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OPERATIONAL EXPERIENCE WITH SLAC'S BEAM CONTAINMENT ELECTRONICS*

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SUMMARY

Considerable operating experience has been accumulated at SLAC with an extensive electronic system for the containment of high power accelerated beams. Average beam power at SLAC can approach 900 kilowatts with the potential for burning through beam stoppers, protection collimators, and other power absorbers within a few seconds. Fast, reliable, and redundant electronic monitoring circuits have been employed to provide some of the safeguards necessary for minimizing the risk to personnel.

This paper describes the electronic systems and discusses the design philosophy and operating experience.

INTRODUCTION

In 1971 it became clear that no mechanical device could be relied on solely to contain high power beams at SLAC for long periods.[1] At that time, design was started on electronic protection equipment, called the "Beam Containment System", which would operate in conjunction with the mechanical beam line components.

The primary function of the electronic equipment is to monitor the beam and beam line devices, and to give an early warning of conditions which might lead to potential damage to mechanical devices, the failure of which might permit beams to escape into occupied areas. As a backup to the electronic equipment, burn-through monitors (Disaster Monitors) and beam shutoff ion chambers offer further protection. The burn-through monitors sense actual damage to and failure of mechanical containment devices. The ion chambers detect excessive radiation levels in and around beam lines in the research area.

It should be noted that the Beam Containment System (BCS) is independent of and distinct from two other protection systems at SLAC. These are the Personnel Protection System and the Machine Protection System which have been described previously.[2,3] By contrast to these, the BCS is designed to keep high-powered beams out of areas occupied by personnel and it utilizes redundancy and self-checking to increase the overall reliability of the system. A violation of the BCS shuts down the accelerator beams by three independent methods, as described below.

SYSTEM DESIGN

The formal requirements for the BCS were established by the Radiation Committee as follows:

1. The beam line must contain at least two electronic and/ or mechanical protective systems which will either prevent a primary beam of greater than P kW striking the device or turn off the primary beam if greater than P kW strikes the device. The device must also be protected by a Disaster Monitor which will react in a time less than 1/10 of the calculated burn-through time and turn off the primary beam.
2. Each beam line above a power level prescribed by the responsible Health Physicist must have a system which determines that the primary beam is arriving at the proper place.
3. All electronic systems must be protected against unauthorized modification. If possible, automatic checking of proper functions will be provided.

To implement these requirements, the following design philosophy was adopted:

a. All systems incorporate continuous self-checking features, which ensure integrity of the transducer, the cabling, and the electronic processing unit (see Fig. 1). All pulsed equipment utilizes narrow window gating (10 μs) at beam and test time, to reduce the effects of noise.
b. The devices utilized in each beam line are independent. In practice, three or more independent devices are used.
c. High power primary beams, above the limit for the line, are sensed by current transformers (toroids) and processed using average current monitors backed up with repetition rate monitors.
d. Dumps and collimators are protected by secondary

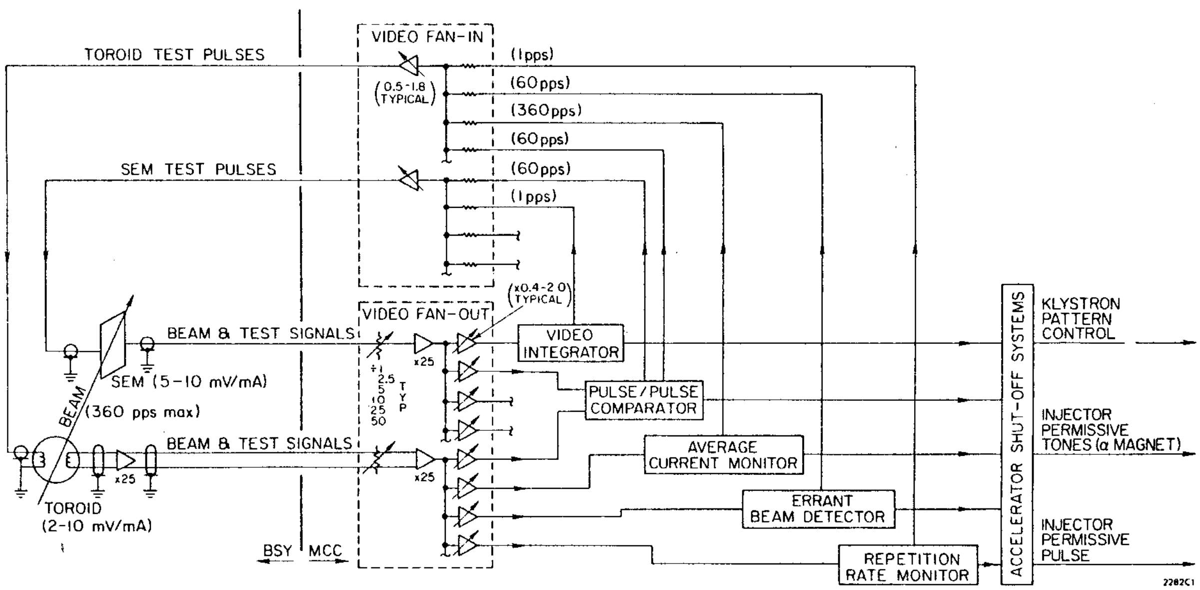

Fig. 1. Typical BCS signal distribution.

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emission monitors (SEM's) and integrating electronic circuits.

e. The requirement for verification that a beam has reached its proper destination has been met by using comparators which measure beam current on a pulse-to-pulse basis at two locations in a beam line. Errant beam detectors are also used.

f. All wiring is protected.

g. When a fault is detected, beams are shut off by three independent paths:

(1) Injector and accelerator klystrons are placed on "stand-by" (nonaccelerate mode) by klystron pattern control.[4]

(2) The "α" magnet immediately following the off-axis guns is turned off via the injector permissive tone system.[3]

(3) The injector guns are delayed by the Injector Trigger Generator via both the permissive tone system and the injector permissive pulse system.[3]

EQUIPMENT DESIGN

The BCS electronics at SLAC consist of the following units:

1. pulse preamplifier (1 per toroid)
2. pulse fan-in amplifier (36 channels)
3. pulse fan-out amplifier (36 channels)
4. pulse-to-pulse comparator (10 channels)
5. average current monitor (24 channels)
6. repetition rate monitor (5 channels)
7. errant beam detector (10 channels)
8. dual-limit meter relay (16 channels)
9. dc detector (50 channels)
10. system summary shutoff module (2 units)

In general, the following design features have been included in the BCS:

1. System amplifiers have a minimum bandwidth of 50 MHz and are calibrated with a 1.6 μs pulse of an amplitude to provide a normal sensitivity of 50 mV/mA of beam at all processing electronics pulse inputs.
2. Front-end integration (τ=200 μs) and polarity switching are used in all modules where pulses are processed.
3. Front panel set points, gain adjusts, interlock status, bypass switches, polarity switches, manual "trip" push-buttons, and test points have been provided on all models.
4. Each pulse processor channel generates and transmits beam equivalent test pulses through the signal cable plant during the interpulse period between beam signals for self-check testing. These are designed to generate a fault condition within each channel and the fault detection logic is inverted at this time to develop shutoff commands only if a fault condition is not sensed.
5. Remote fault status is provided for display at the operator consoles.
6. Two independent interlock outputs are provided from each processor bin of electronics for beam shutoff redundancy.
7. All BCS electronics at the main control center are packaged in NIM modules and bins, and installed in two adjacent racks, as shown in Fig. 2.

A brief description of each type of unit follows:

Pulse Preamplifier. A preamplifier with nominal gain of 25 is located as close to the beam line toroid as radiation levels will permit to raise the toroid signal strength and thereby improve the S/N ratio. It is a fixed gain differential amplifier.

Pulse Fan-in Amplifier. A fan-in module is used as a part of the self-checking scheme developed for the pulsed systems and allows time multiplexed test pulses from more than one signal processor to be buffered and sent out to the calibrate inputs of each beam-line sensor. It is a 6-input summing amplifier of adjustable gain (0.5 to 1.8).

Pulse Fan-out Amplifier. A fan-out module is used to distribute buffered signal outputs to more than one signal processor from the beam-line sensor and it provides a means for normalization of signal levels (gain adjustment) to each processor input. It has six isolated output stages, each independently adjustable in gain from 0.5 to 2, and has a balanced input differential amplifier with switchable gain of from 1 to 25.

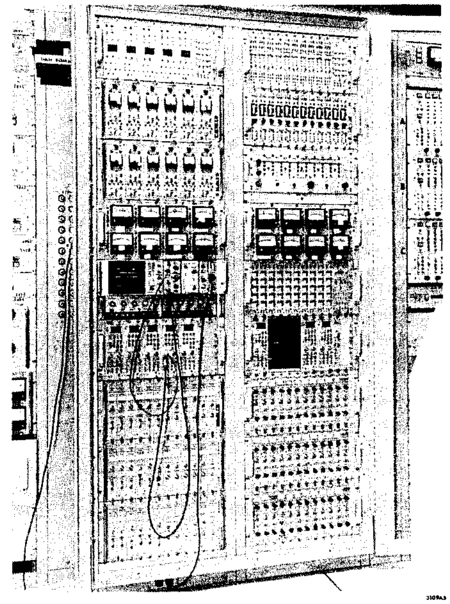


Fig. 2. BCS equipment (main control center).

Pulse-to-pulse Comparator (see photo and block diagram, Fig. 3). Its function is to compare beam derived signals from an upbeam sensor (usually near the beam line entrance) and a downbeam sensor (usually at the end of a beam line in front of a dump) on a pulse-to-pulse basis. It generates a fault output if the downbeam signal is less than a preset percentage of the upbeam signal (i.e., above allowable transmission loss). Three sets of scope traces are included to illustrate some of the design characteristics. Figure 4a shows an expanded sweep on the lower trace to illustrate a typical signal (2 mA) into a toroid calibrate winding. The upper trace shows the input pulse from the toroid amplifiers to the left (5 μs/cm sweep) and on the same time scale a superimposed integrator output signal. Note that the integrator gain is adjusted to yield an output level at comparator strobe time equal to the amplitude of the incoming pulse. The upper trace of Fig. 4b shows the integrator response for equal input signals of 300 mV amplitude with upbeam signal attenuated by 30% (thumbwheel set to 70) at inputs to the difference amplifier. The output of the difference amplifier is also shown (-100 mV at comparator strobe time). Note that the comparator output is zero (i.e., at the base line) at this time indicating a nonfault condition. The lower trace of Fig. 4b illustrates the condition of excessive downbeam signal loss yielding a difference of +80 mV at strobe time and developing a comparator output pulse. This represents a fault condition and will generate an accelerator shutoff command at about 30 μs after the fault occurred.

This module incorporates two self-check schemes, as shown in Fig. 3. The first, called "auto-test" (AT), attenuates every 67th beam pulse response from the down integrator - this is shown in the upper trace of Fig. 4c. At the same time the fault/test decode logic is inverted such that a shut-off command is generated only if the comparator fails to develop an output. The lower trace shows the effect on the difference signal which goes high during auto-test and causes a comparator output. This test checks all the electronics at beam time (including the input gates) up through the comparator. The second test occurs during the beam interpulse period, about 800 μs after beam time at a 60 pps rate. This interpulse test (IPT) is designed to check external signal path

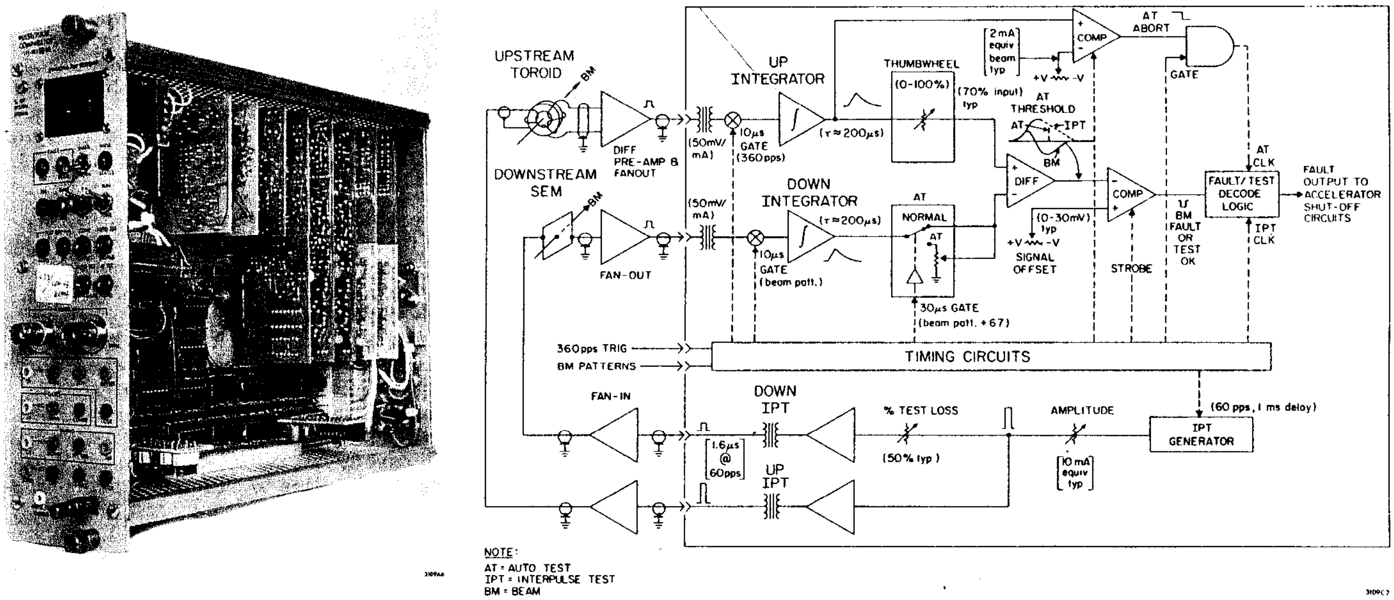
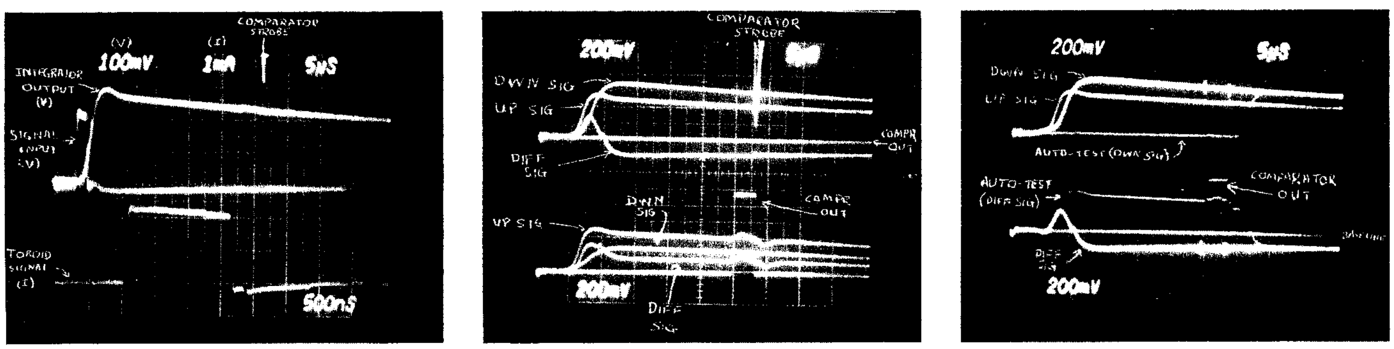


Fig. 3. Pulse-to-pulse comparator module.



(a) (b) (c)

Fig. 4. Pulse-to-pulse comparator waveforms: (a) typical integrator response to toroid signal; (b) difference amplifier input and output; (c) auto-test response.

integrity and overall gain even when beams are off and yields results similar to that of the AT.

Average Current Monitor. This unit is used to limit the average beam power in specific beam lines to preset values and is used with toroid and SEM signals. It consists of a 100 ms resetting integrator, a sample-and-hold circuit, and a hi-trip comparator. Self-check is accomplished by generating a 360 pps test pulse (equivalent to 100 nA at 1 ms before beam time and sensing the S&H output with a lo-trip comparator. A 20 nA to 50 μA range switched meter is included on the front panel and the use of zero suppression of the test pulse response provides direct reading of average beam current.

Repetition Rate Monitor. This unit is used to monitor the beam pulse rate, thereby limiting maximum attainable beam power. It counts beam pulses above a threshold level (typically 1 mA) over a one-second time base; permissive patterns are also counted, providing advance warning of beam rate programming errors even without beam. A fault is generated if a preset rate set on the front panel thumbwheel is exceeded. Self-check transmits an equivalent 2 mA test pulse at 1 pps and, if detected, gates on an internal 1 MHz pulse train which steps the counter to the fault condition.

Errant Beam Detector. This unit is designed to compare beam pulses from toroids at the entrance to beam lines with a predefined beam expectation pattern. A shutoff command is generated if a beam pulse above a preset threshold (typically 0.3 mA) is detected when there is no permissive pattern. The input integrator is bipolar, thereby not requiring polarity switching. Self-check transmits equivalent 0.5 mA alternating polarity pulses at an overall 60 pps rate in the beam interpulse period.

Dual-limit Meter Relays. This unit consists of a sensitive (200 μA FS) electronic meter relay with upper and lower limit set points and is assigned to monitor magnet shunts and power supply voltages to require that they be "inside" or "outside" (switch selectable) of the meter set points.

dc Detector. This unit is used to detect the closure of limit switches, e.g., temperature, flow, pressure, or position. It can sense dc voltage levels from ±1.5 V to ± 100 V (typically 24 V) at a fixed input current drain of 4 mA. The input circuit is optically isolated. It has a self-check scheme which interrupts the input source at a 1 pps rate. Output faults occur when there is an open or a short across the input.

System Summary Shutoff. This unit is a 15-channel logical "AND" which collects an interlock summary output from each Nim bin and drives two independent optically isolated shutoff circuits. These in turn are used to actuate each accelerator shutoff system by interrupting its input.

OPERATIONAL EXPERIENCE

SLAC's experience with the BCS has proven it to be reliable and essential to the operation of high-powered interlaced beams being delivered to a number of different experimenter beam lines. Initially, extensive daily checks were required, but improved equipment reliability and increased operator confidence have reduced the added burden considerably; continual self-check features in all channels have also been a significant factor in this improvement. Enough flexibility, redundancy, and expansion have been provided to accommodate SLAC's ever-changing beam line requirements. After accelerator downtime, calibration and setup, which initially required several weeks, can now be rapidly accomplished within a few days. The inclusion of a wide-band storage scope and pulse generators (see Fig. 2), along with modularity, front panel signal insertion and measurement, and extensive use of test points, has added substantial diagnostic capability with minimal beam interaction.

Remote polarity switching has been provided on some modules and design improvement will incorporate it on all units. Remote control and set point adjustment offer intriguing possibilities for future computer control (perhaps utilizing a microprocessor) to minimize operator burden still further without destroying the ability to interact when necessary; setup and checkout can be brought directly to the operating position (especially significant when considering SLAC's "touch-panel" system[5]).

The system dynamic range is more than adequate. The BCS can reliably operate with beams at the 1 kW level as well as at the maximum capability of the accelerator (presently 900 kW), and with additional gain down to the 200 W level. Although it has been designed to detect full-width pulses (1.6 μs) it has been successfully operating with SPEAR-type pulses (1 ns) and with design improvement will incorporate special calibration techniques to allow self-check with very narrow pulses where required.[6] Toroid and SEM sensitivities and system noise characteristics (low frequency noise is within 20 mV p-p) normally allow detection of 0.5 mA pk and 100 nA average beams and with additional system gain down to 0.1 mA pk and 10 nA average beams. System saturation occurs at levels beyond SLAC's present operating capability.

The independent cable plant and the restricted access have further reduced accidental disruption of beams and have increased overall system reliability significantly. Standard coax and twinax cables have been used, along with "Rexolite" dielectric connectors in high radiation areas associated with beam line sensors. SLAC's experience indicates a need to change local cables and connectors in these areas on the average of every 2-3 years. Preamps located near beam lines have been reasonably well shielded by insertion into holes cut into the high density concrete housing and there has been no incidence of radiation damage to the electronics as yet.

Gating techniques have been very effective in reducing system sensitivity to synchronous noise; however random noise can still drift through gate intervals. This has posed problems in high gain channels where system sensitivity has been increased by a factor of 10 or more to detect and monitor low average current beams (< 100 nA). The frequency of extraneous beam shutoffs averages less than 2 per operating shift at present.

The most difficult problem arises from SEM ambiguity resulting from the fact that SEM plates respond to secondary particles from beams hitting material upbeam of the plate, as well as from direct interception of beams. An SEM can, therefore, unfortunately develop signals indicating "proper" steering, when in fact the beam is being missteered; it can also generate signals reversed in sign. In cases where this occurs, either additional toroids have been incorporated or complex geometries and multiple plate SEM's have been designed in an attempt to reduce the ambiguity. The latter has been only partially successful, but sufficient redundancy has been incorporated in each beam line to satisfy the basic BCS requirements.

CONCLUSIONS

In summary, the electronic beam containment system described above has been an important element in the achievement of safe operation at SLAC. While it has added somewhat to the Operating Group's work load, because of the necessity for regular daily checks, it has been accepted as a desirable, if not an essential, addition to the other safety systems, given the destructive power of the beam.

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