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TESTS AND DESCRIPTION OF BEAM CONTAINMENT DEVICES AND INSTRUMENTATION — A NEW DIMENSION IN SAFETY PROBLEMS*

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Summary

The destructive capability of the beam power of some accelerators was dramatically demonstrated in a series of tests at SLAC using an 18 GeV e⁻ beam at average powers ranging from 165 to 880 kW. The purpose of the experiments was to examine a series of devices which simulated beam stoppers, protection collimators and burnthrough monitors as presently applied at SLAC. Specific attention was given to the recording of burnthrough times, temperature behavior, and to the analysis of failure modes. A summary of the test data is presented. The design of an extensive electronic system to prevent damage to mechanical devices and to detect onset of destruction is discussed. Various sensors are connected to integrating and peak reading circuits to form power, beam verification and errant beam monitors. Burnthrough monitors shut down the accelerator if damage occurs to critical items. New features such as self-checking, protected wiring and rapid on-line calibration are described.

Introduction

With the continual increase of beam power of the linear accelerator at SLAC from an initial 200 kW to the present day capability of 900 kW there was a corresponding increase of problems associated with the absorption and containment of the beams. Moreover, during this period the number of beam lines operated simultaneously has increased from 1 to 8, resulting in a more complex and flexible control system.

The design of power absorbers, beam detectors and associated electronics, and operating procedure prior to 1971 have been discussed, as have the two independent protection systems, the "personnel protection system" (PPS) and the "machine protection system."[1, 2, 3, 4] The former system is to keep personnel out of areas which have high radiation levels while the accelerator is operating, and the latter system serves to prevent damage to beam line components. A violation in the PPS shuts off the accelerator either by turning off the variable voltage substations (VVS) or by putting stoppers into each major beam line and the accelerator itself, and by delaying all gun triggers to non-beam time. A violation in the machine protection system only delays to non-beam time those gun triggers programmed for the beam line affected.

In late 1970 the question of rate of burnthrough of different materials and beam line components was reexamined in light of the laboratory's continual efforts to achieve and maintain high standards of personnel protection. Within this framework, containment of the primary $e^-/e^+/\gamma$ beams is an essential feature of the personnel protection efforts since a nominal average beam power of 100 kW can produce, outside of the machine, a potentially deadly, whole body, ionizing radiation exposure in a few seconds. With no attempt to quantify each component of the electromagnetic cascade, consider just the photon portion in a situation where a 1 kW $e^-/e^+/\gamma$ high energy primary beam strikes a 15 X_0 thick target and a receptor (person, sensor, etc.) is located 1 meter away at 90° to the target. The dose rate in an unshielded situation would be ≈ 0.3 R/s; in the forward direction the dose rate would be approximately 20 times higher, which at the 900 kW presently available at SLAC scales to 5×10^3 R/s.

A real example of such a potentially serious situation has fortunately been known to happen only once at SLAC. During the initial health physics checkout a magnet with reverse polarity allowed the primary e^+ beam of 30 W to escape its proper transport enclosure and interact with the concrete wall instead of the beam dump. High-intensity radiation (360 R/hr) was discovered outside of a 1.8 meter thick concrete enclosure. Scaled to 900 kW, the photon dose rate would have been 3×10^3 R/s.

Thus, any review of the probable operational safety of a beam line poses questions about failure modes and burnthrough times. Burnthrough time in this paper is defined as the time interval from the beginning of beam exposure to the time when the beam emerges substantially unattenuated from the downbeam face of the power absorber, i.e., when the beam has destructively created a passage. Questions are clearly not easy to answer in view of the multitude of materials and geometries employed in the design of beam transport components. However, a series of destructive tests on simulations of collimators and beam dumps, with average beam powers up to 880 kW, greatly helped to answer some of these questions. Included in these tests was an evaluation of devices to detect destruction (disaster monitors) of the test pieces.

The following sections of this paper discuss the destruction mechanisms associated with high energy beams, the tests, and the action which followed. This resulted in improved designs for beam dumps and collimators and in a beam containment system which attempts to meet the safety requirements.

Destruction Mechanisms Associated with a High Energy $e^+/e^-/\gamma$ Beam

Loss of Coolant

Most SLAC power absorbers which are designed and relied upon to dissipate more than a few hundred watts of beam power on a regular basis are water-cooled. Their safe operation depends heavily on the proper functioning of the cooling system. Malfunctions in this system such as loss of coolant due to a leak, loss of flow due to pump failure, or excessive inlet water temperature due to loss of heat exchange capacity can have disastrous consequences for the heat dissipating areas of the power absorbers, even though the beam sensing instrumentation indicates operation within safe limits. Failure is generally due to melting in the areas of high beam power deposition, but other mechanisms such as plastic deformation and/or fracture due to thermal stresses exceeding the yield and tensile properties of the material may also contribute. The latter may occur in combination with thermal fatigue due to the pulsing nature of the beam.

Exceeding Design Limitations

Since not all power absorbing devices are called upon to dissipate the maximum available beam power for indefinite periods of time there exist a wide range of design limitations in each beam line. For example, there are protection collimators with an average power absorption limit of 5 kW in beam lines which are operated at power levels up to maximum machine output. These collimators are guarded against excessive power deposition by means of ionization chambers (fast response) and temperature detectors in the water (slow response).

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Unfortunately, neither of these devices can detect power density and there can be a large difference in local temperature and stress gradients between absorption of a beam with an average power of 5 kW and a 5 kW slice from a beam with an average power of several hundred kilowatts, i.e., the specific beam power density rather than power is the important parameter. Thus, in addition to the simple failure where the power deposition limit was exceeded (due to failure of the interlocks) the not so obvious cases like the one indicated above also need to be considered.

Inadequate Machine Protection

During the first six years of operation at SLAC, a number of beam-caused failures of transport equipment not important to personnel safety occurred which, upon close examination, almost always point out inadequacies in the conceptual design of the machine protection system. If the costs of the beam transport equipment, machine time and operator effort are weighed against the costs of a fail-safe machine protection system it becomes obvious that the decisions on what constitutes a safe power level for a beam line should be carefully engineered into the system. For example, a water-cooled, momentum-defining, copper slit for low-power operations (20 to 40 kW) failed due to thermal fatigue and resulting water leakage into the vacuum system.[4] Failure could at least in part be attributed to the fact that the slit jaws were not always fully withdrawn from the beam during very high power operations. The close proximity to a high-power slit (located just downbeam and used for high-power beams) renders ionization chambers to protect the low-power slit useless. The failure was at least in part blamed on the operator for having failed to fully open the slit, whereas the slit should really have been interlocked with a fully-open status required for operations above 40 kW.

Beam transport system components suffer damage from time to time because the wrong magnet setting is used for an established beam energy. In such cases, the beam usually penetrates the transport system vacuum chamber or destroys a vacuum flange gasket. While with the correct magnet shunt setting the trouble might not have happened, it was actually the inadequate beam containment or machine protection system which in the end allowed the component to fail.

Additional failures have occurred because preset trip levels of ionization chambers, temperature detectors, flow switches, etc., have changed or been changed. Again, tamper-proof, redundant, and fail-safe machine protection and beam containment systems backed up by strict operational rules would greatly reduce the number of malfunctions.

Destructive Tests of Beam Containment Devices

Since a basic approach chosen to protect personnel from dangerous $e^-/e^+/\gamma$ beams involved containing the beam inside an uncooled metal barrier, the question arose as to how long the barrier would last, also what materials and configurations would be most effective, and what devices might be employed to detect the impending or partial loss of the barrier.

To answer these questions a series of destructive tests was conducted at SLAC during January 1971. Thirteen devices were examined ranging from simulations of actual collimators in use, to exotic combinations of different materials which will be described. The tests are summarized in Table 1.

TABLE 1 — COLLIMATOR AND STOPPER TEST RESULTS

Target Description			Power	Total Beam Time On	Burnthrough Time		Switch Response	Material Left After Beam Off	
#	Length Material	Diameter			Visual Observation	Dump SEM			
	r.l. -	cm	kW	s	s	s	s	cm	r.l.
1	6 Fe 10 Fe	12.5 12.5	360	8.6 101	6.0 6.2	5.3 -	6.3 -	3.65 1.43	2.06 0.81
2	6 Cu 10 Cu	15 15	360	59	8.0	11.2	-	3.33	2.30
3	6 Cu 20 Cu	15 15	360	85	23.5	21	- -	2.78	1.92
4	6 Cu 20 Cu Spheres + H_2O	15 12.5	360	133	38.0	43	-	2.38	1.64
5	6 Cu 32 Pb Matrix with Cu Spheres, Ta Plates	15 10×10	360	55	48	37.4	-	2.54	1.75
6	20 W (Heavymet)	3.18×3.18	360	-	12	-	-	-	-
7	52 Cu Stopper with Blowout Fuses	10	500	52	11.8 Radial Blowout 49	48.2	10.5	2.45	1.7
8	20 Cu Edge	15	500	5.3	1.3	1.3	-	2.54	1.75
9	2 Electric Burn-through switches plus 6 Cu	15	500	8.2	0.8	3.1	0.5 Front 0.2 Shower Max	2.7	1.86
10	Pressure Burnthrough Switches 6 Cu 25 Cu	15 15	165	77	68	52.5	8.9 53	5.0	3.5
	6 Cu 25 Cu	15 15	500	4.3	2.0	1.5	0.7 1.3	3.2	2.2
11	20 W (Pure)	2.5	500	0.6	0.4	0.4	-		
12	19 Pb in Ta Container	5×5	500	8.5	0.6	0.6	-	0.1	0.25
13	52 Cu Stopper	10	880	9.6	-	-	9.5	*	*

*Not yet available due to high residual radioactivity.

All targets were uncooled and tested in air. Specific attention was given to the measurement and recording of burnthrough times, temperature, and modes of failure. The beam energy was 18 GeV. Average power levels ranged from 165 to 880 kW. The first experiment contained a set of six targets which were mounted on a motorized platform for remote positioning in the beam. The test setup is shown in Fig. 1. The arrangement also contained a thermal integrator, a shower emission monitor, and a toroidal current monitor to establish burnthrough times. However, in the following discussions most comments are made with reference to the visual burnthrough as observed via the four TV camera monitors. The residual beam was absorbed and dissipated in a water-cooled beam dump which in turn was followed by a 55 X_0 long iron ingot for additional protection. All tests in the first experiment were conducted at an average beam power of 360 kW. For all 6 targets the nominal beam centerline coincided with the centerline of the radiator and target cylinders.

The first three targets compared a piece of iron with two pieces of copper. In all cases there is 6 X_0 long radiator ahead of the actual targets. Were it not for the fact that the beam impinges away from an edge, this would be the most severe exposure condition possible. The radiator simulates any beam line device located upbeam of the collimator. It is thick enough to develop the maximum of the electromagnetic cascade for the experimental energy. Therefore, the target cylinder experienced the most severe heating on the front face. The 5 cm wide gap which separated the target from the radiator allowed for easy flow of molten material from the target. This enhanced rapid formation of a cavity along the beam line and only a small portion of the total heat capacity of the target was utilized. An evacuated cavity on the downbeam end of target #1 was connected to a pressure switch to aid in determining burnthrough. An SEM-like signal (net charge leakage) was recorded from the radiator and the target to interpret the rate of burnthrough. A thermocouple located on the nominal beam centerline and on the downbeam face of the target aided further to establish burnthrough.

Copper proved the better of the two materials and this is attributed principally to its higher thermal diffusivity. All three samples had material left in the early part of the radiator. Burnthrough or "holding" times were from six to about twenty seconds. At powers below 360 kW (like 100 kW) these times should increase at least as the linear inverse, although this remains conjecture.

The reason for the two lengths of copper was because it was felt that it might be easier to interpret the effects of the parameter "length" rather than those of the parameter "power". However, the effect of length is very specific to this test where doubling the length of the piece beyond the radiator resulted in tripling the burnthrough time. Since the material has more difficulty leaving the system in a longer sample, the effect of length is higher than linear; i.e., the molten metal absorbs energy as it flows out of the cavity. Its prolonged presence in the cavity results in heat transfer to the still solid material and a larger portion of the target heat capacity is involved in power dissipation.

Target #4 simulated a water-cooled collimator of the sphere design[5] where, for example, both the water pump and the flow interlock had failed undetected. The combination of 0.4 cm diameter copper spheres and still water was twice as effective as solid copper. The improvement is principally attributed to the presence of water with its high heat capacity and heat of vaporization. The steam carries away energy until most of the water is evaporated. The copper spheres melt, with the liquid phase occupying only about 70% of the volume of the packed bed, thus allowing additional spheres to fall into the beam due to gravity.

Target #5 contained a packed bed of 0.4 cm diameter copper spheres, held in a lead matrix, all cast into a thin tantalum case, and divided into three axial segments. The high melting point tantalum was selected to contain the molten material as long as possible, thereby utilizing more of the total heat capacity of the target.

Target #6 was a mixture of 90% tungsten, 6% nickel, and 4% copper, which is used in some power absorbers and targets at SLAC. One of the reasons for this test was to establish whether the expected high thermal stress gradients in space and time would cause thermal shock and maybe explosion of the target. The target was engulfed in a shower of sparks the moment the beam impinged. Burnthrough was 12 seconds, but subsequent examination showed that the target had cracked, probably very early in the test. Thus the beam was not really effectively absorbed after the first few pulses. This explains the long burnthrough time as compared to one estimated from the target heat capacity.

The second experiment contained again a set of 6 targets mounted as described above and schematically shown in Fig. 2. Additionally, a real SLAC beam stopper as employed in the Personnel Protection System was tested at the maximum available beam power, 880 kW at $E_0 = 18.65$ GeV.

Target #7 was a 52 X_0 long copper cylinder as employed in the beam stoppers of the personnel protection system. The stoppers are protected by thermal fuses[6] which, when melted at 58°C, will cause loss of the beam transport vacuum. Vacuum switches will then turn off the machine. The test resulted in a vacuum response after 10.5 seconds. The copper "volcanoed" in a radial blowout near the shower maximum in 11.8 seconds and burnthrough occurred after 49 seconds with some material still left in the front area.

Target #8 demonstrated the geometry aspects of beam containment. It simulated a collimator with the beam impinging along its beam-defining edge. Simple calculations which associate survival times with reaching the melting point in the beam-affected zone, yield results of the order of one second. The test results confirmed this simple mathematical model. The longer burnthrough times measured in the tests where the beam was buried well inside the target cylinder boundaries suggest that part of the mechanism involves metal removal driven by the energies associated with the vapor phase of the metal. This aspect complicates an analytical treatment of the problem.

Target #9 was a test of two "Disaster Monitors" of the "electrical burnthrough switch" variety which were separated by 6 X_0 of copper. Disaster Monitor is a name coined at SLAC for a device which detects a burnthrough and thus a potentially disastrous condition in the beam containment component. The switches in this test consisted of plates which shorted if the woven glass insulation between them was destroyed and the plates touched. Such a device appeared to be a feasible disaster monitor.

Target #10 tested a simulation of a copper collimator with the beam impinging 0.5 cm (one beam diameter) away from the collimating aperture. Failure was detected utilizing loss of pressure in an enclosed cavity. This is a disaster monitor of the "pressure switch" variety. At 165 kW loss of pressure in the cavity at shower maximum occurred after 8.9 seconds, whereas at 500 kW the response came after only 0.7 seconds. The decrease in survival time by a factor of 12 for an increase in power by only a factor of 3 is related to the heat of fusion and the thermal diffusivity of the material, as well as the effective diameter of the heated zone. The nonlinearity of scaling power and burnthrough time were clearly demonstrated in this test. The times for burnthrough of the cavities located at a depth of 25 X_0 were 53 and 1.3 seconds respectively for the two powers. In both tests melt-out occurred into the aperture of the collimator, in much the same fashion as in the case of the edge.

Target #11 was a rod of pure tungsten. Its behavior was to be compared to that of target #6. The target fractured "instantly" at 500 kW and burnthrough was indicated after 0.4 seconds or only approximately 150 beam pulses. The calculated temperature rise for the estimated effective beam diameter at the shower maximum was approximately 250°C per pulse, resulting in a thermal stress rise of about 50,000 psi.

Target #12 was $20 X_0$ of lead in a thin-walled tantalum case. Substantial beam power leakage occurred after 0.6 seconds.

Target #13 was a real beam switchyard stopper, installed in the beam transport system, under vacuum, and instrumented. The beam was shut off by the vacuum pressure interlock (machine protection system) after 9.6 seconds. Inspection of the stopper after the test revealed a radial blowout in the area of shower maximum similar to the one observed in target #7.

The test results showed that the rate of destruction or burnthrough is extremely rapid, particularly along beam-defining edges. Existing collimators were found to be adequate beam containment devices if the beam was properly centered, i.e., if it impinged away from the edge, and if coupled to highly reliable electronic systems which could detect the impending loss of the barrier. Most importantly, the tests demonstrated, that even for beam exposures many times those of the recorded burnthrough time, there was always some material left undamaged in the front part of the targets, ahead of shower maximum. This remaining material adds a large momentum spread to the beam and it also scatters it. Thus, transmission through secondary beam lines downbeam of the collimator is reduced. The tests also showed that the disaster monitor is a feasible device, capable of detecting destruction and turning the beam off before a situation hazardous to personnel can arise. They also showed clearly that neither of the two types of tungsten are suitable to contain high power density beams, not even for short periods of time; the more brittle, pure tungsten perhaps being the poorer of the two. The results showed further that no mechanical device could be solely relied upon to contain the beam for a long period of time, i.e., long enough for operator reaction to be certain. One area not covered by the tests but present in all real-life situations is where the targets have large lateral and axial size as compared to the distance to shower maximum and are not preceded by a radiator. In this case, failure occurs presumably by melt-out through the front face and successive material removal through the cavity thus formed.*

The Beam Containment System and its Devices

After considering the tests reported above the Radiation Safety Committee reviewed beam safety practices in general and each beam line in particular. The conclusion was that side by side with the Personnel Protection and the Machine Protection Systems there was a need for a third category of protection schemes. It is called the "Beam Containment System" and depends not only on mechanical beam line components, but relies heavily on a flexible array of protected, redundant, and fast electronic systems to prevent destruction of critical beam containment components. It was decided that the systems be redundant as to sensors, wiring paths, and techniques of shutting off the accelerator. In general, two or more sensors were agreed upon whose processed signals shut off the accelerator by delaying gun triggers and accelerating RF to non-beam time. A fault in these systems usually is wired to trip all beams because of uncertainty that the failure mode of triggers and/or magnet systems precludes sending any beam to any beam line. It also was requested that the response time from sensing to shut-off be short, and it was expected that the reliability of the systems would be improved by self-monitoring and by protected electronics and wiring where feasible. This Beam Containment System is backed up by two subsystems of disaster monitors and beam shut-off ion chambers,^{1} which operate through the protected wiring and relays of the Personnel Protection System. They sense, respectively, the failing of a critical containment device and excessive radiation levels in and around beam lines in the research yard.

Mechanical Beam Containment Devices

The mechanical devices used in the Beam Containment System cover a wide range of designs and functions. The devices are:

(1) Protection collimators which are placed in strategic locations to shadow another beam port or a poorly shielded penetration. These devices are either cooled or uncooled, depending on whether or not they intercept beam on a regular basis. They are typically 20 X_0 long or longer and offer good protection except in the case where a high-power beam impinges at grazing angles along the aperture. If the protecting device does not shut the beam off, burnthrough might occur within 0.5 to 1 second for power levels of 500 kW.

(2) Beam dumps are designed to absorb a specific beam continuously.

(3) Burnthrough switches or disaster monitors are often used in connection with devices covered under items 1 and 2. Only pressure switches are now employed.

(4) Permanent magnets are used in conjunction with pulsed magnets to prevent beam transport for all but the desired beam having the proper pulse repetition rate. In some instances they are used as sweeping magnets only.

(5) Bending magnets are sometimes used as active devices in the containment system. The polarity and/or field strength are interlocked such that the allowed beam is swept into a safe place. Magnets may also be required to be off or locked off during entry into a certain area, or for operation of a particular beam setup.

(6) Toroidal current monitors and shower emission monitors are frequently used in the containment system. Their applications are described below.

(7) Blowout fuses are employed in the beam stoppers as described above.

(8) Temperature detectors are used in connection with the blow-out fuses (item 7), protection collimators, slits, and beam dumps.

(9) Flow switches are used for many water circuits.

(10) Ionization chambers are installed protecting many devices from excessive power, and also in the beam shut-off ion chamber system to control the radiation level in and around secondary beam transport systems in the research yard.

Beam Containment Electronics

Electronic devices were required which (1) ensure that beams are directed toward, and arrive at designated dumps, (2) limit the beam power to the capability of the particular dumps, and (3) sense when a beam accidentally hits a containment device with enough power to damage it.

To rapidly establish the Beam Containment Electronic System and yet avoid slippage in the accelerator running schedules, existing machine protection equipment, both sensors and chassis electronics, were commandeered to serve the new functions. This equipment has been in operation for two years. From the maintenance and operational point of view, its performance has been a source of concern. Noise pickup on the sensor lines, long term instability of the "processing" electronics, and the possibility of undetected interruption of data transmission path continuity reduced the reliability of these early circuits, necessitating frequent interruption of beam operating schedules to ensure proper

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*A movie was made of the tests. It is available for loan from the SLAC Public Information Office upon request.

calibration of the beam containment electronics. This initiated a major program for the redesign and development of the specialized electronics and overall system concepts needed to provide adequate and reliable beam containment electronics. In the following section, the features of the new equipment will be described.

The processing of data from various sensors falls into four broad categories:

(1) Integration. This category involves integration of pulsed data transmitted from beam-line sensors such as toroids, shower emission monitors, and ion chambers. The integrated signal is compared to a preset upper-limit dc reference and a fault is generated when the limit is exceeded. The "Average Current Monitor" features a range-switched meter readout for monitoring toroid signals and is used to limit average beam power in specific beam lines to preset values. Another scheme, the "Difference Comparator", compares the difference of the integrated signals from two toroids against a preset dc level. This is used in a multiple beam situation where, with the use of pulsed switching magnets, beams are selectively distributed to beam lines to the left, straight ahead, or to the right and where there is a need to limit the beam power delivered to two of the three lines (specifically the left and right B-beam lines at SLAC). A third scheme, the "Video Integrator", is used normally with shower emission monitors and ion chambers for protecting specific containment devices.

(2) Pulse comparison. This category involves comparison of pulse amplitudes from an upbeam toroid and a downbeam target shower emission monitor or toroid on a pulse-to-pulse basis. Single pulse integration is employed to improve the performance in a high-frequency noise environment. A fault is generated if the processed signal from the downbeam sensor is less than a preset percentage of that from the upbeam sensor. This package of electronics is called the "Pulse-to-Pulse Comparator". It is used to determine that the beam has arrived at the designated dump or target, and that beam loss between the upstream and downstream sensors is not excessive.

(3) Analog comparison. Amplitude comparison of magnet current falls into this category. Comparison with preset upper and/or lower limits is accomplished by the use of commercially available "electronic" type meter relays and serves to ensure that proper magnet power supply settings are being maintained. These are referred to as "Dual-Limit Meter Relay Interlocks".

(4) Binary comparison. This category involves the detection of dc levels or binary data from beam line sensors such as toroids. Specifically, it includes the monitoring of switch closures (flow switches, thermostats, etc.), repetition rate of specific beam lines and errant beam detection. The "dc Detector" is used for processing dc data and is essentially a collection of "solid-state" relays capable of detecting the presence of dc levels from ±5 volts to ±24 volts. The "Rep Rate Monitor" counts beam pulses above a preset input threshold over a 1 second time base, and develops a fault interlock if the count is above a preset rate. The "Errant Beam Detector" compares beam pulses with a predefined beam expectation pattern and generates a fault if a beam pulse occurs when there is no permissive pattern.

Design Considerations

Reduction of noise pickup dictates the use of Twinax and doubly shielded coax for signal transmission from beam-line sensors to the processing electronics, with special attention given to routing and to segregating these cables from the bulk of the existing cable plant (especially in the vicinity of large current carrying cables to magnets, etc.). Improper routing can result in several hundred millivolts of noise spike pickup on typical cables. Greater transducer sensitivity for beam-line sensors, improved shielding for these sensors, and the use of carefully shielded, balanced differential amplifiers for local preamplification of toroid signals have provided better signal-to-noise ratios. Even with these precautions, input gating of pulse signals from sensors is essential to reduce the possibility of random noise bursts causing circuit trips. Input gates are typically 10 μs wide.

A decision was made to adopt a modular concept in packaging and in internal electronic circuit blocks thereby standardizing the design of similar circuits such as integrators, signal gates, comparators, etc. This allows rapid replacement of an entire channel of electronics should a failure occur and for rapid replacement of internal circuit packages (mini-P.C. boards) on the "bench" during repair. All tolerance adjustments are accessible from the front panel and include the use of thumbwheel switches for digital reference data entry.

The self-checking of each detector channel is of prime importance in achieving fail-safe operation. The problem involves a solution which not only guarantees the continuity of the signal transmission path, but also continuously checks that the processor is able to generate a fault command when preset limits are exceeded. The self-check should also determine that the beam-line sensor is still physically present in the beam line and acting as a beam-pulse transducer. The latter is the most difficult and, to date, has been achieved most successfully with toroids.

Self-checking has been accomplished by transmitting single pulses of preset amplitude and 1.6 μs width down to the sensor over separate coax lines during the 2.8 ms period between beam pulses. In the case of toroids a calibrate winding is used to couple the test pulse into the sensor. In the case of shower emission monitors, two separate connections are made to opposite ends of the emitter plate to establish a continuous path. This does not guarantee that the sensor is still in the beam path.

Fan-in amplifiers are used to distribute test pulses from various processors to the same sensor; and fanout amplifiers are used to distribute composite sensor outputs to the various electronic processors (see Fig. 3). These amplifiers have adjustable gain to permit normalizing system gain in each channel. Each processor is gated to accept only its own test pulse during the interpulse period. The test pulse gate is generated from the beam-time gate as a further check on the existence of the beam-time gate. Time multiplexing is used to separate test pulses for each processor (see Fig. 4).

The self-test procedure for each processor is described separately because of inherent internal differences.

(1) Average current monitors are tested at a 360 pps rate, 1 ms before beam times, with the amplitude adjusted to produce the equivalent of 0.1 μA average current. The meter zero is suppressed to allow zero reading with the "housekeeping" pulse present. The test pulse is delivered to a calibrate winding of the current sensing toroid and the integrator output is checked by a low-limit comparator which generates a fault command if the "housekeeping" pulse is not present. The upper limit of the processor is not checked.

(2) Video integrators are tested at a 1 pps rate, 300 μs after beam time, with the amplitude adjusted to produce a processed response 5% greater than the preset upper-limit reference level. The integrator output is reset to zero once per second, 50 μs after the last beam pulse. The comparator output is suppressed for 500 μs from beam time, after which a fault is generated if the test pulse has not done so, or is missing.

(3) Pulse-to-pulse comparators are tested at a 60 pps rate, 300 μs after beam time. The amplitude of the pulse sent to the downbeam sensor is less than the preset allowable percentage of signal amplitude sent to the upbeam sensor. In addition, the upbeam sensor integrator output is compared

to a preset reference level to ensure that its signal path is continuous. During this test the comparator output is suppressed but a fault will be generated immediately if the compared test pulse fails to do so.

(4) Repetition rate monitors are tested at a 1 pps rate, after the internal time base is reset and at 500 μs after beam time, with the test pulse amplitude set 5% above the input threshold. The received pulse generates a high rate pulse train containing the same number of pulses as the preset value. If the internal count does not equal the preset value, a fault is generated.

(5) Errant beam detectors are tested at a 60 pps rate, 500 μs after beam time, with the test pulse amplitude set 5% above the input threshold. The comparator output is suppressed but a fault will be generated if the test pulse failed to do so during the test period.

In addition, the cable plant has been designed with direct runs and locked racks and distribution facilities to minimize the probability of interrupting signal transmission paths and system wiring.

A summary of the operating specifications for each type of processor is included in Table 2. Response time represents time to develop beam shutoff command after receiving fault input.

TABLE 2 — OPERATING SPECIFICATIONS OF BEAM CONTAINMENT ELECTRONICS

Processor	Input Signal Levels	Test Pulse Data	Response Time
Average Current Monitor	Equivalent of: 15 nA average min 50 μA average max	1.6 μs @ 360 pps 1 ms before beam	100 ms
Video Integrator	Equivalent of: 15 nA average min 50 μA average max	1.6 μs @ 1 pps 500 μs after beam	200 ms
Pulse-to-Pulse Comparator	0.5 - 100 mA peak 0.5 - 2 μs	1.6 μs @ 60 pps 500 μs after beam	< 1 ms
Repetition Rate Monitor	100 μA peak min 0.5 - 2 μs	1.6 μs @ 1 pps 500 μs after beam	< 1 ms
Errant Beam Detector	100 μA peak min 0.5 - 2 μs	1.6 μs @ 60 pps 500 μs after beam	< 1 ms
dc Detector	±5 V - ±24 V	---	< 1 ms

Operational Experience

As noted above, the containment equipment initially used was backed up by frequent performance checks during operation. The need to do such tests to insure that the electronics was operating properly has decreased due to the more reliable equipment now installed. However, the detection devices employed often have problems which are difficult to solve. Shower emission monitors have often given erratic and ambiguous signals. Unfortunately, in many instances (i.e., targets) these devices are the only ones which are suitable. A recurring problem is one where the sensor output signal is equal to an on-target signal, but is caused instead by the beam striking an upbeam part of the beam line. This often requires additional detection devices, adding undesired complexity. Ion chambers and toroids may also have this problem. Some toroids, and shower emission monitors operating in air, have had severe differentiation of their output at high power levels. Cracked ferrite cores were found and they may be the explanation to the toroid problem, but the emission monitor problem is even less understood. These effects point to the need for operator vigilance in checking output from containment sensors, even though these devices may not be required for operating experimental beams. Such problems also underscore the need for redundancy even when protected and "fail-safe" equipment is used in a containment system.

The requirement that a fault turns off all beams also interacts strongly with operation. It is therefore essential that the operators should obtain information as promptly as possible on the cause of a trip to keep lost time to a minimum. Calibration checks (for example, to compensate for a change in sensor sensitivity) also create the same problems. It is perhaps obvious that it is desirable to keep the number of electronic devices to a minimum, consistent with the safety of the line.

In summary, a beam containment system has been described which was designed and installed in beam lines at SLAC as a result of tests which demonstrated the destructive capability of the accelerator. The task is by no means finished and some of the devices employed in the system still have operational shortcomings. However, the system is continually being improved and allows simultaneous operation of eight beams with widely varying characteristics in a safe manner.

Acknowledgement

The authors gratefully acknowledge the help of the large number of people in the various groups at SLAC who have contributed to the work described above.

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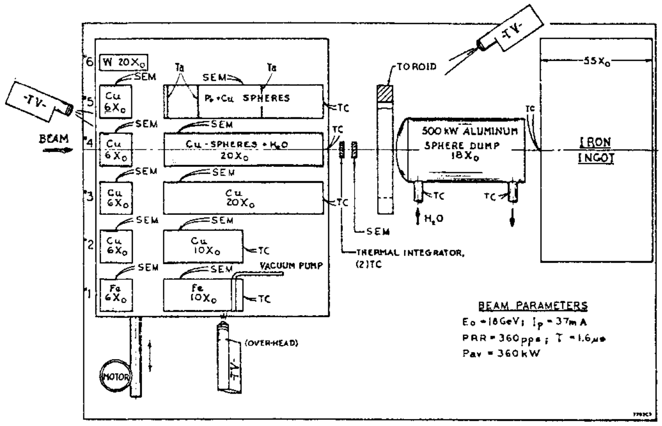

FIG. 1--Target arrangement for experiment #1.

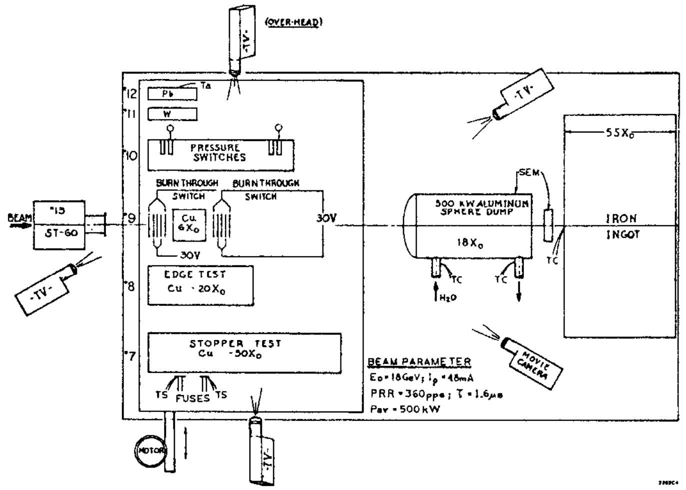

FIG. 2--Target arrangement for experiment #2.

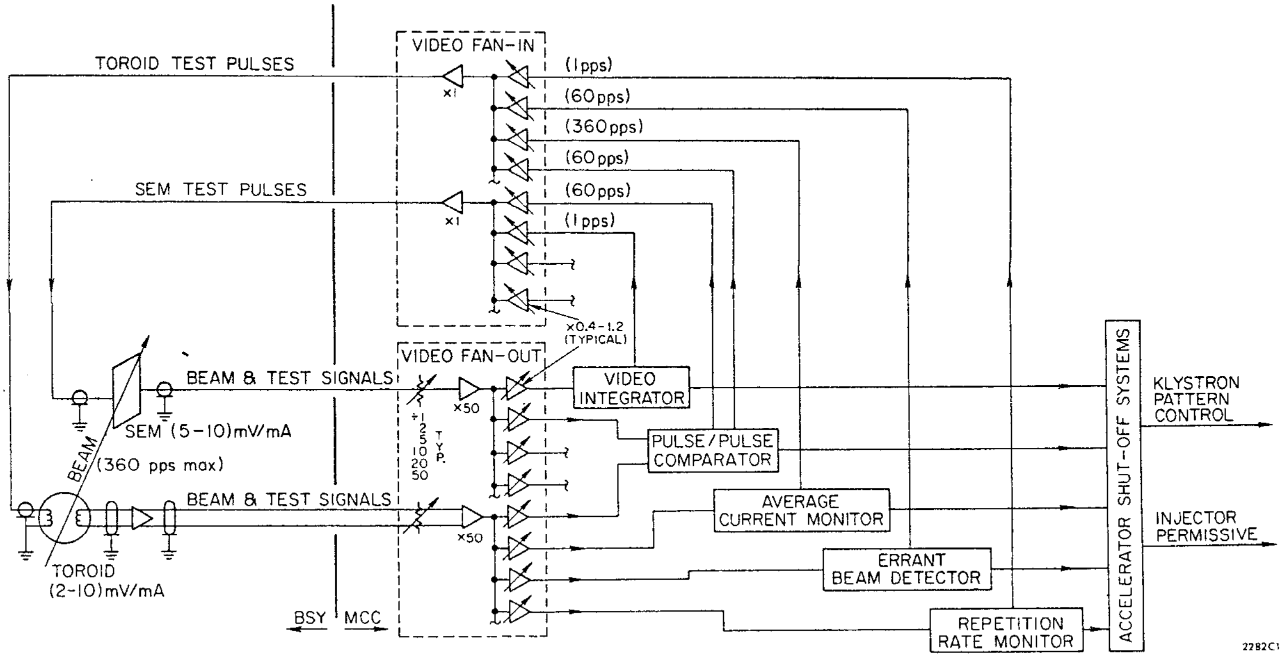

FIG. 3--SLAC Beam Containment System electronics (typical signal distribution).

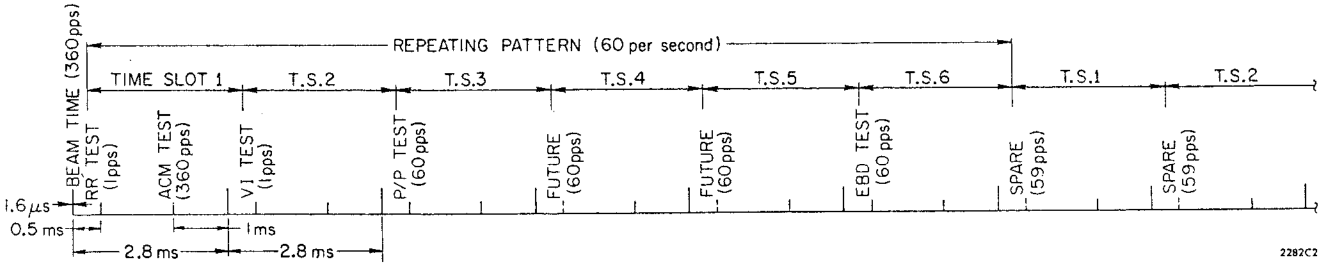

FIG. 4--Beam Containment Signal timing.