plug in the LEBT effectively prevents acceleration of beams in the accelerator structure, thereby removing an additional layer of complexity.

Given these factors and other specifications for RSS components the following basic design criteria were developed.

- The beam plug body will be made of copper thick enough to stop 0.750 MeV beam with adequate safety margin.
- The fusible surface will be made of stopping-length stainless steel to maximize heat transfer and local temperature rise.
- Two independent air passages will be provided to the fuse cavity between the stainless steel and copper to ensure that the possibility of blockage is minimized.
- Actuator design will permit the most rapid possible insertion.
- Provision will be made for the ability to mechanically lock the plugs in the inserted position.
- The plugs will auto-insert on loss of either drive solenoid electrical power or compressed air.

The design of the beam plug actuators is such that they will fit on standard beam boxes that are used throughout the LANSCE facility. This restricted the flange width and length to 2.25 inches and 5.25 inches. The bellows used on the majority of LANSCE diagnostic actuators is used in this application and is a standard welded bellows available from a number of different manufacturers. OFHC copper was used for the body of the plug because it was going to be hydrogen furnace brazed to stainless steel; stainless steel was used for the fusible window because of strength and low coefficient of thermal conductivity. Two independent air passages are used so that air can be forced through them to prove that the atmospheric cavity is not blocked. Provision was made for locking the beam plugs in their inserted position so that safety to workers or other personnel downstream could be assured. These beam plugs take less than 0.5 second to complete the cycle from full retraction to full insertion. An air cylinder with a cushion must be used to keep the devices from being self destructive. The limit switches that must be used are standard for the RSS in that they are a direct acting switch that will break welded contacts apart. A mechanical drawing of the beam plug assembly is shown in Fig. 1, and a photograph is shown in Fig. 2.

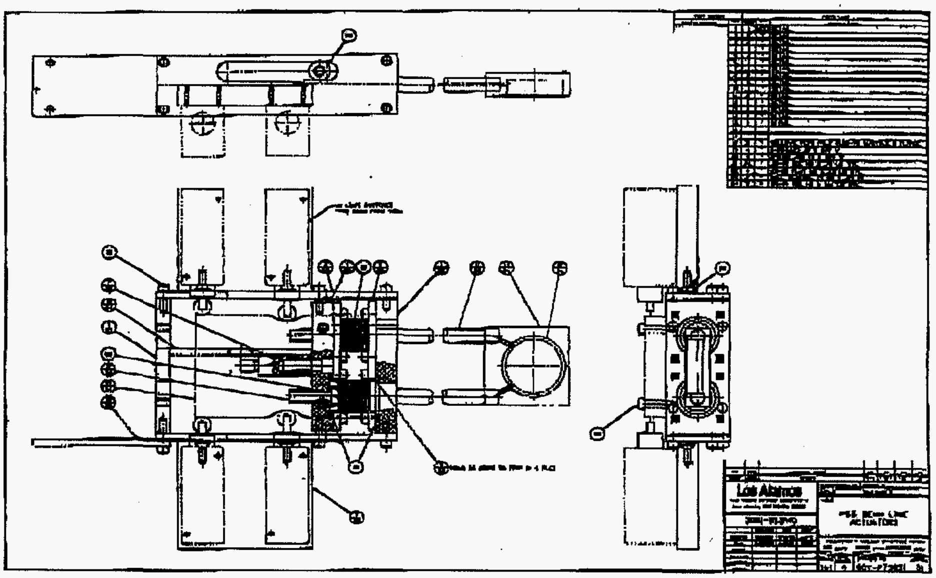

Figure 1: Mechanical drawing of the 0.750 MeV Fusible Beam Plug assembly.

Figure 2: Photograph of the 0.750 MeV Fusible Beam Plug assembly. The plug surface is illuminated on the left hand side of the photograph. Limit switches are visible toward the top, and the actuation air solenoid on the right.

Fabrication

Fabrication of the actuators is fairly simple. Stock sizes of materials were used where possible, and there are very few places close tolerances must be held. The only welds which must be made are those connecting the flanges to the bellows ends. All other seals on the actuators are elastomers. The only thing that must be measured at assembly is the depth the air cylinder shaft threads into the block carrier. This determines the final position of the beam stop block.

The beam stop block itself is fairly simple. The counter-bored holes on the top must be held to close tolerances as this is where the tubes are brazed in to locate the block in the actuator. The tubes that are brazed into the block assembly must be of the same length to within about 0.010 inch as this is what holds the block to the actuator.

All parts of the device are interchangeable so that one set of spare parts can supply all devices in service. One assembled and leak checked device is kept on hand so that if there is a problem with one in service the turnaround time for replacement can be kept as short as possible.

The brazing operation on the block itself is performed in a hydrogen atmosphere furnace. Standard practice is that the brazing be carried out in two separate heats using two different melting point alloys. Parts should be jigged to keep alignment. Holes into the block cavity may have to be filled with graphite to keep brazing alloy from filling when the tubes are brazed into place.

Performance Testing Methodology

Before installation a prototype plug was assembled. Destructive tests were performed to characterize the performance of the fuse under normal operating conditions. Among the questions to be answered by the tests were:

- How fast does the fuse fail in the worst case situation?
- What are the consequences of failure?
- What, if any, damage results to the beam stop itself?
- Does the fuse operate correctly when melting both quickly and slowly?
- Does the molten material "blow out" so that it cannot plug the air inlets?

The tests were made as realistic as possible by locating the prototype where the production models would be placed and by configuring the ion source and LEBT magnet parameters to standard operating values. Two scenarios were investigated. First, the full ion source current was used. Second, the current was limited to 10-20% of the maximum value by insertable jaws. After each test the beam stop was removed, cut apart, examined and photographed.

Performance Testing Results

These devices must actuate in less than 0.5 second, which can stress a number of parts in the assembly and the limit switches must perform reliably. To prove that the device is reliable and durable, a test was done over a long weekend. The actuator was cycled twice a minute from 5:00 p.m. Friday until 8:00 a.m. on Tuesday for over 10,000 cycles. All screws were checked for tightness, the actuator was again leak checked, and the limit switches were checked. All passed the test.

For the destructive tests, the high current test was conducted first. Beam parameters were ~25 mA peak current at a repetition rate of 120 Hz with a gate length of 825 μs. This corresponds to a duty factor of 9.9%, an average current of 2.38 mA and beam power of 1.78 kW. Fuse blowout occurred in ≤ 3 seconds; failure was fast enough that an accurate measure of the time was not obtained. All the vacuum valves in the LEBT closed, but the ion source and Cockcroft-Walton accelerating column vacuum recovered without requiring rough-out. Figure 3 below shows the front face of the stainless steel plate. Figure 4 shows a close-up of the back of the stainless steel plate and the copper surface of the beam plug which forms the other side of the air pocket. Note that there is sign of a little beam impingement on the front surface of the copper beam stop but no material was present on the back of the stainless plate or inside the cavity that could have plugged the air holes. The damage shown in Figure 3 clearly demonstrates that the material clearly "blew out" in the forward direction as intended. Sufficient loss of vacuum occurred such that beam delivery was positively prevented.

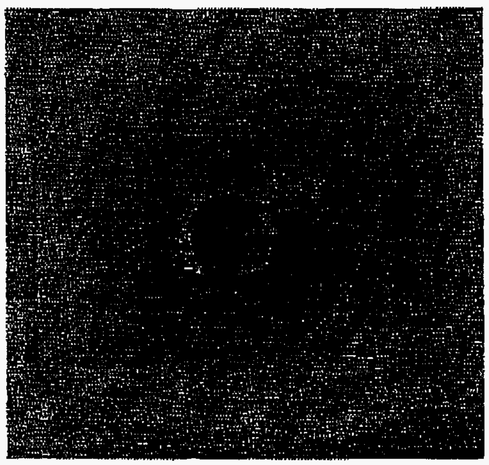

Figure 3: Surface of the stainless steel test fuse after ≤3 seconds of full-power beam impingement.

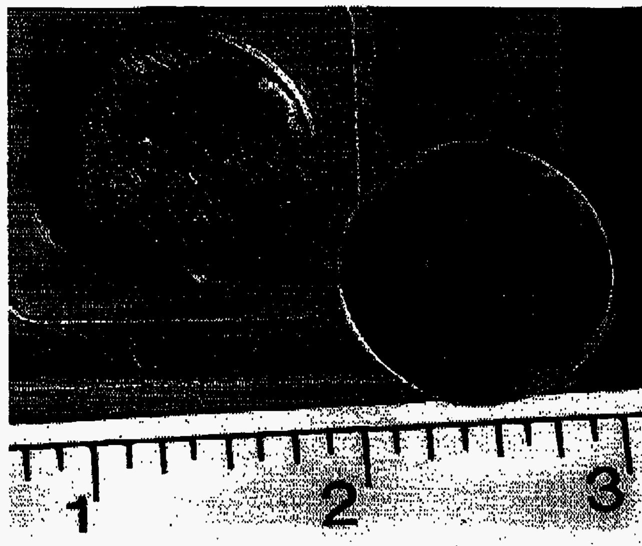

Figure 4: The copper beam stop (left) and the back surface of the stainless steel test fuse after ≤3 seconds of full-power beam impingement.

The low power, slow burn-through test was conducted next. A 1.2 mA peak current 120 Hz beam of pulse length 825 μs was delivered on to the test plug for 15 minutes. This corresponds to an average current of ~120 μA and beam power of 90W. No failure occurred. The beam current was then raised to 2.25 mA peak at the same duty factor for an average current of ~225 μA and beam power of 180W. Failure occurred after an additional 11.5 minutes. Total time to failure was 26.5 minutes. In this case there was no cratering effect. The exit hole through the stainless steel plate is quite small and there was no evidence of beam impingement on the front face of the beam stop. Again the LEBT vacuum system vented, and ion source and accelerating column vacuum were recovered quickly. Sufficient loss of vacuum occurred such that beam delivery was positively prevented. There was no sign of any material behind the stainless steel plate and no compromise of the air passages.

Consequences for Radiation Protection

The use of a dual-function fusible beam plug is designed to prevent inadvertent acceleration of beam when an unsafe condition exists downstream of the LEBT. The beam plug body is sufficiently thick to fully stop a beam of 0.750 MeV protons up to the greatest possible injection current available. Of more concern is the possibility that a burn-through of the copper body could occur at high power levels, resulting in unacceptable acceleration of beam in an unsafe situation. The intent of the fuse is to protect against this possibility. The high-power tests clearly indicate that the fuse will readily terminate a high-power abnormal situation.

The discerning reader will have noted that, at the power level of a few hundred watts, the time to burn through the fuse is quite long. This is not a concern as both the stainless steel fuse and the beam plug body are capable of fully stopping the incident beam. This is evident from the fact that, in the slow burn-through test, there was no visible beam impingement on the downstream copper surface.

Three beams are routinely run in the LEBT; a high-power proton beam of about 1 kW at 6.25% duty, a medium-power H^- ion beam of about 80 W at 1.2% duty factor, and a very-low-power micro-pulse H^- ion beam of about 3 W at 6.25% duty factor. Inadvertent delivery of the 1 kW beam would likely actuate the fuse in ≤ 10 seconds. The medium-power beam would possibly persist for 30 to 60 minutes as this power level is similar to that used for the low-power destructive test. Dependence on duty factor has not been investigated, but, given the low thermal conductivity of stainless steel, is thought not be a significant factor. The very-low-power beam is unlikely to damage the stainless steel surface, and protection is then provided by the stopping-length construction of the beam plug.

Operational History

After the successful prototype tests the production models were fabricated and installed. The units have been in service since April 1993. Prior to the beginning of each operating period the plugs are inspected for evidence of beam impingement, and functional tests are performed to check for air passage blockages and insertion on loss of compressed air and electrical power. If the RP and FP systems work correctly there should be no evidence of beam impingement found. Evidence of

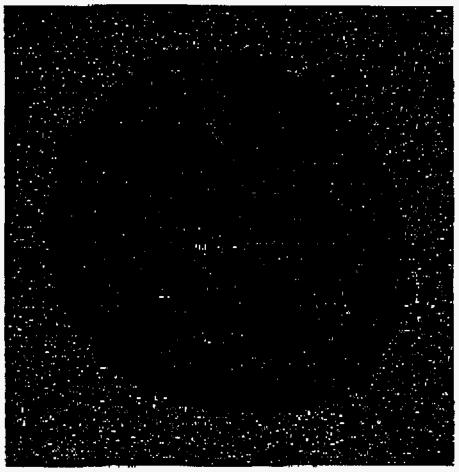

Figure 7: Magnified (x400) photograph of unintended beam impingement on a production plug surface.

beam impingement has been found once. This was attributed to a system fault in which the most downstream plug only was actuated and the fast protect system permitted a very short (~10 μs) burst of beam to strike the plug. This plug did not burn through, but was removed from service. A photograph of the damage (magnification x400) is shown in Figure 7. The granular surface of the stainless steel is clearly evident.

Weekly surveillance tests of plug operation are conducted. The RSS is intentionally faulted and the actuation of the beam plugs is observed in the Central Control Room through limit switch contact indications. The plugs have not failed to actuate. Unplanned actuations (RSS trips) occur with an approximate frequency of 2-3 times each week. Certain special evolutions have resulted in actuation on the order of 20 times a day for 2-3 days. No failure of the vacuum bellows associated with the drive mechanism has occurred.

Summary and Conclusions

The fusible beam plugs have been shown to perform as intended. A high degree of reliable operation has been demonstrated over an operating interval of 3.5 years. Accidental beam impingement has occurred only once in this time, without catastrophic consequences. Routine surveillance validates the operation of these plugs weekly.

In conclusion, the fusible plugs are relied upon as an integral part of the Radiation Security System at the LANSCE complex. There is a high degree of confidence that they will perform as intended should other beam shut-off systems fail to operate properly.

Acknowledgments

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