B Beam Containment System

B.1 Introduction

Radiation safety at an accelerator requires that beams deposit their energy at preselected locations. If beams diverge from their proper channels, high radiation levels can occur in unprotected areas. The Beam Containment System prevents accelerated beams from diverging from the desired channel, and detects excessive beam energy or intensity that could cause unacceptable radiation levels in occupied areas.

Containment of beams is usually accomplished by a combination of passive devices such as collimators, that are designed to absorb errant beams, and active devices, such as electronic monitors, that shut off beams when out-of-tolerance conditions are detected. The combination of these mechanical and electronic devices is called the Beam Containment System.

Beam containment may be lost for a number of reasons. In one instance, a magnet was connected backwards in a new beamline. This was discovered during the initial radiation survey. In another case, a beamline component was significantly damaged by the beam. Following the discovery of this damage, tests were conducted on 13 different devices. These were irradiated at various beam power levels, and the time for burn-through was recorded. As an example, a copper cylinder, 15 cm in diameter and 38 cm long, burned through its length in 22 seconds when struck by a 360 kW beam (Reference 1).

Given the destructive power of SLAC beams and the possibility of excessive radiation in occupied areas as illustrated above, formal guidelines and procedures have been adopted to ensure that appropriate protective devices are installed to contain beams. These guidelines, and the devices that are used to provide protection, are described in the following sections.

It should be noted that the Beam Containment System (BCS) is distinct and separate from the Machine Protection System (MPS). The BCS protects personnel against elevated radiation levels in occupied areas. One of the means by which this protection is achieved is to prevent damage to beamline devices that have been designated as having a safety function. The MPS also protects beamline components from damage due to high power beams, but in this case, the components being protected do not have a personnel safety function. Thus even if there were to be significant damage to an MPS device, there would be no increase in radiation levels in occupied areas. The MPS uses many of the same protection techniques and instruments as the BCS, but there is less redundancy and less rigid administrative control compared to the BCS.

B.2 Beam Containment Principles

We can define a *properly contained beam* as one that terminates on a device that can absorb either

1. The *maximum credible beam* or
2. The *allowed beam power* indefinitely.

In this latter case, the device must be protected by appropriate means. (See Glossary, page B-10, for definition of the terms in italics.)

For example, the maximum credible beam that could be delivered to a particular beamline might be as high as 100 kW if all the beam power-limiting interlocks failed. If the dump at the end of the line could absorb 100 kW indefinitely, then the beam would be safely contained at the dump. If, however, the dump had a rating of 50 kW, then it would have to be equipped with a *burn-through monitor* (BTM) and protected by devices such as *ion chambers* or *temperature detectors* that would shut off the beam when the power exceeded 50 kW. (A BTM is a pressurized container that ruptures when excessive beam power causes damage to a mechanical beam containment device.)

Now take the situation where a 50 kW beam is targeted on a 50 kW dump, and the beam is diverted from its proper trajectory in the beamline by either a steering misadjustment or a magnet failure. If the beam hits a safety collimator that is rated for 50 kW, no additional protection is needed. If the collimator is rated for less than 50 kW, it must be protected by BCS devices in a similar manner to the dump protection.

These two examples illustrate the need for an electronic protection system in addition to the mechanical devices. The electronic system serves three basic functions:

1. To monitor and limit the beam power in a beamline to the allowed value,
2. To limit the losses along a beamline that is operating at its allowed power, and
3. To protect safety-related beamline components from damage.

Thus we can arrive at a definition of beam containment as follows:

> The Beam Containment System (BCS) is a combination of mechanical devices (e.g., collimators and beam dumps) and associated protection devices (e.g., current toroids or ionization chambers) that assure that a beam is confined to an approved beam channel at an approved allowed beam power.

B.3 BCS Policy and Implementation

The SLAC Beam Containment Policy is given in Appendix I and the Implementation Guidelines are given in Appendix II. These are formal documents that are used by the Radiation Safety Officer and the Radiation Safety Committee to ensure that all safety requirements are incorporated into the design of new or modified beamlines.

B.4 Mechanical Beam Containment Devices

B.4.1 Failure Mechanisms

Mechanical devices that are used to contain beams are subject to damage or destruction from either loss of coolant or when design specifications are exceeded. (See Reference [1] for a detailed discussion of this topic.)

B.4.2 Loss of Coolant

Most SLAC power absorbers that are designed 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 exchanger capacity can have disastrous consequences for the heat dissipating areas of the power absorbers, even though the beam power may be within the rating of the absorber. 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 pulsed nature of the beam.

B.4.3 Design Limits Exceeded

Since not all power-absorbing devices are called upon to dissipate the maximum allowed beam power for indefinite periods of time, there are a wide range of design limitations for the devices in each beam line. For example, there are protection collimators with an average power absorption limit of 5 kW in beam lines that are operated at power levels up to maximum machine output. These collimators are protected against excessive power deposition by means of ionization chambers and temperature detectors in the water system, and are equipped with BTMs that shut off the beam if the collimator is damaged.

B.4.4 Device Descriptions

The specific mechanical devices used for containment are:

B.4.4.1 Protection Collimators

These are placed in strategic locations to intercept a missteered beam and prevent it from entering another beam port or from striking a shielding barrier. These devices are either cooled or uncooled, depending on whether they intercept the beam on a regular basis. They are typically at least 20 X_0 (radiation lengths) long. They offer good protection, except where a high-power beam impinges at grazing angles along the aperture. Typically they are equipped with a BTM and protected by devices such as ionization chambers, temperature sensors, and flow switches. If the electronic protective devices fail to shut off the beam, collimator burn-through could occur within a few seconds at power levels of 100 kilowatts. In this event, the BTM would turn the beam off within one to two seconds after the detection of damage to the collimator.

B.4.4.2 Beam Dumps and Beam Stoppers

These are designed to absorb a beam of specific power for an indefinite period. If they are designed to absorb the maximum credible beam, no protection devices are needed.

B.4.4.3 Burn-Through Monitors

Burn-Through Monitors (BTMs) are used to detect the onset of damage to collimators, dumps, and stoppers. BTMs are pressurized cavities, usually located at or near shower maximum, that are designed to rupture when the device being protected absorbs greater than its allowed beam power. A pressure switch connected to the cavity turns off the beam through the Personnel Protection System. The switch acts through energized relays that de-energize on either a BTM fault, the loss of power, or a short or open circuit on any connecting cable.

B.4.4.4 Blow-Out Fuses

These fuses are an integral part of the stopper assembly. When excess power is absorbed by the stopper, the fuse melts, allowing air to enter the beamline vacuum pipe, resulting in the beam scattering.

B.5 Electrical Beam Containment Devices

B.5.1 Bending Magnets

These are frequently used as protective devices in the containment system. Typically the magnet polarity, the magnet current, and the on/off status of the power supply are monitored and interlocked, such that when an out-of-tolerance condition is detected, the beam is deflected into a safe location, or is prevented from entering a beamline that has an inadequate power rating.

B.6 Electronic Beam Containment Devices

If mechanical containment devices could be designed to absorb the maximum credible beam power, there would be no need for additional electronic protection or for the installation of BTMs. However, cost and physical space limitations preclude such an approach in most beamline designs. The alternative is to provide fast electronic protection for devices and beamlines. The electronic devices in the BCS provide this protection. (As noted earlier, the BTMs do not act through the electronic shut-off circuits of the BCS. They operate directly through the Personnel Protection System to shut-off beams.)

B.6.1 BCS Electronics

Each electronic protection path or system, from the sensor (ion chamber, flow switch, etc.) to the processing electronics, is designed to be as fail-safe as possible, with self-checking signals that serve to confirm the correct operation of the sensor and electronic module. This continuous self-checking coupled with formal administrative procedures, provides a protection system that has both high reliability and high availability. (See Reference [4] for more information.)

B.6.2 Design Philosophy

- All systems incorporate continuous self-checking features to ensure integrity of the transducer, the cabling, and the electronic processing unit.
- All pulsed equipment, with the exception of ion chamber electronics, utilizes narrow window gating (5-10 μs) at beam and test time to reduce the effects of noise that may be introduced into the electronic modules via the cable plant.
- The protection devices in each beam line are independent of each other and are different whenever possible. For example, one protection channel might monitor the average beam current while another monitors the beam repetition rate. Type diversity such as this reduces the chances that a common mode failure would disable both channels simultaneously. In practice, three or more independent devices are used for protection in most beamlines.
- Beam power is monitored by measuring beam current. Beam energy is known because the number of klystrons accelerating the beam is known, or the field strength of bending magnets (or the magnet currents) can be measured. Beam current is typically measured by beam line current transformers (toroids).
- The requirement for verification that a beam has reached its proper destination without significant beam loss is met by using toroid comparators that measure and compare beam current on a pulse-to-pulse basis at two locations in a beam line.

Beam loss in a beamline may also be measured by discrete ionization chambers placed near mechanical devices or by long ion chambers that protect a section of the beamline or the whole beamline.

When a fault is detected, beams are shut off by three independent methods.

Equipment and cabling is protected in locked racks.

Operation of the equipment is checked daily using formal procedures.

B.6.3 Beamline Sensors

Typical sensors, or transducers, used in the BCS include ionization chambers, beam current toroids, flow switches, and temperature detectors.

B.6.4 Processing Electronics

Signals from transducers are processed in electronic modules that shut off the beam when out-of tolerance conditions are detected.

Processing modules measure:

- Average current
- Charge per pulse
- Beam repetition rate
- Beam loss between two beamline sensors (toroid comparator)
- Beam loss along a beamline (long ion chamber)
- Beam loss at a point (discrete ion chamber)
- Temperature of devices or water systems
- Position of stoppers and other mechanical devices

B.6.5 Beam Shut-off Paths

Beam shut-off for a BCS fault has the following characteristics:

- High speed — within a few beam pulses
- Redundant — three shut-off methods are used
- Diversity — each shut-off method is different

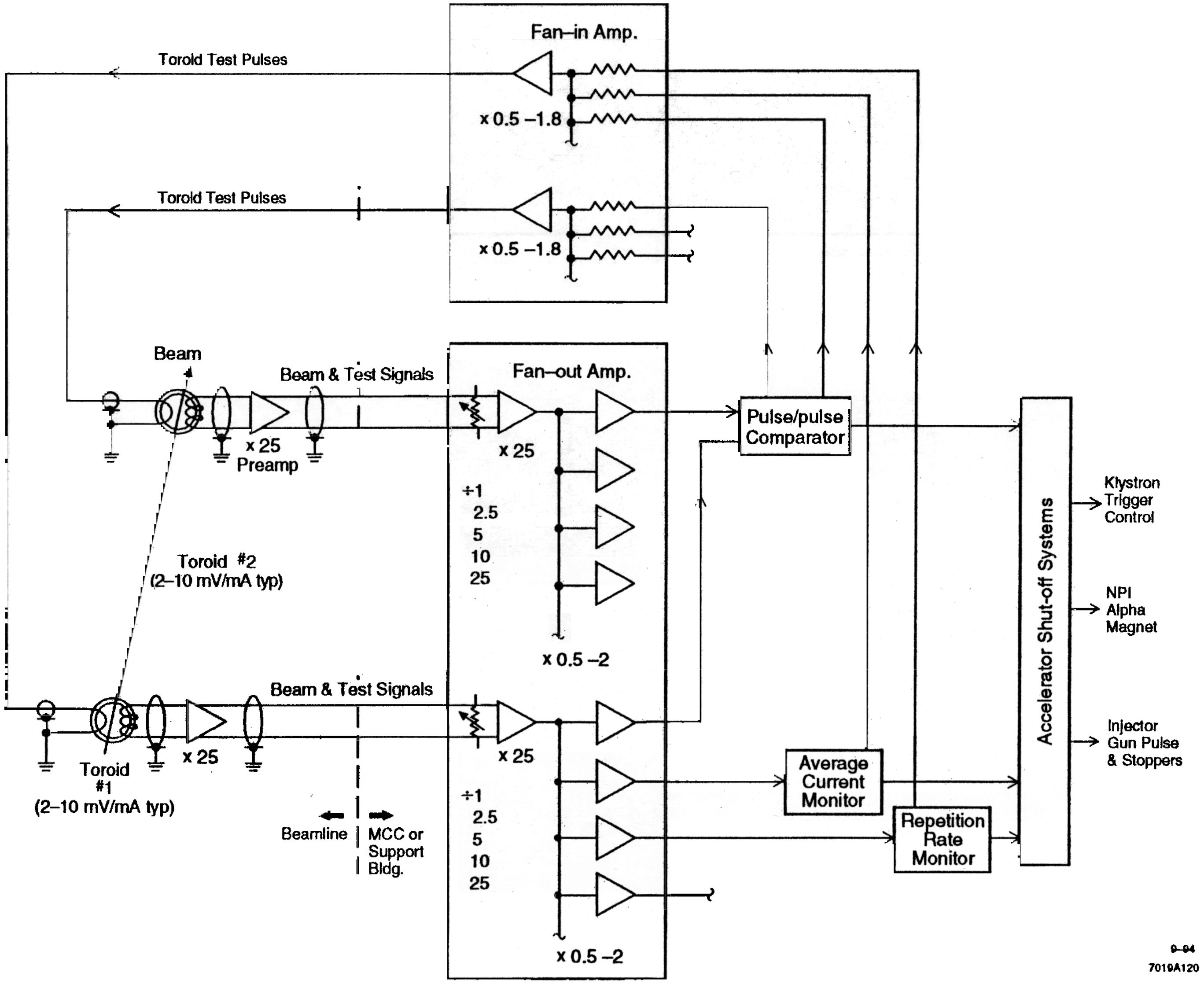

Figure B.1: Typical BCS Signal Distribution

Beam Containment Policy[1]

The SLAC policy for containing beams requires all three of the following to be met:

1. Primary beams must be prevented from escaping Beam Containment.
   Secondary beams must also be confined if they are of sufficient power to exceed SLAC radiation design limits.
2. Primary and secondary beams must be prevented from striking beamline components or the shielding enclosing the Radiation Containment Area if this results in radiation levels in occupied areas that exceed SLAC radiation design limits.
3. Primary and secondary beams must be turned off if excessive radiation levels occur in occupied areas or if the beam power striking a device, which is designated to contain the beam, exceeds the power limit of the device.

Implementation Guidelines

To achieve the goals stated in the policy, the following guidelines have been adopted.[1]

B.8.1 Beamline Design

Beamlines are designed by beamline engineers or physicists:

- With advice from Radiation Physics;
- Using these Beam Containment guidelines;
- With consultation from the Radiation Safety Officer for variances;
- With the advice from Radiation Safety Committee before construction starts.

Design of beamline includes an estimate of the maximum credible beam power that can be delivered, and the specification of the locations of mechanical containment devices with their power absorption capabilities. Ray traces should be included that demonstrate the normal beam path and the consequences of beam missteering. Shielding calculations must be made for potential beam losses.

In the description below, unless otherwise stated, the radiation levels in occupied areas must not exceed the allowable levels for normal beam operation.

B.8.1.1 Equipment Requirements

1. The beam power in a beamline must be limited to the allowed beam power by each of three independent protection devices if the allowed power is less than the maximum credible beam power.

   Beam losses in Radiation Containment Areas may need to be limited by two protection devices to prevent radiation levels in occupied areas from exceeding those given in Section B.8.1.3 on page B-9 for normal beam operation.
2. Mechanical Beam Containment devices, such as dumps, collimators, and stoppers must either
   a. Be capable of intercepting the maximum credible beam power for an indefinite time period, or
   b. If not able to absorb the maximum credible beam power, must be protected by at least two protection devices.

Current policy at time of writing. Contact the Radiation Safety Office for latest revision.

These devices must turn off the beam to prevent exceeding the power limit of the mechanical device. If the mechanical beam containment device is capable of intercepting the allowed beam power, the protection devices in Point 1 may serve this function.

If the protection devices mentioned in Points 1 or 2 fail and the maximum credible beam strikes a mechanical device, the radiation levels in occupied areas must not exceed the allowable levels for accident cases given in Section B.8.1.3 on page B-9.

3. Mechanical beam containment devices as described in Point 2 must also be equipped with a Burn-Through Monitor (BTM) over as large an area as the beam can be steered if the device cannot absorb the maximum credible beam indefinitely.
4. Beam containment devices, such as magnets, and mechanical and electronic protection devices, must be designed or implemented to fail in a safe manner.
5. PPS stoppers are considered to be beam containment devices in that their function is to "contain" the beam upstream of a secured area when access is permitted. The required redundancy of PPS stoppers depends on the beamline design.
    a. If the beamline is designed to permit the beam to be incident on the first stopper when access is permitted to the beamline downbeam of the stoppers, two additional PPS stoppers are normally required. If fewer stoppers are used, the design must be justified on the basis of adequate safety.
    b. If the beamline is designed so that the beam cannot be incident on the first PPS stopper unless a prior failure occurs, then at least two PPS stoppers are normally required. If fewer stoppers are used, the design must be justified on the basis of adequate safety.
    c. One or more magnets can replace one of the stoppers.
    d. These stoppers must meet the criteria for beam containment devices as indicated in Points 2, 3, and 4 above.
6. Beam Shut-Off Ion Chambers (BSOIC) should be associated with each beamline unless it is proven that they are not needed. The BSOIC is responsive to radiation levels, and is not considered as one of the electronic protection devices for limiting beam power or losses.
7. Primary beams must be prevented from entering secondary beam channels unless the secondary beam channels are also completely confined. This may be accomplished by one or more of the following:
    a. All bends in the primary beam line must be in different planes than the secondary beam channels.
    b. Failure of magnets or the most radical steering, at all energies, must not send the primary beam into the secondary beam channels.
    c. Secondary beam channels must be plugged or shadowed with a beam containment device meeting the criteria in Points 2, 3, and 4 above.
    d. A redundant system of permanent magnets must prevent the primary beam from entering the secondary beam channels. The permanent magnets must be protected from beam related damage.
    e. Charged particle secondary beams can be controlled by proper secondary transport magnet polarity and/or transport energy. The polarity must be properly controlled and/or interlocked into the Beam Containment Shut-Off System.

B.8.1.2 Administrative Requirements

1. All devices described in Section B.8.1.1 above must be certified to function properly before the beamline is operated.

2. Sufficient scheduled accelerator time must be provided for adequate beam containment checkout as prescribed by the responsible Radiation Physicist and the Accelerator Department Safety Office, or the Stanford Synchrotron Research Laboratory Safety Office. To ensure that this time is allocated, line items may be included on the Beam Authorization Sheet.
3. All protection devices must be protected against unauthorized modification or bypassing. Wherever possible, appropriate fail-safe and self-checking features are to be included in the design.
4. Protection devices should be reviewed by the Radiation Safety Committee.
5. The burden of proof for the safety of the beamline design lies with the designer. It is not the responsibility of the Radiation Safety Committee to prove the safety.

B.8.1.3 Maximum Allowable Radiation Design Levels

The maximum allowable radiation levels in potentially occupied areas are limited to the following:

1. Normal beam operation — The total integrated dose equivalent to an individual outside secured area must not exceed 10 millisievert (1 rem) in a year when running the allowed beam power and the beam is fully contained. This limit shall include radiation levels caused by normal beam losses and occasional missteered beam conditions.
2. System Failures — In the event of a BCS failure, the total integrated whole body dose equivalent to an individual outside secured area shall not exceed 30 millisievert (3 rem) for broad beam exposure. Narrow beam, ≤2 inch diameter, exposures shall not exceed 120 millisievert (12 rem). With dose rates on the order of 250 millisievert/hr. (25 rem/hr) under accident conditions, the beam must be turned off in approximately 1/10 hour to meet these criteria. Burn-Through Monitors (BTMs) must be used to limit the duration of the accident.

System failures are defined as follows:

   a. All the beamline containment protection devices have failed, thereby permitting the maximum credible beam to enter the beamline. Loss of this maximum credible beam at any point shall not cause radiation dose exposure levels to exceed those stated in Section B.8.1.3, Point 2, above.

   b. If any beam containment device or its associated protection devices fail, such that the beam is no longer properly contained, the resulting radiation levels must be limited as in Section B.8.1.3, Point 2. Since PPS stoppers are categorized as beam containment devices, the above criteria applies in the event of the failure of any stopper. As long as one stopper remains, the above criteria applies.

B.8.1.4 Documentation (For presentation to the Radiation Committee)

1. A documentary description of each beam line should be prepared and circulated to the Radiation Safety Committee. Its preparation should be the responsibility of the beam line engineer and the responsible Radiation Physicist.
2. The documentation should contain the following elements:
   a. A general beam layout drawing showing all elements of the beam and the adjacent equipment.
   b. Ray traces of areas of interest.
   c. A list of all safety components and a quantitative description of their function.
   d. A statement of assumptions.

   e. A description of the accidents envisioned in the design.
   f. A list and description of routine inspections required to ensure integrity of the safety system.
   g. Description of tests or presentation of calculations that support performance claims of safety features or devices.
   h. Description of conditions and limitations of the design analysis, that is, what conditions were not covered in the analysis.
3. All drawings and sketches should contain SLAC drawing numbers and all components should be clearly identified.

Glossary

Allowed Beam Power	The highest primary power permitted for the beamline in question by administrative and/or electronic restraints. The Radiation Physicist responsible for the beamline determines the allowable beam power.
Beam Containment	A beam channel defined by a system of devices, that is, shielding, dumps, collimators, stoppers, magnets, or electronic restraints, designed to "contain" the beam and/or limit the beam power and/or beam losses to prevent excessive radiation in occupied areas.
Beam Containment Shut-off System	This system utilizes two electronic summary modules that shut off the beam by three independent methods.
Beamline Engineer	The engineer responsible for the design of the beamline, including the provision of all safety devices such as collimators, dumps, ion chambers, and other containment devices.
Beam Shut-Off Ion Chamber (BSOIC)	A device wired into the PPS to put in beam stoppers (or turn off gun High Voltage) if radiation is detected above a pre-set level.
Blowout Fuse	A thermal plug that is part of a stopper assembly. It is designed to rupture when the beam power absorbed by the stopper exceeds the design value. Air enters the accelerator vacuum pipe and the beam is scattered.
Burn-Through Monitor (BTM)	A device wired into the PPS to turn off the VVSs if the mechanical beam containment device has melted. Burn-Through Monitors are presently limited to pressure or vacuum release. The BTM must turn off the VVSs in less than 1/10 of the calculated burn-through time of the beam containment device when the device is absorbing greater than the specified beam power.

Controlled Area	Areas that may contain potential radiation hazards. In these areas, a dosimeter badge must be carried at all times. These areas are: • Inside the Controlled Area fence with entrance points at the Sector 30 guard shack, the SSRL/SPEAR gate, and the Alpine road gate. • The high bay area of the Test Lab (Building 44). • Certain areas of the Cryogenics Building (Building 06), Building 08, and Building 24.
Ion Chamber	A beamline device that responds to beam-related ionizing radiation. It consists of a gas-filled chamber with an inner electrode at high voltage. The output signal current is transmitted on coaxial cable to an integrating circuit in one of the support buildings. The integrator output trips a comparator circuit when the ionization level exceeds a preset level.
Maximum Credible Beam	The highest credible beam power the accelerator can deliver to the point in question assuming all protection devices have failed.
Normal Beam Operation	Beamlines operated within the allowed beam power, and with well-steered beams.
Properly Contained Beam	A beam that terminates on a device that can absorb the Maximum Credible Beam indefinitely, or one that can absorb the Allowed Beam indefinitely, provided it is protected by appropriate means such as ionization chambers, and is equipped with a Burn-through Monitor (BTM).
Protection Devices	Electronic circuits or modules connected to beamline transducers such as toroids, flow switches, or ion chambers that prevent the beam rate, beam power, temperature, or beam losses from exceeding specified values. When out-of-tolerance conditions are detected by these electronic modules, beams are shut off by the Beam Containment Shut-Off System.
Radiation Containment Area	An area designed to confine hazardous radiation and prevent personnel access by means of shields, fences, procedures, etc. The adequacy of such enclosures must be approved by the Accelerator Department Safety Office or the SSRL Safety Office and the Radiation Physics Department.
Responsible Radiation Physicist	That member of the Radiation Physics staff assigned to the design and operation of a specific beam line.
Secondary Beam Channels	A beamline in which the incoming beam is the result of an interaction of the primary beam with a target or a synchrotron radiation beamline.

Secured Areas	Radiation containment areas whose doors or gates are locked with strictly controlled keys or are interlocked in the Personnel Protection System.
System Failure	System failure of the BCS occurs when all the beamline containment protection devices have failed, thereby permitting the Maximum Credible Beam to enter the beamline or when any beam containment device or its associated protection devices has failed such that the beam is no longer Properly Contained.

References

[1] "Tests and Description of Beam Containment Devices and Instrumentation — A New Dimension in Safety Problems." D. Walz et al. IEEE Trans. *Nuclear Science*. March 1973. NS-20, 465.

[2] "Safety of Accelerator Facilities." DOE 5480.25, November 1992.

[3] "A Precision Actuator and Shaft Encoder for a High Radiation Environment and Other Beam Component Developments at SLAC." L. R. Lucas and D. R. Walz. SLAC Pub 879, March 1971. IEEE Trans. *Nuclear Science*, June 1971. NS-18 #3, June 71.

[4] "Operational Experience with SLAC's Beam Containment Electronics." T. Constant, K.F. Crook, D. Heggie. SLAC Pub. 1901, March 1977. Particle Accelerator Conference 1977.