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Radiation Safety System for Stanford Synchrotron Radiation Laboratory*

James C. Liu, N. E. Ipe and R. Yotam

Stanford Linear Accelerator Center, P. O. Box 4349, Stanford, CA 94309

ABSTRACT

Radiation Safety System (RSS) at the Stanford Synchrotron Radiation Laboratory is summarized and reviewed. The RSS, which is designed to protect people from prompt radiation hazards from accelerator operation, consists of the Access Control System (ACS) and the Beam Containment System (BCS). The ACS prevents people from being exposed to the lethal radiation level inside the shielding housing (called a PPS area at SLAC). The ACS for a PPS area consists of the shielding housing, beam inhibiting devices, and a standard entry module at each entrance. The BCS protects people from the prompt radiation hazards outside a PPS area under both normal and abnormal beam loss situations. The BCS consists of the active power (current/energy) limiting devices, beam stoppers, shielding, and an active radiation monitor system. The policies and practices in setting up the RSS at SLAC are illustrated.

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INTRODUCTION

The Stanford Synchrotron Radiation Laboratory (SSRL) is located within the Site of the Stanford Linear Accelerator Center (SLAC). Although they are operated independently, SSRL conforms to the same requirements as SLAC with regard to environment, safety, and health issues. Figure 1 shows the SSRL consisting of an injector and a storage ring called SPEAR (Stanford Positron Electron Asymmetric Ring). The injector is comprised of a 2.5-MeV radio-frequency gun, a 150-MeV Linac, and a 3-GeV Booster synchrotron. There are three beam transport lines. The Linac-to-Diagnostic room (LTD) line transports the beam from the Linac room to the Faraday cup in the Diagnostic room for beam diagnosis. The Linac-to-Booster (LTB) line directs the beam from the Linac room to the Booster for further acceleration through a 760-keV RF cavity. The Booster-to-SPEAR (BTS) line takes the beam from the Booster and inject into SPEAR. SPEAR can accelerate the stored beam (100 mA, 4.9×10^{11} e^-) through its two RF cavities. Note that the beam parameters (energy and intensity) shown in Figure 1 are design limits, not physical limits. Figure 1 also shows the main synchrotron radiation beamlines. There are potential radiation safety issues for the workers and the general public from the SSRL operation. This paper will only address the Radiation Safety System (RSS) used at SLAC to protect the workers from the prompt radiation hazards inside and outside the shielding enclosure.

RADIATION SAFETY SYSTEM (RSS)

Figure 2 shows that the two subsystems of the RSS and its interlock system. The ACS keeps people from being inside a PPS area where beam may be running. The BCS limits the beam power and protects people from the prompt radiation hazards outside a PPS area under both normal and abnormal beam loss situations.

SSRL has four major PPS areas: the Linac and Diagnostic rooms (called the Linac here), the Booster synchrotron, SPEAR, and the synchrotron radiation experimental hutches. The beam may be in one or more PPS areas, while the remaining PPS areas are in safe-access states. The radiation safety system for the x-ray beamline hutches is called the Hutch Protection System (HPS) at SSRL. However, for our discussions in this paper, it will be called RSS since the HPS has functions similar to those of a RSS. Detailed descriptions of the ACS logic and the BCS for the SSRL Injector (i.e., Linac and Booster) and that for the SPEAR have been given by Yotam [1,2].

Access Control System (ACS)

The 10CFR835 [3] requires that the access control shall function automatically (or locked) to ensure that no people are inside a High Radiation Area where he can receive more than 0.01 Sv in any one hour. The lethal radiation level inside the PPS areas of SSRL obviously requires the use of an interlocked ACS. There are generally four access states for a PPS area:

1. Permitted Access (PA): The PA state allows unlimited and uncontrolled entry, and both the radiation and electrical hazards are interlocked to be off.
2. Controlled Access (CA): The CA state allows limited and controlled entry, and both the radiation and electrical hazards are interlocked to be off.
3. Restricted Access (RA): The RA state allows very limited and controlled entry, and only the radiation hazards are interlocked to be off. Persons are allowed to enter a PPS area with electrical hazards on to perform special electrical tests with the Restricted Access Safety Key (RASK).
4. No Access (NA): This state allows no one in a PPS area, and both radiation and electrical hazards can be on.

The ACS at SSRL consists of 3 elements: beam inhibiting devices, shielding housing (concrete structure for accelerator housing and lead-wall housing for hutches), and an entry module at each entrance of a PPS area (see Figure 2).

The beam inhibiting devices are interlocked safety devices that remove beam and hazards in the occupiable PPS areas (e.g., interlocked power supplies for the high voltage to the gun and modulators; beam stoppers in the beamline between two PPS areas). The shielding housing itself also serves as a physical barrier, which makes the access to a hazardous PPS area possible only through the entry points.

Figure 1 shows the six entry points to the PPS areas of the Injector and SPEAR. The typical features of the entry module of a PPS area (e.g., see the PPS area A in Figure 3) include:

1. An interlocked and lockable outer door with emergency entry and exit capabilities.

2. An interlocked and unlocked inner gate and a maze. This is the situation for SPEAR entrances. For the Injector, a movable concrete shielding block is used at each entry point, instead of an inner gate and a maze.
3. A keybank with keys. In the CA and RA states, everyone entering the area is required to take a key from the keybank and carries it with him/her during the period of access.
4. A key switch and push button for door release by operators.
5. An access and beam status display.
6. Intercom or telephone for communication between workers and operators.
7. TV camera for better visual control.
8. Search pre-set and reset buttons (used in a search). A search of a PPS area, following a well-defined procedure, is required after the area has been in the PA state.

The emergency-off push button and the emergency exit are two features that allow people to be able to respond to dangerous beam situations if they are accidentally left inside a PPS area. The above features allow the operators to maintain access control and allow people a safe entry and they are all required in the guidance [1] and most of them are standard features at SSRL with only a few exceptions. For example, the Linac and the x-ray hutch PPS areas do not have the keybank, because there are no CA and RA states. The features 2, 6, and 7 above are not necessary in the hutch PPS areas either.

Beam Containment System (BCS)

Complementing the ACS, the BCS is designed to protect the people outside the PPS area from exposure to the radiation resulting from the normal and abnormal beam losses. Abnormal beam losses can be resulted from either mis-steered beam or safety system failure situation, which will be defined later. Therefore, the BCS consists of four elements (see Figures 2 and 3): active power (current and energy) limiting devices (PLDs), beam stoppers, shielding (shielding housing and local shielding), and active radiation monitoring devices (ARMDs). These four elements of the BCS are described below.

Active Power Limiting Devices (PLDs)

There are three beam power levels to be considered; normal power, allowed power and maximum credible power. SLAC policy requires a minimum of three interlocked current-limiting devices to monitor and limit the beam power to be less than the allowed beam power. The energy of the beam also needs to be limited if it is not limited by physics of the accelerator.

The allowed beam current in Linac (and thus the Booster and SPEAR) was controlled by a magnet chopper, which removes 99.9% of the beam from the RF gun, to no more than 3.1×10^{10} electrons per second (10 pulses per second), equivalent to 14.4 W at 3 GeV. The beam intensity is monitored by three average current monitors (ACMs) in Linac (see Figure 4). Due to beam loading effect, the maximum credible power at 3-GeV was only 45 W.

Beam Stoppers

Figure 4 shows the beam stopper systems, as well as the three average current limiting devices, at SSRL. The SLAC policy requires at least two, generally three, beam stoppers to protect people in a downstream PPS area (e.g., area B in Figure 3) while the beam is in the upstream PPS area (e.g., area A in Figure 3). The beam stopper can be either a mechanical device that can fully absorb the beam at the maximum credible power indefinitely, or a bending magnet that prevents the beam from entering an occupiable PPS area. For example (see the LTB line in Figure 4), the three beam stoppers between the Linac and Booster are one bending magnet (B1) and two mechanical devices (LTB ST1 and ST2). The three beam stoppers between the Booster and SPEAR are the ejection septum and two mechanical devices (BTS ST1 and ST2) in the BTS line. The three beam stoppers inside the SPEAR ring to dump the stored beam are the RF and two mechanical devices (18ST1 and 18ST2), which are thin metal plates to scatter the stored beam so that the beam is lost over a large distance around the ring.

Not all synchrotron radiation beamlines have the same radiation safety features. Only the general features are described here to illustrate the safety requirements and principles for the synchrotron radiation beamlines. Figure 4 shows that there are two injection stoppers in each main beamline to block the SPEAR injection beam if the injection beam accidentally goes into the beamline during injection. The water-cooled movable mask is used to protect the two injection stoppers from the intense synchrotron radiation. The movable mask and the two injection stoppers in every main beamline are interlocked to be in when the injection septum of SPEAR is on. The beam stoppers to block the gas bremsstrahlung from going to the X-ray hutch are two mechanical devices called hutch shutters in the X-ray branch line. The two hutch shutters are interlocked to be in when the hutch is in the PA state. There is also one fixed lead beam stop in the end of the x-ray hutch or in the median plane of the VUV line to absorb the gas bremsstrahlung. There is one (or two) beam shutter followed by an isolation valve for each VUV branch line, similar to the function of hutch shutters for the x-ray line.

Shielding

The shielding housing serves not only as a barrier for ACS, but also to shield the radiation from beam losses. In some cases localized shielding like metal is also used to supplement to shielding housing, in particular in the cases of abnormal beam loss situations. The Injector shielding design has been described in details elsewhere [4,5]. A few examples of the Injector shielding design are described here using Figure 5 to show the current policies and practices of shielding design at SSRL and SLAC.

There are three shielding design criteria used for three different beam loss situations (normal, mis-steering, and system-failure):

1. For normal beam losses, the annual dose equivalent outside the Injector concrete shield surface is less than 10 mSv. This is a DOE-mandated shielding design limit [3]. An example in this case is that the Linac beam can go to the Faraday cup in the Diagnostic room for 2000 hours per year (item labeled FC in Figure 5). Therefore, the dose equivalent rate outside the room from this normal beam operation is designed to be less than 5 μSv/h (so the annual dose equivalent for 2000 h is < 10 mSv). The storage ring shielding design is currently under revision for SPEAR3 project and a shielding design limit of 1 mSv/y is used because of the high occupancy of non-radiation workers in experimental floor around the ring. Note that normal beam losses from the Linac to Booster and to SPEAR are estimated and given by accelerator physicist.
2. In the mis-steering case, it is assumed that the beam at the allowed beam power can be lost at any point along the beamline. Since there are no DOE or SLAC mandated limits, a guideline of 4 mSv/h maximum dose rate at the shield surface from such missteering was used. For example (see Figure 5), the B2 bending magnet in the LTB line can be misadjusted to have zero or reversed polarity fields. The missteered beams would be intercepted by the lead brick shielding placed inside the B2 coils so that the beams will not shower in the Booster ring outer wall. The resulting maximum dose equivalent rates from the containment of these missteered beams (zero and reversed polarity fields) were estimated to be 3.75 and 1.8 mSv/h, respectively, which were below the guideline of 4 mSv/h. The radiation levels resulting from the missteered beam losses in the Linac are all below the guideline, due to the Linac's lower beam energy. Note that this missteered beam containment analysis has been performed for most bending magnets and some quadruples, for which the missteering is possible and the dose results is also significant.
3. The third criterion is a SLAC policy that, for a safety system failure event, the integral dose equivalent per event shall be less than 0.03 Sv or the maximum dose equivalent rate is below 0.25 Sv/h. One example of system failure situations is that two (or one) out of three beam stoppers fail. The worst case of a system failure event in Linac is that the beam (at the allowed beam power) is hitting the last beam stopper ST2 while people are inside the Booster ring (i.e., the bending magnet Dl is on while it should be off, the stopper ST1 is out while it should be in and only ST2 is in). The resulting maximum dose equivalent rate inside the Booster ring was 0.15 Sv/h, which is below the limit of 0.25 Sv/h. Another example is that when all ACMs fail and the beam with the maximum credible beam power is lost at a point. However, simultaneous failure of power limiting devices and beam stoppers are considered incredible.

Active Radiation Monitoring Devices (ARMDs)

ARMD is required to terminate or mitigate the radiation hazards from abnormal beam losses in areas that are potentially occupied by people. The Beam Shut Off Ionization Chambers (BSOIC), a tissue-equivalent ionization chamber with an electrometer designed and made at SLAC, are used as the active radiation monitoring devices at SSRL. For example, BSOIC S3 and S4 in Figure 5 are used to monitor and terminate the missteering and system-failure situations mentioned above. The BSOICs are interlocked to trip the beam off, if the preset trip level (generally at 0.1 mGy/h) is exceeded or the BSOIC power supply is lost. BSOICs also have a lower alarm level generally set at 0.05 mGy/h for warning purpose. The response times of the BSOICs around the SPEAR ring have been increased so that they will not respond to the short radiation spike resulting from a stored beam dump.

Beam Interlock Network

The interlock network of the PPS for SSRL is shown in the dotted lines in Figure 2. If any ACM detects a current higher than the preset limit, the interlock system will remove the triggers to the modulators and the triggers to the RF amplifiers. Any BSOIC detecting radiation levels higher than its trip level will also remove the triggers. These problems can be regarded as violations of the BCS.

The access state of a PPS area is also interlocked to the status of the relevant beam stoppers. For example, the access to the Booster ring requires that the LTB stoppers (LTB B1 magnet, STl, and ST2) be in/off and the Booster RF cavity be off (the electrical hazards are also off). If there is an ACS violation in a PPS area, e.g., a forced entry, the relevant stoppers will respond. Such responses are shown in Table 1 [1]. If there is an ACS violation in any X-ray hutch, the two hutch shutters, the three SPEAR ring stoppers, and the three BTS stoppers will respond (i.e., the mechanical devices will be in and the magnets will be off). The LTB stoppers and the Booster RF will respond unless the BTS stoppers were already in. No response in the Linac is necessary in this case. If there is an ACS violation in the Booster ring, the first response is that the LTB stoppers will be in and the Booster RF will be off. The Linac will respond unless the LTB stoppers were already in. The Linac response is that the high voltage power supply for the modulators and the triggers to the modulators will be off.

Synchrotron radiation accelerator facilities are low power facilities, compared with other types of accelerator facilities (e.g., the SLAC main facility). Because of the low power of the primary electron beam, the BCS of the Injector and SPEAR are less complex in that there is no need to protect the shielding and beam stoppers from potential beam damage. For example, for radiation safety purpose, there are no cooling water, burn-through monitor, or ion chamber attached to, and to protect, any local lead shielding or beam stoppers that are used to contain the beam. However, due to the high power of the synchrotron radiation, the devices that contain or absorb the synchrotron radiation in the beamlines (e.g., masks, hutch shutters, and beam stop) must be water-cooled and/or equipped with burn-through monitors.

CONCLUSIONS

Radiation safety problems at accelerators facilities are different from those of nuclear facilities, especially in the protection against the prompt radiation fields. Using the Radiation Safety System of SSRL as an example, the radiation protection policies and practices at SLAC and SSRL are described. The shielding, entry control, beam inhibiting devices, active power limiting system, and active radiation monitoring system are important engineering measures of the RSS to control the prompt radiation hazards. It is hoped that this overview would assist to narrow down the difference in the radiation protection policies and practices among accelerator facilities.

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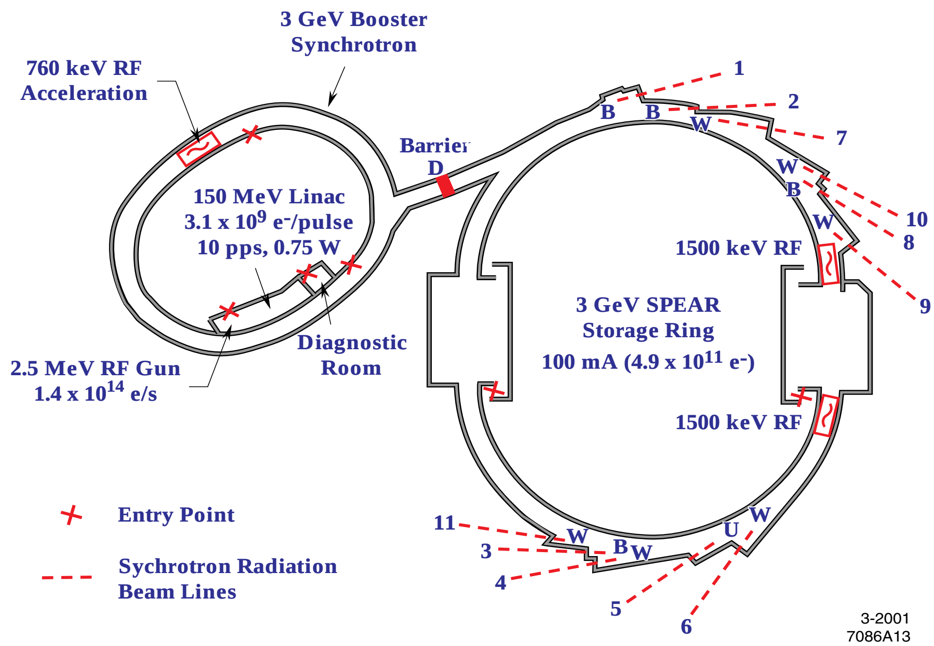

Figure 1. A schematic layout of SSRL showing the Injector (Linac and Booster Synchrotron) and the storage ring SPEAR. The parameters (beam energy and intensity) shown are design limits, not physical limits. The six entry points to the Injector and SPEAR are also shown. Eleven main synchrotron radiation beamlines are also shown (B: bending magnet, W: Wiggler, U: undulator).

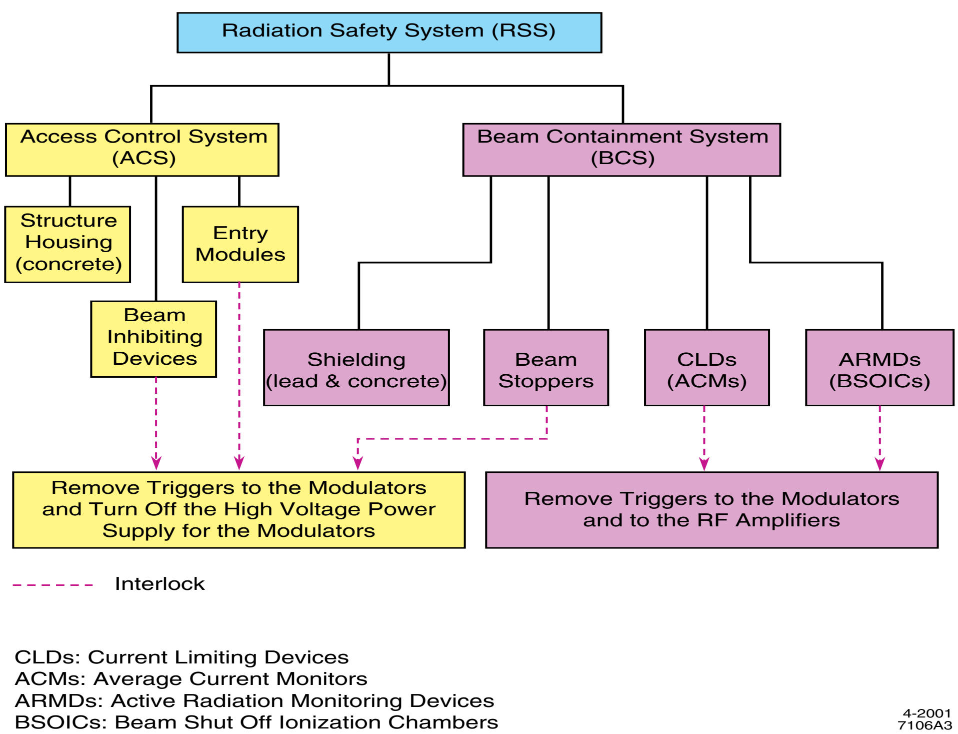

Figure 2. The Radiation Safety System (RSS) consists of the Access Control System (ACS) and the Beam Containment System (BCS). The interlock network is shown as the dotted lines (see text for detail description).

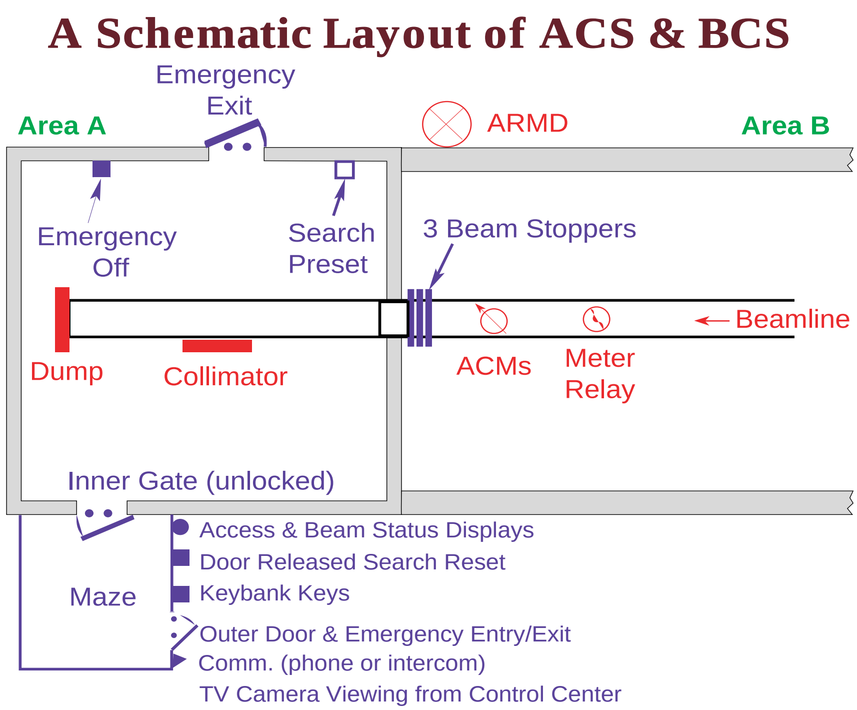

Figure 3. The features of an ACS entry module of a PPS area. The four elements of the BCS are also shown (see text for more detail).

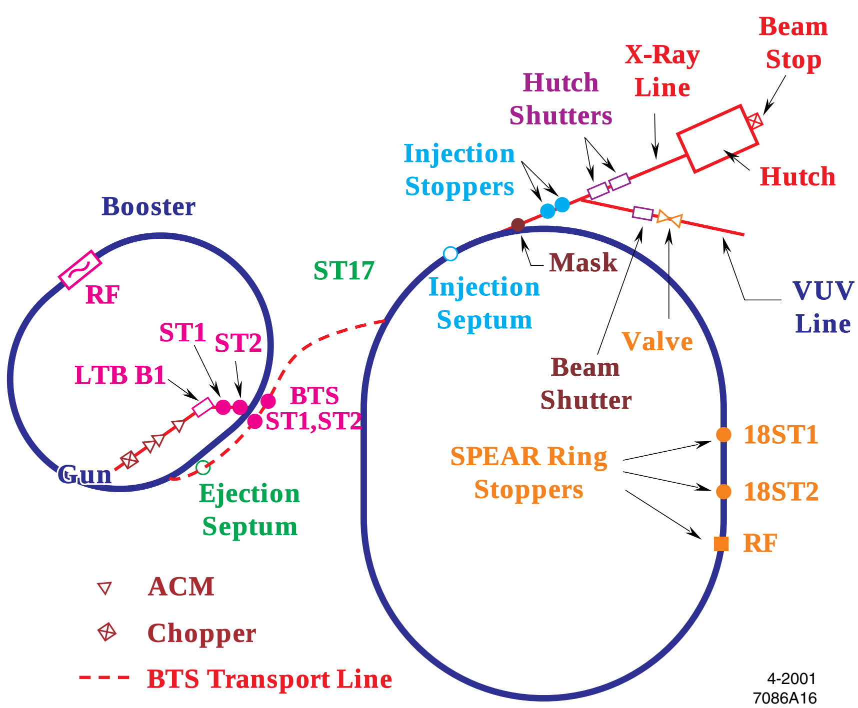

Figure 4. Active current limiting devices (average current monitors) and beam stopper systems at SSRL.

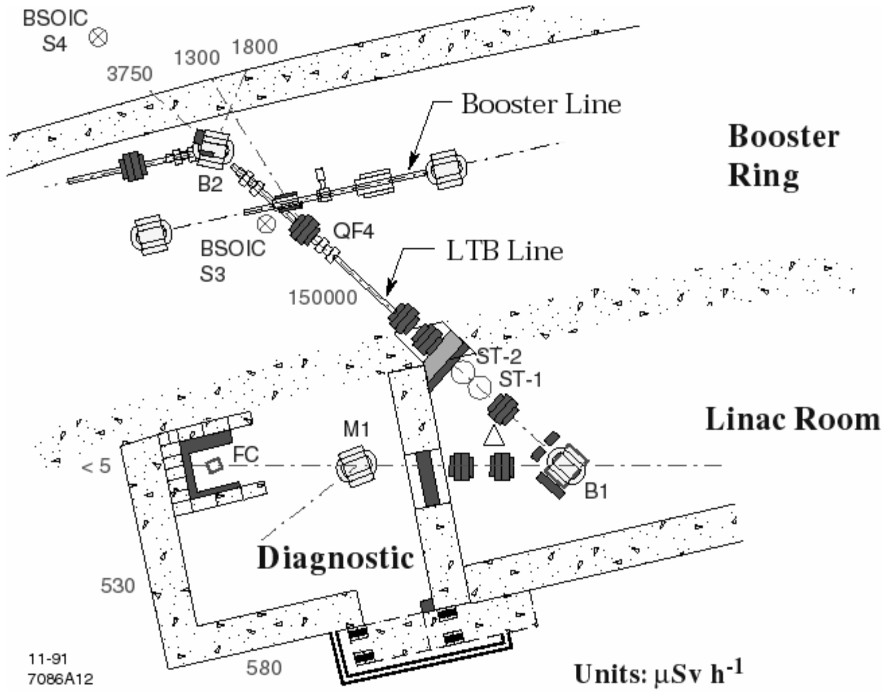

Figure 5. A few examples illustrating the shielding design principles and practices for the SSRL Injector (see text for the explanation of the numbers and symbols).

Table 1. The beam stopper response of the beam interlock safety system in case of an ACS violation [1].

Response / ACS Violation	Hutch Shutters	SPEAR Ring Stoppers [a]	BTS Stoppers [b]	LTB Stoppers [c] and Booster RF	Linac [d]	Additional
Hutch	In	In	In / Off	In / Off if BTS Stoppers are not In	N / A	—
SPEAR Ring	N / A	In	In / Off	In / Off if BTS Stoppers are not In	Off if LTB or BTS Stoppers are not In / Off	SPEAR Electrical and RF Hazards Off
Booster Ring	N / A	N / A	N / R	In / Off	Off if LTB Stoppers are not In / Off	Booster Electrical and RF Hazards Off
Linac	N / A	N / A	N / R	LTB Stoppers In / Off	Off	—

N / A = Not Applicable N / R = Not Required
a) 18STI, 18ST2 and RF
b) Ejection Septum, BTS ST1, and BTS ST2
c) LTB B1 Magnet, LTB ST1 and LTB ST2
d) High Voltage Power Supply for Modulators and Triggers to the Modulators

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