SLAC-PUB-7786 (August 1998)

RADIATION SAFETY SYSTEM OF THE B-FACTORY AT THE STANFORD LINEAR ACCELERATOR CENTER

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Abstract – The radiation safety system (RSS) of the B-Factory accelerator facility at the Stanford Linear Accelerator Center (SLAC) is described. The RSS, which is designed to protect people from prompt radiation exposure due to beam operation, consists of the access control system (ACS) and the radiation containment system (RCS). The ACS prevents people from being exposed to the very high radiation levels inside a beamline shielding housing. The ACS consists of barriers, a standard entry module at every entrance, and beam stoppers. The RCS prevents people from being exposed to the radiation outside a shielding housing, due to either normal or abnormal operation. The RCS consists of power limiting devices, shielding, dump/collimator, and an active radiation monitor system. The inter-related system elements for the ACS and RCS, as well as the associated interlock network, are described. The policies and practices in setting up the RSS are also compared with the regulatory requirements.

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INTRODUCTION

The B-Factory is one of the high-energy physics projects at the Stanford Linear Accelerator Center (SLAC). Like other accelerator facilities at SLAC, a radiation safety system (RSS) was designed for the B-Factory, which consists of the access control system (ACS) and the radiation containment system (RCS). The ACS is to keep people away from the prompt, dangerous radiation inside the beamline shielding housing during accelerator operation, while the RCS is to contain/limit the beam and radiation such that people outside the shielding housing do not receive doses beyond acceptable limits. The shielding part of the RCS also ensure that the annual doses to the general public living near the SLAC boundary, from skyshine radiation, are within the design limit of 0.1 mSv y^{-1}. In this paper, a brief description of the B-Factory is given first and the details of the RSS (ACS and RCS) of the B-Factory follow. Examples to reflect the relevant SLAC policies and practices are also described, as well as comparison with regulatory requirements (DOE 1988).

B-FACTORY ACCELERATOR FACILITY

SLAC is a national high-energy accelerator laboratory. B-Factory is the latest project aimed to study the CP violation from the collisions between circulating electrons (maximum 12 GeV) and positions (maximum 4 GeV) up to a maximum stored current of 3 A (1.4×10^{14} e^- or e^+). Figure 1 shows a schematic layout of the B-Factory accelerator facility. The B-Factory uses the existing SLAC 2-mile-long LINAC (divided into 30 sectors) to provide the electron and positron beams at proper energies. The electron beam is directed to the high-energy (HE) bypass line through the HE extraction line at sector 10 (positrons to low-energy bypass line at sector 4). Further downstream in the Beam Switch Yard (BSY) area, the high-energy north injection transport line (HENIT) takes the electron beam into the high-energy storage ring (HER), while the low-energy south injection transport line (LESIT) takes the positron beam into the low-energy storage ring (LER). LER is positioned about 1 m on top of HER in an underground tunnel of 2200-m-circumference (called the PEP-II ring).

The two stored beams circulate in opposite directions and intersect only at the center of the large BaBar detector located at the Interaction Region 2 (IR2). There are four other similar IR halls around the PEP-II ring. The ring tunnel is divided into 6 straight and 6 arc sections. The IR halls are in the straight sections and they are the personnel and equipment access points to the PEP-II ring. As described in the Shielding section later, these IRs constitute the least-shielded locations, because all other parts of the PEP-II ring are covered by earth soil at least 5.5-m-thick.

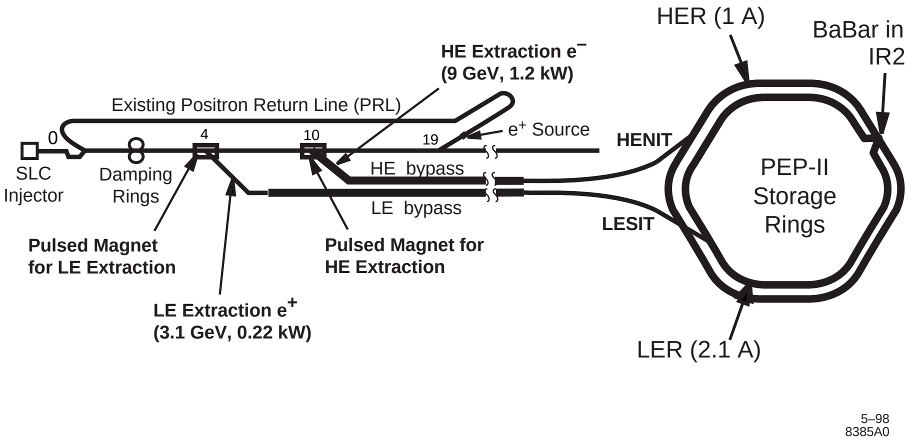

Figure 1. A schematic layout of the B-Factory accelerator facility, which consists the existing LINAC to provide the electron and positron beams, two extraction lines, two bypass lines, north and south injection lines, and two storage rings (HER and LER) in an underground tunnel of 2200-m-circumference (called the PEP-II ring). The two stored beams circulate and intersect at a detector located at the Interaction Region 2 (IR2).

RADIATION SAFETY SYSTEM (RSS)

To facilitate accelerator operation and access control, a large accelerator facility at SLAC is generally divided into a few areas (called the Personnel Protection System, PPS, areas). For example, B-Factory has three major PPS areas: the LINAC, the BSY, and the PEP-II ring (which is sub-divided into 4 PPS areas for ring RF operation). Personnel can safely occupy one or more PPS areas while the remaining areas (generally the upstream ones) have beam radiation and/or electrical hazards. Personnel can also safely occupy the areas outside the shielding (or barrier) of a PPS area. These are the purposes of a radiation safety system. The access control system for a PPS area can ensure that personnel are not exposed to the high prompt radiation levels inside the PPS area. The radiation containment system can ensure that personnel outside the PPS area are safe from radiation due to excessive beam power, normal and abnormal operations, etc. Figure 2 shows the fully inter-related and interlocked system elements of the ACS and RCS for B-Factory[*], which are described in details as follows.

ACCESS CONTROL SYSTEM (ACS)

The beam/radiation can be in one or more PPS areas, while the remaining PPS areas are in safe-access states. At SLAC, 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): In general, the RA state allows no entry, and only the radiation hazard is interlocked to be off. However, under the Restricted Access Safety Key mode, workers are allowed to enter a PPS area with electrical hazard on to perform special tests.

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[*] SLAC actually uses the terms: Personnel Protection System (PPS) and Beam Containment System (BCS), instead of ACS and RCS. The PPS consists of ACS and ARMDs described here. The BCS consists of PLDs, dump/collimator, and shielding.

4. No Access (NA): The NA state allows no one in a PPS area, and both the radiation and electrical hazards can be on.

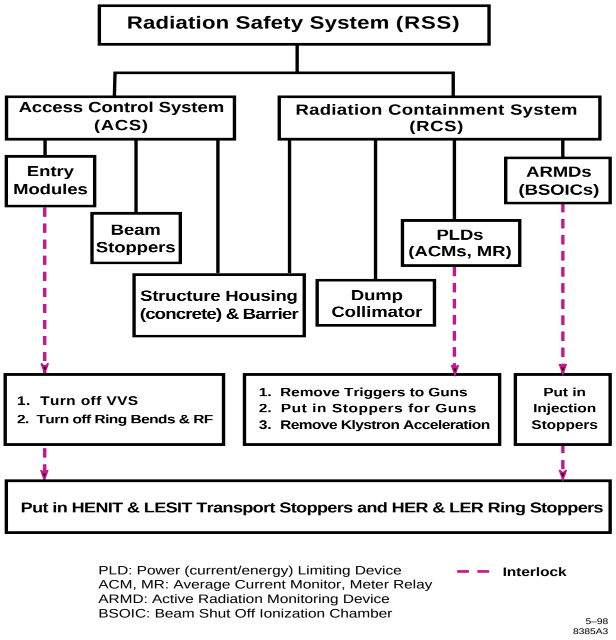

Figure 2. The radiation safety system (RSS) of B-Factory consists of the access control system (ACS) and the radiation containment system (RCS), which have their own system elements. The ACS is to protect people from being exposed to the dangerous, prompt radiation inside a beamline area. The RCS is to protect people from radiation outside a beamline area. The interlock network related to the PEP-II ring area is shown as the dotted lines.

The DOE Order 5480.11 (1988) requires that the entry control system for very high radiation areas shall function automatically to ensure that no people are inside a beamline area where a very high radiation level exists. The PPS areas of B-Factory have radiation levels during operation much higher than 0.05 Sv h^{-1} (definition of a Very High Radiation Area) and, therefore, require the use of ACS. The ACS consists of barrier, a standard entry module at every entrance, and related beam stoppers (see Fig. 2). The shielding wall is generally also a physical barrier, which makes the access to a PPS area possible only through the entry points.

Entry Module

Typical features of an entry module for a PPS area, illustrated in Fig. 3, include:

1) An interlocked, and lockable, outer door (with emergency entry and exit).
2) A maze and an interlocked, but not locked, inner gate.
3) A keybank with keys. In the CA and RA states, everyone entering the area is required to take a key (released by operator) and carries it with him/her during the period of access.
4) A key switch and push button for door release (controlled by operator).
5) An access and beam status display.
6) Intercom or telephone for communication with operator.
7) TV camera to facilitate access control by operator.

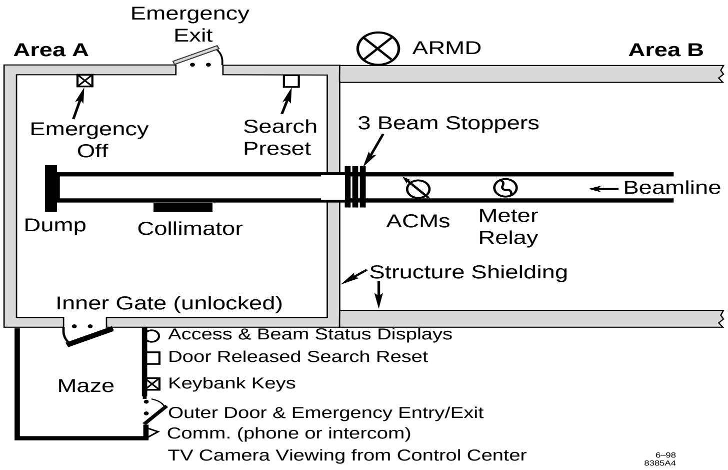

Figure 3. Beam stoppers and typical features of an entry module for the ACS of a PPS area. The four RCS systems (power limiting devices, radiation monitors, dump/collimator, and shielding) are also shown (see text for more details).

The above features allow the operators to maintain access control and allow people a safe entry. A search of a PPS area by the operators, following a well-defined written procedure and route to clear people away, is required after the area has been in a PA state. People are warned of possible beams by dimmed tunnel lights and audible warnings. The emergency-off push buttons and the emergency exits are two features that allow people to be able to respond to dangerous beam situations if they are accidentally left inside a PPS area. Most features above are required by NCRP (1986).

Beam Stopper

The beam stoppers serve to keep an area safe by containing the beam/radiation elsewhere. At SLAC it is required to have at least three beam stoppers in the *primary* beamline between two neighboring PPS areas (see Fig. 3). Figure 4 shows the three PPS areas (LINAC, BSY, and PEP-II ring) and associated beam stopper system at B-Factory. For example, there are three HENIT transport stoppers (two mechanical stoppers ST6049 and ST6155, bending magnets B2-B9) to keep the PEP-II ring safe for access while the injected electron beam remains in BSY. To prevent HER from running, there are two mechanical ring stoppers (ST8096 and ST8097), ring RF cavities, and ring bends.

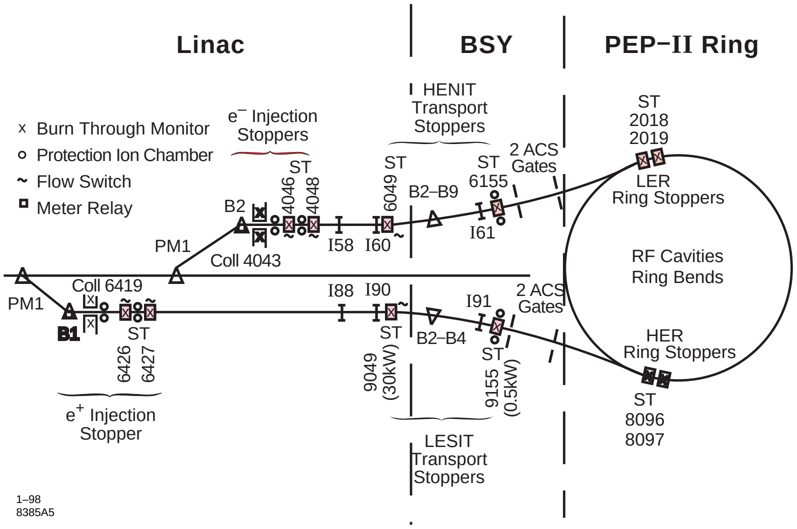

Figure 4. Beam stoppers and power limiting devices (average current monitors and meter relays for bends in this case) at B-Factory (see text for more details).

Using the PPS areas of the PEP-II ring as an example, the ACS for an IR PPS zone consists of the following: IR concrete shielding walls, a maze entrance equipped with a standardized entry module, the HENIT and LESIT transport stoppers, the HER and LER ring stoppers, and the ring RF and bends.

Figure 4 also shows that the injection stoppers to keep the BSY safe while the injected electron beam remains in upstream of LINAC are the pulse magnet PM1, bending magnet B2, and mechanical stoppers ST4046 and ST4048. Note that there is a meter relay interlock to the bend B2 to ensure the electron beam energy is correct.

Figure 2 shows that the ACS of the PEP-II ring is interlocked such that, when there is an ACS violation (e.g., crash in or pushing an emergency-off button), the immediate response is the LINAC variable voltage supply (VVS) for the klystron modulators and the ring bends and RF cavities will be turned off. The HENIT and LESIT transport stoppers and the HER and LER ring stoppers will also function automatically (in or off).

At SLAC, it is required that each mechanical beam stopper or collimator be equipped with a burn through monitor (BTM) and protected by at least two other devices from possible damage due to excessive beam powers (as well as to detect and terminate the beam). For example (see Fig. 4), the beam can be parked on the first HENIT mechanical stopper in normal operation. Thus the stopper is water-cooled (monitored by a flow switch, FS) to withstand a power of 30 kW and is protected by two average current monitors (I58 and I60) upstream. The last HENIT mechanical stopper ST6155 has a power rating of 0.5 kW and can be hit by beam only when the first two beam stoppers fail. The stopper ST6155 is protected by a pair of protection ion chamber (PIC), which is set to trip the beam when hit by 0.1 kW beam. The bends B2-B9, on the other hand, need not be protected. This is because, even if they are damaged by beam, the beam still can not be transported and the area downstream remains safe. There are also interlock devices to ensure that the beam stoppers are working properly, e.g., two microswitches to indicate a mechanical stopper is in and a redundant OFF status for a bend’s power supply.

The BTM will trip the beam off when it is melted and the internal pressure is dropped below one atm. The response to a BTM trip is similar to that for an ACS violation (see Fig. 2). On the other hand, the response for a PIC or FS trip is less severe and is the same as that for an ACM or a meter relay trip.

The level of stopper or collimator protection is obviously dependent on the beam power to be considered. At a low power facility, e.g., a synchrotron light facility, there is no need for protection at all, except for synchrotron radiation damage (Liu 1991). In that case, active radiation monitoring devices can be used to detect and terminate abnormal operations

RADIATION CONTAINMENT SYSTEM (RCS)

Complementing the ACS, the RCS is designed to protect people outside a PPS area from radiation exposure resulting from both normal and abnormal operations. Abnormal operations can be due to mis-steered beam and system-failure situations (to be defined later). The RCS not only limits the beam power, but also prevents beam from escaping its prescribed channel. The RCS consists of four elements (see Figs. 2 and 3): power limiting devices (PLDs), shielding, dump/collimator, and active radiation monitoring devices (ARMDs). The four RCS system elements are described as follows.

Power Limiting Device (PLD)

There are three beam power levels (energy for stored beams) to be considered for shielding design at SLAC: normal, allowed and maximum credible beam powers. Table 1 lists the three types of injected beam power and stored beam energy for the PEP-II ring. B-Factory plans to run at normal beam power (and energy) most of the time and occasionally inject at the allowed beam power. Under extreme conditions, the accelerator is also capable of delivering the maximum credible beam power to the ring, which shall be prevented by power limiting devices (PLDs). SLAC requires a minimum of three PLDs be used to limit the injected beam within the *allowed* beam power (see Fig. 3). At the B-Factory, for example, three average current monitors (toroids of I58, I60, and I61 in HENIT line in Fig. 4), as well as the meter relay for the bend B2, are used to limit the electron beam power to 3.5 kW.

Figure 2 shows that, when an ACM or meter relay is tripped, the triggers to the LINAC guns are removed, stoppers for the guns are put in, and the klystron acceleration is terminated by mis-tuning the RF time structures among klystrons. Because the consequence of an ACM trip is less severe than an ACS violation, the ensuing termination of beam is also less destructive.

Table 1. The normal, allowed and maximum credible beam powers for the injected electron and positron beams (energy for stored beam) at the PEP-II ring.

	Injected Beam Power (kW)		Stored Beam Energy (kJ)	
	Electron	Positron	Electron	Positron
Normal Beam[a]	1.2	0.22	67 (1 A)	49 (2.1 A)
Allowed Beam[b]	3.5	1.5	269 (3 A)	90 (3 A)
Maximum Credible Beam[b]	333	10	NA	NA

[a] Energy: 9 GeV electron and 3.1 GeV positron.

[b] Energy: 12 GeV electron and 4 GeV positron.

Shielding and Dump/Collimator

As mentioned in the previous ACS section, the shielding housing serves not only as a ACS barrier, but also to shield the normal beam losses (together with localized heavy metal shielding sometimes) so that the radiation levels outside the housing are below the limit. Heavy-metal collimator may be used to intercept the missteered beam so that the radiation levels outside the PPS areas are within the acceptable limit. Therefore, the shielding at SLAC is designed such that:

1) The *annual* dose outside the shielding from *normal* beam losses, including operations at both the *normal* and *allowed* beam powers, is no more than 0.01 Sv,
2) The dose rate outside the shielding from *missteered* beam loss at the *allowed* beam power is no more than 1-4 mSv h^{-1} (a guideline only), and
3) The integrated dose outside the shielding from a *system-failure* event (e.g., beam loss at the *maximum credible* beam power in case of all ACMs fail) is no more than 0.03 Sv per event (or the dose rate no more than 0.25 Sv h^{-1}).

The above three shielding design criteria for three different beam loss situations are further illustrated below by using the shielding examples in the PEP-II ring:

1) For *normal* beam losses, the DOE shielding design limit (DOE 1988) is that the annual dose equivalent outside the shield surface is no more than 10 mSv, if the area is occupied continuously by radiation workers. The annual amounts and locations of normal beam losses were provided by the PEP-II accelerator physicists as source terms. For the PEP-II ring, both the injected and stored beams are normally lost in the ring collimators, whose locations are in or near the arc sections of the ring, above which there are at least 5.5-m-thick of earth. On the other hand, the IR halls, which can be occupied frequently by workers, are the areas that need more attention to shielding. For example, in IR8 where the positron injection beam merges with LER, the injection septum and the stored positron beam abort dump are two major points of normal beam loss. It was found that a 30”-thick concrete shielding, in addition to the existing 40”-thick IR concrete wall, is needed on the sides of the septum and dump to reduce the dose below 0.01 Sv y^{-1} (i.e., 5 μSv h^{-1}, assuming an occupancy of 2000 h

y^{-1}). For other IR halls, because of the small amounts of normal beam losses there, the 40”-thick IR concrete wall is sufficient to meet the shielding design limit.

2) Due to *missteering*, the beam may be totally lost at a local point along the beamline. Since no DOE-mandated limit is available, a limit of 3 mSv h^{-1} maximum dose rate at the shield surface from such an abnormal beam loss at the *allowed* beam power was used for the PEP-II ring design. For example, if some quads in a straight section were misadjusted such that the injected electron beam is totally lost in the IR center, the instantaneous dose rate would be too high. Therefore, an equivalent of 4”-thick lead shielding was added along the side of HER in each IR. There is no shielding needed for LER for this purpose due to the lower *allowed* power of positron injection beam. Another example is that, for RF penetrations and air vents around the ring, a fence around the top of each penetration or vent is needed in case that the electron injection beam is fully lost near the bottom of the penetration or vent. The collimator 4043, downstream of bend B2, is also an important RCS device for this purpose (see Fig. 4). In this case, the collimator intercepts possible beam missteered by bend B2 or intercepts beam at wrong energies and, thus, keeps the RF penetrations in LINAC and the BSY area safe.

3) The third criterion is a SLAC policy that, from an abnormal beam loss due to *system-failure*, the integral dose equivalent per event shall be no more than 0.03 Sv or the dose equivalent rate shall be no more than 0.25 Sv h^{-1}. A system-failure situation refers to the cases when there is at least one interlocked device fails. A typical worst case is that when two out of three beam stoppers fail and the beam is still delivered at the *allowed* beam power. For example, when the HENIT ST6049 fails to be in and bends B2-B4 fail to be off, a 3.5-kW electron beam hits the stopper ST6155. The resulting dose rate in the ring downstream of the

ACS gate is still less than 0.25 Sv h^{-1}. Another system-failure situation is that when all three ACMs fail and the beam is delivered at its *maximum credible* beam power. One example for this case is that the ACMs I58, I60 and I61 fail and a 333-kW electron beam is delivered to hit the vacuum chamber in any IR. The resulting dose rate outside the IR concrete wall will be higher than 0.25 Sv h^{-1}. However, in this high power case, the vacuum chamber will also be burned through within seconds. Therefore, the injected beam can not be sustained and the integrated dose per event is less than 0.03 Sv. It has also been found that the power threshold of vacuum chamber burn-through is 110 kW. At this power level, the dose rate outside the IR concrete wall (with the 4”-thick lead shielding added for missteered beam loss) is already less than the limit of 0.25 Sv h^{-1}.

The above shielding analysis was performed for all major beamline components from LINAC to the ring for which missteering or system-failure is possible and the dose consequence is significant. In general, the injected beam dominates over the stored beam on the storage ring shielding design.

At SLAC, interlocked devices may be used to monitor the normal beam losses. Such devices can be a pair of current monitor (or a pulse-to-pulse comparator) positioned at both ends of a beamline or radiation sensors positioned along the beamline. These devices can replace or complement the function of ARMDs.

Active Radiation Monitoring Device (ARMD)

The active radiation monitoring device used at SLAC is also called the Beam Shut Off Ionization Chamber (BSOIC). Most BSOICs at SLAC have a tissue-equivalent ion chamber with an electrometer, designed and made at SLAC (Liu 1993). B-Factory has started to use instruments that are commercially available: an Anderson-Braun remmeter type probe for neutrons and an air ion chamber probe for photons, both connected to a modern electronic readout unit. At least one BSOIC with a neutron probe and a photon probe is mounted side-by-side on each IR concrete wall.

The BSOICs are used to detect the radiation levels from either the missteered or the system-failure beam loss situations. They are interlocked to terminate the beam, if the preset trip level (generally at 0.1 mSv h^{-1} at occupied areas like an IR) is exceeded or the instrument has a failure, e.g., a power supply fails or a detector probe is not working. Figure 2 shows that, if a BSOIC at PEP-II ring trips, the injection stoppers, the transport stoppers, and the ring stoppers will be in/off. The BSOICs at PEP-II ring also have an alarm level set at 0.05 mSv h^{-1} for warning purposes. A small ^{137}Cs source is fixed on every ion chamber probe, generating a signal of about 20 μSv h^{-1}, to act as an internal check source to ensure that the BSOIC is working continuously. Neutron probe's internal check source is the signal produced by the cosmic ray neutrons (about 3.4 nSv h^{-1}).

Figure 5 plots the neutron and photon dose rates, measured by the BSOIC outside the IR6 concrete wall, during the period of a HER commissioning survey (around 5 pm of June 24, 1997). The radiation was resulted from a 7-W electron beam missteered to produce losses near the vacuum chamber in the IR6 center. The measured dose rates of 3 μSv h^{-1} for neutron and 1 μSv h^{-1} for photon agree well with those calculated with the analytical SHIELD11 code (developed at SLAC). Note that, if the *allowed* beam power of 3.5 kW is missteered to be lost there, the dose rate is 2 mSv h^{-1}, still less than the 3 mSv h^{-1} limit.

Shielding for SLAC Boundary Dose

The shielding element of the RCS also ensures that the annual doses to the general public living near the SLAC boundary, from skyshine radiation, are within the SLAC design limit of 0.1 mSv y^{-1}. Around the PEP-II ring, it is clear that the major source term to the boundary dose is the annual normal beam losses near an IR, whose concrete roof is only 4'-thick (~10 m above the beamline, 16 m wide, and 20 m long). The worst case is the SLAC boundary near IR6 (33"-thick roof), where the occupied boundary is only 60 m away and there is a LER energy collimator inside IR6. With an estimated annual normal beam loss of 10 kWh y^{-1} at the collimator, the calculated neutron boundary dose is 0.023 mSv y^{-1}, assuming an occupancy period of 7200 h y^{-1}. The other major source to the IR6 boundary is the annual normal beam loss in IR8 (300 m away from IR6 boundary), which is 115 kWh y^{-1} producing a boundary dose is 0.007 mSv y^{-1}. The total neutron annual boundary dose near IR6 was estimated to be 0.03 mSv y^{-1}. Outside the 4'-thick concrete roof, the calculated photon dose is about a factor of two less than the neutron dose. The photon scattering in air is also about a factor of 10 less than that of neutrons. Therefore, the gamma dose at boundary is much smaller than the neutron dose.

Figure 5 also shows that, for a 7-W beam loss inside IR6, a peripheral monitoring station (PMS5) 50 m away measured a skyshine neutron dose rate of 10 nSv h^{-1} (assuming the average energy of skyshine neutrons is 0.5 MeV). This is a factor of 7 lower than that calculated with the analytical SKYSHINE code (developed at SLAC).

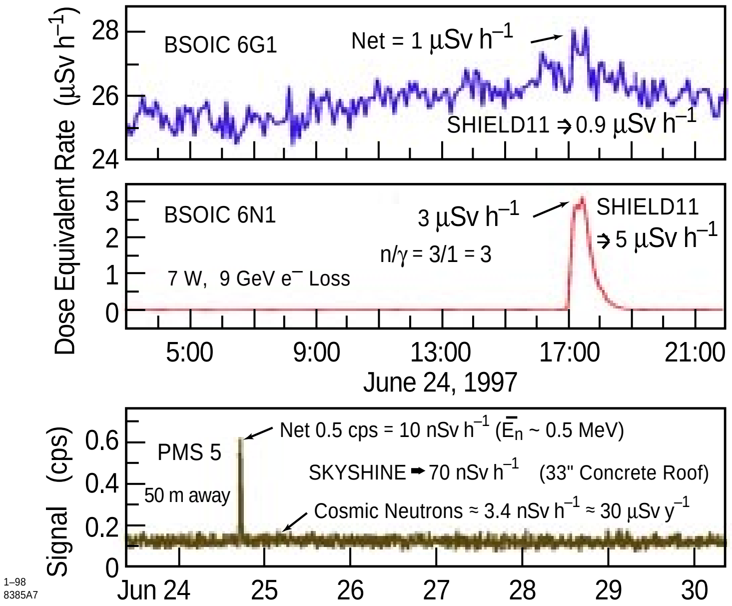

Figure 5. Neutron and photon dose rates measured by the BSOIC outside the IR6 concrete wall during the period of a HER commissioning survey, when a 7-W electron beam was missteered to produce losses near the vacuum chamber in the IR6 center. A peripheral monitoring station near IR6 also measured skyshine neutrons. Calculated values using analytical SHIELD11 and SKYSHINE codes are also shown for comparison.

DISCUSSIONS AND CONCLUSIONS

Both ACS and RCS system elements are important engineering measures to control the radiation hazards. The rationale of SLAC radiation safety system is a risk approach, which evaluates the risk of an exposure event according to both the probability and the consequence of such an event, and then determines the acceptability of the associated safety system. As mentioned early, three criteria are used for three different beam loss situations in the SLAC shielding design. The design limit of 0.01 Sv y^{-1} for normal beam loss is the lowest and is the only one that is mandated by DOE. A normal beam loss event should have an event probability of high ($> 10^{-1}$). However, the consequence from the normal beam loss exposure (< 0.01 Sv) is small ($< 10^{-4}$), compared with other industrial hazards. Therefore, the risk from normal beam loss scenario is low (~10^{-4}) and, thus, acceptable. On the other hand, a system-failure event should have an event probability of low and a consequence level of medium (up to 0.03 Sv). Therefore, the risk is still low and the safety system is acceptable. The event of all three beam stoppers failing is incredible and its event probability is so small (< 10^{-6}) that it needs not be addressed, as well as the case of a simultaneous failure for both beam stopper and ACM systems.

The shielding design for the missteered beam loss situations is perhaps the most complex, if not the most difficult, due to its wide range of situations that can be envisioned. Missteered beam loss scenarios can have probability levels from medium (e.g., a beam loss from turning a single beam-control knob or klystron self-cycling) to low (e.g., a beam loss from a combination of misadjustments of several beamline components at the same time). Such missteered beam, if not contained by shielding, could result in consequence levels from very low (e.g., missteered beam is self-shielded by components) to high (e.g., beam showers on the shielding wall directly). A dose equivalent limit of 3 mSv h^{-1} for all missteered beam loss scenarios was chosen for B-Factory. This corresponds to a consequence level of very low or low at most. Therefore, the risk levels for all missteered beam losses would be acceptable, unless the probability of missteering is as high as that of the normal beam loss situation.

In a risk approach, the consequence level is determined by the dose equivalent, not the dose equivalent rate. Therefore, two extra factors can be considered: occupancy factor (the frequency that an area may be occupied) and event period (how long the event persists). The occupancy factor can be included in the estimation of the event probability. Note that, in cases of abnormal beam losses, the operator attention and the use of ARMDs greatly reduce the consequence level.

To ensure that the accelerators are operated in accordance with written procedures, the Beam Authorization Sheets (BAS) is used at SLAC to authorize and govern the accelerator operation in a radiation-safe manner. The BAS is prepared, approved, and issued by the responsible Radiation Physicists, Accelerator Department Safety Officers, and concurred by the most senior B-Factory project manager. The BAS specifies the operation envelope within which the accelerator can be operated. The BAS contains pre-running conditions that have to be met before operation (e.g., shielding verification, BSOIC calibration, and interlock system certification) and running conditions that have to be met during operation (e.g., administrative safety requirements).

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