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Operational Radiation Protection in Synchrotron Light and Free Electron Laser Facilities

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Abstract – The 3rd generation synchrotron radiation (SR) facilities are storage ring based facilities with many insertion devices and photon beamlines, and have low injection beam power (< few tens of watts), but extremely high stored beam power (~ 1 GW). The 4th generation x-ray free electron laser (FEL) facilities are based on an electron Linac with a long undulator and have high injection beam power (a few kW). Due to its electron and photon beam characteristics and modes of operation, storage ring and photon beamlines have unique safety aspects, which are the main subjects of this paper. The shielding design limits, operational modes, and beam losses are first reviewed. Shielding analysis (source terms and methodologies) and interlocked safety systems for storage ring and photon beamlines (including SR and gas bremsstrahlung) are described. Specific safety issues for storage ring top-off injection operation and FEL facilities are discussed. The operational safety program, e.g., operation authorization, commissioning, training, and radiation measurements, for SR facilities is also presented.

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INTRODUCTION

Synchrotron radiation (SR) facilities providing synchrotron light for studies of various basic and applied science are now common in the world (1-2). A SR facility utilizes high-energy electrons passing through dipoles (2nd generation) and insertion devices (3rd generation) to generate intense low-energy photons (from a few tens of eV to a few MeV) for experiments (3). The 3rd generation SR facilities are storage-ring-based and consist of an injector, a storage ring with many insertion devices, and many photon beamlines around the ring, while the 4th generation x-ray free electron laser (FEL) facilities utilize a linear accelerator (Linac) with extremely low emittance and a long insertion device to deliver photons with extremely high peak power to several photon beamlines.

The injector of a storage ring SR facility is generally a short Linac, followed by a synchrotron accelerator (booster), which can accelerate electrons (or positrons) up to a few hundred MeV or a few GeV. The injector injects electrons to the storage ring where the electrons can be accumulated and circulated (or stored) in bunches up to a stored current of a few hundred mA. A storage ring, configured as a set of curves with ring dipoles and quadruples connected by straight sections, is used to maintain the stored electrons in a fixed orbit. With a storage ring vacuum in the 0.5 μPa range or better, the stored beam lifetime in a storage ring can exceed 24 hours. Thus, one typical ring operation mode consists of long periods of circulating stored beam, alternated with short injection events to replenish the stored beam when needed.

When a dipole bends the circulating electrons, SR is emitted tangentially to the electron path, creating a SR fan in the ring median plane. The insertion devices (IDs), called wigglers and undulators, are placed in the straight sections. An ID consists of a periodic array of magnets with alternating polarities to produce a series of deflections of the electron beam in the place of its straight-line orbit in the storage ring, which tremendously enhance the SR energy, flux and/or brightness. Third-generation SR facilities utilize IDs intensively and are capable of producing SR greater than 100 keV or even MeV.

A photon beamline guides the tangentially emitted SR from its source to exit the ring chamber and to penetrate through perpendicularly the ring ratchet (or transverse) wall. A dipole or wiggler photon beamline has a wide SR fan and generally has a few branch lines available simultaneously for experiments on the experimental floor around the outer rim of the ring concrete wall. The undulator beamlines have a small cone of light and has only one beamline available. Optical components such as mirrors and monochromators can be placed inside ratchet wall or in optics hutch (the hutch immediately downstream of the ratchet wall) to tune and select the energies and intensities of the photon beams delivered to experimental hutches or stations.

When the circulating electrons interact with the residual gas particles inside the ring vacuum chamber (this is one of the main reasons for stored beam decay), highly forward-peaked bremsstrahlung photons (gas bremsstrahlung or GB) are produced and will be channeled down into the photon beamline together with SR. Therefore, the safety analysis for photon beamlines needs to consider hazards from both the high-intensity, low-energy SR and the low-intensity, high-energy GB.

Currently storage ring based SR facilities can be divided into 3 classes in terms of stored beam energy: low-energy ring to generate mainly VUV light (1-2 GeV, such as the Advanced Light Source, ALS), medium-energy ring (about 3 GeV such as Stanford Synchrotron Radiation Laboratory, SSRL), and high-energy ring to generate mainly hard x-ray (6-8 GeV such as Advanced Photon Source, APS). Due to economic reason, advancement of storage ring and IDs, and wide application of photon beams, the medium-energy ring is gaining popularity. This can be evidenced by the commissioning and/or construction of many medium-energy facilities (e.g., ALBA, ASP, CLS, DLS, NSLS-II, SLS, SOLEIL, SSRF, SPEAR3 and TPS) in the last few years.

Comparing SR facilities with other types of accelerator facilities, it is the storage ring and photon beamlines that are unique and present specific radiation safety aspects not encountered anywhere else. SR facilities are characterized by low injection beam power (typically no more than a few watts and 10 Hz) but extremely high stored beam power. For example, at SSRL SPEAR3 ring, a stored current of 500 mA at 3 GeV is equivalent to a stored electron energy of 1200 J (*i.e.*, 2.43×10^{12} stored electrons) but a stored beam power of 1.5 GW! The losses of injection beam and stored electron energy affect ring shielding design. On the other hand, the stored beam power, SR parameters such as the critical energy and intensity, and the optical components affect the SR and GB hazards for photon beamlines.

Radiation protection for general electron accelerator facilities has been reviewed and presented (4-7) and is also in a companion paper of these proceedings (8). Examples of injector radiation protection and interlocked safety systems to protect the workers from prompt radiation hazards have also been reported (9-12) and in a companion paper of these proceedings (13). Building upon two previous papers (14,15) and some others, this paper will address the radiation protection associated with storage ring and photon beamlines of the 3rd generation SR facilities and the 4th generation x-ray FEL facilities. The subjects include the followings:

1) Shielding design limits, operational modes, and beam losses (normal and abnormal),
2) Shielding analysis for photon/neutron doses outside ring concrete wall from injection and stored beam losses,
3) Shielding analysis for SR and GB hazards of photon beamlines,

4) Specific safety issues for top-off injection mode, such as trickle-charge injection, of the storage ring facilities,
5) Specific safety issues for x-ray FEL facilities, and
6) Operational safety program for accelerators and photon beamlines (e.g., operation authorization, commissioning, training, and radiation measurements). Radiation safety systems used as interlocked or monitoring devices are also described throughout the text.

STORAGE RING

Table 1 summarizes the key storage ring parameters for four US facilities (ALS, SSRL, APS and NSLS-II). SR facilities are production type facilities with a main purpose of producing high-quality and readily available photon beams for user experiments and, therefore, most SR facilities have similar beam parameters and modes of operation. The safety policies and practices for the 3rd generation SSRL and the 4th generation Linac Coherent Light Source (LCLS) at the SLAC National Accelerator Facility (SLAC) will be used in this paper to illustrate the radiation protection issues and measures, which may be applicable to most SR facilities. Readers interested in specific aspects of other SR facilities are encouraged to consult two reports for SR facility comparison (16,17) and the series of proceedings of the International Workshop on “Radiation Safety at Synchrotron Radiation Sources”.

The process of determining the storage ring shielding requirements is: 1) set shielding design limits based on regulatory and facility’s requirements, 2) obtain accelerator and facility layout, injection and stored beam parameters, modes of operation, and annual run schedule, 3) determine normal and abnormal beam loss scenarios, including beam loss points and the amount of beam losses, and 4) calculate the required shielding using analytic or Monte Carlo methods. The principle of reasonable conservatism should be followed for this process.

Shielding Design Limits

Because the experimental floor around the ring is frequently occupied by users with limited training, it is desired to set the ring shielding design limit close to the general public dose limit of 1 mSv y^{-1} (2000 h per year occupancy). The shielding design limit for photon beamlines is generally set at the same level. A person on the floor can be exposed to photon/neutron radiation from the ring wall and the SR and GB from the beamlines. Considering the likely case that a person is not exposed to the maximum doses from both ring and beamlines at the same time and users do not occupy the floor near 2000 h per year, the above shielding design limits for ring and beamlines are reasonable. In addition, the shielding design limit for off-site public, dominated by skyshine neutrons, is generally set at no more than 0.1 mSy y^{-1} (7200 h per year occupancy). As shown in later sections, because of the low injection beam power and the amount of annual beam losses, the above shielding limits generally result in storage ring walls that are no more than 1.5-m-thick normal concrete. The shielding experience for SSRL SPEAR3 ring walls shows a desired “rule-of-thumb” of 60-90-120, i.e., 60-cm-thick concrete for less-occupied roof, 90-cm-thick concrete for lateral wall, and 120-cm-thick concrete for ratchet wall (due to forward-peaked bremsstrahlung characteristics), and 5-cm-thick lead may be used to replace 30-cm-thick concrete.

Beam Parameters and Operation Modes

Figure 1 shows the SSRL injector, 3-GeV storage ring SPEAR3, and main photon beamlines (currently 4 bend beamlines, six wiggler beamlines, and three undulator beamlines). The electron beam (allowed beam of 3.1x10^9 electrons per pulse, 10 Hz) is accelerated up to a maximum of 150 MeV (0.75 W) in the Linac and is taken to the Diagnostic room or to the booster for further acceleration. After a few thousand turns in the booster ring, the RF accelerating cavity will have accelerated the electrons up to 3 GeV and the electron beam is then taken through the Booster-to-SPEAR3 (BTS) transport line to the SPEAR3 ring for on-energy injection. The allowed injection beam power into the ring is limited at 5 W (1.7 nC s^{-1}). With an injection efficiency of 75%, the SPEAR3 ring (234 m circumference) can be filled from 0 mA to the maximum stored current of 500 mA (2.5 x10^{12} e^-, 400 nC, 1200 J) within 7 minutes. The energy losses of the circulating beam due to the SR production in all ring dipoles and IDs are replenished by four RF cavities in the ring.

A generally accepted rule states that the product of current and lifetime is a constant of 5 A-h for a facility with low vertical emittance. Therefore, the SPEAR3 stored current will decay with a lifetime of 50 h at 100 mA or 10 h at 500 mA. Therefore, the traditional operation mode is to have a fresh fill injection (*i.e.*, from 0 mA to 500 mA) and 2-3 refill injections (*e.g.*, from a few hundred mA to 500 mA) in a day. During this mode, the beamline safety shutters upstream of ratchet wall (called beamline injection stoppers at SPEAR3) are generally closed to prevent the injection beam from being mis-steered into the beamlines.

A special injection mode called trickle charge injection is gaining popularity, in which the stored current loss is replenished with a series of frequent (e.g., once every a few minutes) and small charge injections to maintain the stored current at its maximum and a constant SR thermal stress on beamline optical components. Therefore, this mode requires that the beamline safety shutters remain open during injection. It is now possible that injection beam may be mis-steered into a photon beamline and the experimental floor; a significant hazard that must be prevented by additional safety interlocks. In this paper, to differentiate the safety hazards between the injections with safety shutters closed or open, the injection with safety shutters open (such as trickle-charge injection) is called "top-off" injection.

During stored beam operation, the bremsstrahlung from stored beam losses, particularly those near ring IDs, can channel into beamlines adding normal doses in addition to SR and GB. In top-off injection mode, the bremsstrahlung from injection beam losses can also channel into beamlines adding doses to experimental floor.

Note that the injection modes, injection efficiency, and stored beam lifetime have implications for normal beam losses and, thus, ring shielding design, and they may vary among facilities.

Annual Schedule and Beam Losses

Table 2 summarizes the annual SPEAR3 ring operation schedule and gives a reasonably conservative estimate of the total number of electrons injected into the ring (18). The schedule has 1-month start-up and 10-month science program. The 3-GeV, 4-W beam (1.33 nA, $8.3x10^{9}$ s^{-1}, 10 Hz) is assumed to inject into the ring with an injection efficiency of 75%. Therefore, it takes 6.5 minutes to fill the ring from 0 to 500 mA ($2.43x10^{12}$ stored electrons) and the number of electrons injected per fresh fill is 3.24x10^{12}. The science program has one fresh injection and three refill injections (313 mA to 500 mA) per day and 26 days per month (SSRL has 2 accelerator physics days every 2 weeks). The number of electrons injected into the ring for the science program is then 1.8x10^{15} per year. The1-month start-up and accelerator physics studies give total injected electrons of 1.3x10^{15} and 0.4x10^{15} per year, respectively. Therefore, the total electrons injected into the ring are 3.5x10^{15} per year (*i.e.*, 467 W h y^{-1} or 117 hours of injection at 4 W per year). The science program contributes 50%, while the short start-up and accelerator physics periods contribute 40% and 10%, respectively, to the total number of electrons injected annually. Note that users may set up the experiments and occupy the experimental floor during the start-up and accelerator physics periods.

All electrons injected into the ring will be lost either during the short injection period or the long stored beam period. Figure 2 summarizes the SPEAR3 normal beam loss scenarios (18). At 75% injection efficiency, 25% of the injected beam (*i.e.*, 1 W out of 4 W injection beam) is lost during the injection period and the remaining 75% is stored (this is slowly lost within the lifetime).

Injected particles will primarily execute horizontal betatron motion with some component of synchrotron motion. The injected particle bunch will circulate a few thousand turns in the ring before being completely damped and added to one of the stored beam bunches. A reasonable estimate is that 50% of the particles lost during injection (*i.e.*, 0.5 W) are at the injection septum (one of the smallest apertures in the ring). The remaining 50% loss is equally distributed across ten ring limiting apertures (5 horizontal and 5 vertical, which have a small position/angle phase space) yielding ~5% loss rate at any one aperture. The five horizontal apertures are: injection septum, SR mask for injection septum, SR mask for RF cavities, SR mask in diagnostic straight, and the designated stored beam dump (a special 1-m-long copper device designed to intercept most of the SPEAR3 stored beam losses). Five vertical apertures are the IDs of beamlines 4, 6, 7, 9 and 11.

On the other hand, the stored beam decay will be dominated by inelastic scattering with gas particles (creating GB) and the Touschek large-angle inelastic scattering within a bunch. In these cases, the electrons will lose energy, spiral in radially, and hit points of high dispersion. The stored electrons will also have elastic scattering (Coulomb scattering) with residual gas in both planes. It was estimated that 50% of the stored beam losses is at the stored beam dump, 25% at the eight quadrupole magnet (QFC) points, and 25% at the above-mentioned ten limiting apertures for injection beam.

In summary, the loss averaged over a year for SPEAR3 is 38% at the stored beam dump, 16% at the injection septum, 3% at each of the ten limiting apertures (excluding injection septum), and 2.4% at each of the eight QFCs. With an injection of 3.5×10^{15} electrons over 11 months (1.7×10^{6} J over 7200 h), the power loss rate averaged over a year is 25 mW at the stored beam dump, 11 mW at the injection septum, 2 mW at each of the ten limiting apertures (excluding injection septum), and 1.6 mW at each of the eight QFCs. These numbers constitute the normal beam loss values used for SPEAR3 ring shielding design. The low-loss of 2-mW at a point is used to estimate the general ring shielding need while thicker concrete or local heavy-metal shielding is added for locations with high losses (*e.g.*, the beam dump and injection septum).

The normal loss points are dependent on machine lattice design and layout of physical apertures. Some facilities actually install special devices such as scrapers whose only function is to be the limiting aperture in the machine such that losses are controlled and can be locally shielded. Note that, if the SPEAR3 limiting apertures were not identified and instead the losses were simply assumed to be uniformly distributed over the 234-m ring circumference, the average line-loss rate would then be 0.3 mW m^{-1}. As shown later, a ring shielding design based on the line source model may underestimate the shielding requirement for a point source model.

During the short 7-minute injection period, the instantaneous power loss rate is 550 mW at the injection septum and 50 mW at each of the remaining nine limiting apertures. Therefore, the instantaneous dose rate from the beam loss at a limiting aperture during injection is much higher than that during the stored beam operation. For example, if a dose rate of 10 μSv h^{-1} (clearly measurable) from a loss of 50 mW at an aperture is observed outside the ring wall during injection, the dose rate from a loss of 2 mW at the same aperture during the stored beam operation would be lower by a factor of 25, *i.e.*, 0.4 μSv h^{-1} (not easily measurable). However, because of the high injection efficiency (75% for SPEAR3), more particles are lost in stored beam mode than in injection mode (1.5 times higher at each limiting aperture). Therefore, the integrated annual dose from stored beam losses is still higher than that from injection loss, though the instantaneous dose rate is higher during injection. Clearly for facilities with poor injection efficiencies, the injection losses may dominate the integrated doses. The start-up and accelerator studies, which have more frequent injections, will also have higher dose rates than the user operation period.

The above normal beam loss estimation depends on the number of limiting apertures. SPEAR3 experience shows that, in addition to several identifiable high-loss points such as injection septum, stored beam dump, and special masks, ID straights tend to be the limiting apertures (and they do not have same losses either). As the facility adds more IDs to the ring, the limiting apertures may change and a re-examination of beam losses is needed. Therefore, it is prudent to have conservatism and a safety factor built into the initial shielding design. The SPEAR3 experience shows that the 2-mW low-loss may be underestimated by a factor of 2-4 for a few ID apertures, which have smaller ratios of ID chamber sizes and beta functions.

In addition to the above normal beam losses, abnormal beam losses should be considered in the ring shielding design. Abnormal beam losses are most likely due to beam mis-steering (*e.g.*, mis-adjusted injection lattice and optics, ring RF trip, loss of magnet power supply, *etc*) and less likely due to interlocked safety system failure (*e.g.*, the current-interlocked devices fail and the injection beam is then delivered at a power higher than allowed) (19). Abnormal beam losses can result in persistent high dose rates outside the ring wall during injection losses and instantaneous doses during stored beam losses. Since the regulations and standards do not give prescriptive requirements in this case, the SR facility should identify the likely or credible abnormal beam loss scenarios, define the corresponding shielding design limits based on the likelihood of the beam loss scenarios, and implement the passive and active control/mitigation measures. For example, at SLAC (20), a shielding design limit of 4 mSv h^{-1} is set for the mis-steered case of the allowed beam power loss at a point (5 W at SPEAR3 limited by 3 interlocked current toroids at BTS line). In addition, a limit of 250 mSv h^{-1} is set for the safety system failure case that the maximum credible beam is lost at a point (45 W for SPEAR3, assuming all injector and BTS toroids fail and, at the same time, injector is mis-tuned to generate the maximum output). For abnormal injection beam loss cases, reliable measures via interlocked systems to detect and terminate the radiation hazards are also required.

Some facilities may use the loss of full stored beam at a single point to determine the ring shielding requirements. The issue of this approach is that the relationship between beam loss and dose limit may not have a clear basis. It is better to determine the shielding based on the above-mentioned normal beam losses and abnormal injection beam losses and then calculate the dose from the full stored beam loss to ensure that the total doses from such stored beam losses are acceptable, if such beam losses are reasonable (actually full stored beam losses are likely during operations due to machine trips).

A parameter called Normalized Dose Limit (NDL), which is the ratio between shielding design limit and the corresponding beam loss, may be useful for comparing facility shielding criteria and shielding need. The lower the NDL, the more demanding the shielding will be. For example, the NDLs for a SPEAR3 low-loss aperture under the normal, mis-steered, and system-failure beam loss cases are: 0.5 mSv h^{-1} W^{-1} (0.001 mSv h^{-1} at 2 mW), 0.8 mSv h^{-1} W^{-1} (4 mSv h^{-1} at 5 W) and 5.6 mSv h^{-1} W^{-1} (250 mSv h^{-1} at 45 W). Therefore, the SPEAR3 ring shielding design is dictated by the case of normal beam loss. For SPEAR3 high-loss points, the normal beam loss dictates even more the shielding requirements. The comparison report (17) shows that the NDLs for five SR facilities range from 0.002 to 5.6 mSv h^{-1} W^{-1} with a median value of 0.1 mSv h^{-1} W^{-1}.

Ring Shielding Calculations

Any beam loss in the ring will create an electromagnetic shower in the ring components, producing bremsstrahlung photons and neutrons, which dictate the ring shielding design. The SR and GB determine the beamline shielding design, but do not affect ring shielding design.

Due to the low average power losses at most ring apertures (a few mW), a storage ring generally does not need to have very thick concrete walls and roof. Locations with high losses, *e.g.*, the injection septum and the stored beam dump at SPEAR3, have thicker walls and/or additional local lead shielding. For examples (21,22), SPEAR3 ring has 60-cm-thick concrete lateral walls, but in the injection section (1/8 of the ring) the lateral wall is 120-cm-thick. The ratchet wall is thicker (90-cm-thick concrete for SPEAR3), because the bremsstrahlung is forward-peaked toward the ratchet wall. Another storage rings shielding constraint is the need for straight SR beamline penetrations in ratchet walls. Shielding blocks placed around a beamline upstream of ratchet wall, *i.e.*, the injection stopper and shadow walls at SPEAR3, are necessary to block these penetrations from bremsstrahlung and neutrons from the ring chamber. Therefore, ray trace study is important for the ratchet wall and penetration shielding design, particularly when local heavy-metal blocks are used to complement the concrete ratchet wall (23). The inherent self-shielding provided by the ring magnets and beamline components can be considered in the ray trace study.

The analytic code, SHIELD11 (24), developed at SLAC for high-energy electron accelerator shielding design, can calculate the photon and neutron dose equivalent rates outside a shielding wall from a cylindrical target hit centrally at its front face by electrons. The dose rate is function of the target material and size, the shielding material and thickness, as well as the distances and relative angles between the target, shielding, and dose point.

Clearly the actual geometries for beam losses in the ring will be more complicated than the simplified geometry in SHIELD11. For complex geometries or to gain better accuracy, the common general-purpose Monte Carlo codes such as EGS4 (25), FLUKA (26) and MCNPX (27) can be used for shielding calculations. For example, the photon/neutron radiation levels as a function of the ratchet wall thickness and the angle from beam losses in the ring have been pre-calculated (28) using FLUKA so that a generic ratchet wall shielding design can be developed (29). The radiation profile over the SPEAR3 roof from a beam hitting the inner side of the thin ring vacuum chamber at shallow angles was also calculated (30) using FLUKA. A Monte Carlo approach, including the consideration of magnetic transport, has also been used to calculate the dose over the roof from beam losses in the ring at the European Synchrotron Radiation Facility (ESRF) (31).

To illustrate the storage ring shielding design and requirements, the dose equivalent rates for a few lateral concrete wall thicknesses were calculated using SHIELD11 and are shown in Table 3. The typical ring target was simulated with an iron cylinder of 5-cm radius and 30-cm length, hit by 3-GeV electron beam. The inner surface of the lateral wall is 1 m from, and parallel to, the beam direction. The following observations from the calculations are worth mentioning:

1) For a concrete wall up to 90 cm thick, the photon dose exceeds the neutron dose. At 120-cm-thick concrete, neutron dose is slight higher than photon dose. For a 150-cm-thick concrete wall (not shown), Monte Carlo calculations (32) and spectrometry measurements (33) show that the dose is dominated by neutrons with an equilibrium spectrum (7,8), *i.e.,* the neutron spectrum shape no longer changes much as the concrete thickness increases and the neutrons above 20 MeV contribute about 50% to the total neutron dose equivalent. For the SPEAR3 "thin" walls, a non-equilibrium neutron spectrum exists and the neutrons above 20 MeV contribute less than 20% to the total neutron dose equivalent (34).

2) The maximum dose rate outside a 60-cm-thick lateral concrete wall is 0.3 mSv h^{-1} W^{-1}, less than the SPEAR3 NDL of 0.5 mSv h^{-1} W^{-1}. Thus, the maximum dose rate is 0.6 μSv h^{-1} from a 2-mW, low-loss point at an SPEAR3 aperture. The annual dose to an individual who

occupies the area immediately outside the wall over a period of 2000 h y^{-1} would be 1.2 mSv, slightly higher than the regulatory annual dose limit of 1 mSv for general public. Statistics show that a SSRL user occupies the experimental floor for no more than 760 hours per year at most and, therefore, would receive an annual dose less than 0.5 mSv.

3) During SPEAR3 injection, the instantaneous dose rate is 15 μSv h^{-1} from a normal loss of 50 mW at a limiting aperture and 1.2 mSv h^{-1} if an abnormal loss of the full 4 W injection beam occurs at any point. On the other hand, a normal injection loss of 550 mW at the injection septum, which is well shielded with a 120-cm-thick concrete wall, would only give 7 μSv h^{-1}. If the loss of 550 mW occurs at a location with a 60-cm-thick wall, the dose rate will be 0.15 mSv h^{-1}, higher than the trip threshold of 0.1 mSv h^{-1} for the interlocked area radiation monitors placed around the SPEAR3 ring.

4) As mentioned earlier, if the limiting apertures were not identified and the SPEAR3 annual loss was assumed to be uniform over the ring circumference, the average loss rate is 0.3 mW m^{-1}. SHIELD11 calculation gives 0.2 μSv h^{-1} for the line source model, a factor of 3 lower than the 2-mW point loss. Therefore, the ring wall design estimated using the line source model would underestimate the shielding needed for the point loss model.

5) A full 500-mA stored beam loss at a single point (an abnormal and unlikely event) would produce a maximum dose of 0.1 mSv outside the 60-cm-thick concrete lateral wall. Unlike injection losses, a stored beam loss event obviously cannot be terminated or mitigated and, therefore, shielding is the only option to reduce its resulting dose. At SPEAR3, there are machine protection systems, *e.g.*, discrete radiation detectors positioned near the ring vacuum chamber, to detect any excess beam loss and trigger the deflection of the stored

beam into the well-shielded stored beam dump.

6) Because the roof is at a farther distance (1.5 m for SPEAR3) and has a higher dose limit (due to low occupancy), the thickness is thinner than the lateral wall (23,30).

7) Based on the generic ratchet wall shielding design (29) and the fact that the SPEAR3 ratchet wall is at least 10 m from its associated ID or dipole source , the ratchet wall need was 90-cm-thick concrete (or 60-cm-thick concrete with 5-cm-thick lead on the inner surface).

Skyshine Consideration

Like other accelerator facilities, skyshine neutron radiation is probably the dominant source for off-site doses for SR facilities. Both measurements and calculations for SSRL (23, 35) indicate that, for a 3 GeV, 1 W electron beam hitting the SPEAR3 lead Faraday cup (0.6 m under a 60-cm-thick concrete roof), the skyshine radiation is dominated by low-energy neutrons (peaked at 0.5-1 MeV) with a dose rate of 9 nSv h^{-1} at a distance of 100 m and 0.3 nSv h^{-1} at 400 m (SLAC site boundary). Since there is a total of 467 W h y^{-1} of injected particles for SPEAR3 (see Table 2), the annual skyshine neutron dose at 100 m is 4 μSv y^{-1}, if the neutron yield from beam losses in the ring is assumed to be the same as that from the beam intercepted by the Faraday cup. Note that 75% of the annual dose of 4 μSv occurs during stored beam period (7200 h y^{-1}) and, thus, the corresponding dose rate is 0.4 nSv h^{-1} at 100 m. The remaining 25% of the annual dose occurs during injection periods (117 h y^{-1}) and the corresponding dose rate is 9 nSv h^{-1} at 100 m. These skyshine neutron levels are to be compared with the natural background neutron radiation of ~4 nSv h^{-1} at sea level. Therefore, a very high sensitivity neutron detector is needed to measure these skyshine neutrons.

PHOTON BEAMLINES

This section describes the SR and GB hazards and shielding analysis for photon beamlines, including source terms, shielding calculation methodologies, and interlocked safety systems.

Overview of a Photon Beamline

Figure 3 shows a SSRL hard x-ray beamline, wiggler beamline BL11 (38), to illustrate the radiation safety aspects of a photon beamline. A photon beamline can be divided into the in-alcove section (or frontend, i.e., the portion upstream of ratchet wall) and out-of-alcove section (the portion downstream of ratchet wall).

Along each beamline, the optical components are used to define the SR ray envelope and to tune the beam quality and quantity for experiments. The three types of optical components that may serve as SR and GB targets are:

1) Mirror, which is a low-pass filter that removes preferentially high-energy photons above the cut-off energy, depending on the mirror's inclined angle and coating material, e.g., a Pt-coated mirror at an angle of 0.16^o has a cut-off of 23 keV. The cut-off energy refers to the energy at which the photon intensity is reduced to 50% of original. Therefore, for shielding design purposes, the presence of high-energy photons beyond the cut-off still needs to be considered.
2) Single or double monochromators, which selects mono-energetic photons (at fundamental and harmonic wavelengths) from the incident SR beam. Though the photons at higher

harmonics have lower intensities than the fundamental line, the harmonics photons may dominate the shielding requirement due to their higher energies.

3) Apertures (such as masks, slits, baffles) and filters, which are likely to intercept some or all of the SR and/or GB fan.

Safety Considerations for In-Alcove Section of a Photon Beamline

Figure 3 shows an in-alcove layout for a SSRL photon beamline with a few safety components: a movable water-cooled mask that is used to protect the injection stoppers from possible SR thermal damage, a collimator in front of the first injection stopper and shadow walls (each consisting of 15-cm-thick lead followed by 15-cm-thick polyethylene), as well as 30-cm lead and 15-cm polyethylene shielding surrounding the beampipe in the ratchet wall hole.

The beamline in-alcove safety shall be an integral part of the ring safety design. Similar to the lateral wall and ratchet wall, it is the injection and stored beam losses in the ring (both normal and abnormal cases), as well as the GB and credible beam losses in the frontend, that need to be considered for the in-alcove safety design.

During beam injection into ring (except in top-off mode), two interlocked injection stoppers (each 15-cm-thick tungsten alloy, Hevimet, density 17 g cm^{-3}) have to be inserted to block the injection beam that may be mis-steered into a beamline. The collimator and shadow walls along each beamline are used to block any photon and neutron radiation from electron beam losses in the ring chamber that may penetrate the hole in the ratchet wall and/or to complement the ratchet wall shielding. The collimator and shadow wall design may be replaced by a single collar (or collimator) design placed near the most downstream end of the in-alcove section.

There are locations where the in-alcove section of a beamline does not exist yet while the corresponding ratchet wall already exists (without the beampipe penetration in the ratchet wall). In that case, a thick shielding block (minimum 10-cm-thick lead at SSRL) should be placed immediately downstream of the beamline exit port of the ring chamber to fully block any forward-angle bremsstrahlung from beam losses in the ring to directly hit the ratchet wall, if the wall is not designed for that scenario.

Several reports (21,29,36,37) can be consulted for more detailed safety analysis for the in-alcove section of the SPEAR3 beamlines.

Safety Considerations for Out-of-Alcove Section of a Photon Beamline

SR and GB are the main hazards to be considered for the out-of-alcove section of the beamline (called beamline hereafter). There are two types of SR beamlines that have different beamline layouts, hazard analysis and mitigation: hard x-ray (> a few keV) and vacuum-ultra-violet (VUV) or soft x-ray beamlines.

As shown in Figure 3, a hard x-ray beamline generally has an optics hutch followed by one or more experimental hutches. The optical components are generally located in optics hutch, though some beamlines may have apertures and mirrors located in alcove. The hutches are large enclosures with lead or iron shielding walls to attenuate the SR (up to 1-cm-thick of lead is used at SSRL wiggler hard x-ray beamlines). There are interlocked hutch shutters between optics hutch and an experiment hutch to intercept the SR and GB when the experimental hutch is in an accessible state (for optics hutch, the injection stoppers are the hutch shutters). SSRL is required to use at least two injection stoppers and two hutch shutters for each SPEAR3 beamline (10,11). However, there are facilities using only one injection stopper and one hutch shutter (*e.g.*, ALS and NSLS) by requiring multiple position-sensing microswitches for each stopper and shutter (17).

On the other hand, the energies of the VUV or soft x-ray, which come from SR reflected from one or more mirrors at large inclined angles, is so low that the experiment has to be performed inside vacuum. Therefore, the vacuum chamber or beampipe itself has to be used to attenuate and contain the VUV light. Instead of hutches, a VUV beamline such as the undulator beamline BL5 (39) consists of only free-in-air beam transport pipes and tanks and it may utilize vacuum isolation valves as safety shutters.

Compared to the thin SR shielding need, mitigation of the GB hazard requires thicker heavy-metal shielding. Because the secondary photons from GB hitting a target are forward-peaked, the GB shielding tends to be thicker in forward angles and thinner at lateral directions (up to 25-cm-thick of lead at 0-degree and 5-cm-thick lead for 90-degree at SSRL). Common forward-angle GB shielding are lead collimators, hutch shutters, and GB beam stops (see Figure 3). Local lead shielding lateral to the optical components hit by GB may also be needed. Some facilities utilize thick hutch walls (up to 5-cm-thick lead) to shield both SR and GB, particularly for those beamlines with very high SR critical energies (> tens of keV).

In the sections below, a summary of the SR and GB hazard calculations and mitigation is given and some reports (40-46) can be consulted for more details.

Synchrotron Radiation (SR)

The SR energy, intensity and angular characteristics have been described in details (3,15). For radiation safety purposes, a few special SR characteristics are worth mentioning:

1) SR from both bending magnets and wigglers has a broad, continuous spectrum while that from an undulator has a spectrum with quasi-monochromatic peaks. While the intensity of high-energy photons may be orders of magnitude less than that of low-energy photons, the very different attenuation in shields (particularly in lead) may make the high-energy photons the dominant concern in shielding design
2) The vertical opening angle of SR is very narrow (it has the same characteristic angle as that of GB; 0.17 milliradian for a 3 GeV beam), but its horizontal fan depends on the stored beam's curved path that is viewed by the beamline. Therefore, similar to GB, ray trace study needs to be performed to ensure that any SR ray will be blocked by at least one or more components along the beamline,
3) The polarized nature of the SR would cause asymmetric scattering from a target,
4) Since an ID may be tunable, *i.e.*, the magnetic field strength is adjustable by changing the gap, the most conservative SR source term based on the smallest gap of an ID should be used in the beamline shielding design.

The SR issues can be divided into three light categories:

1) White light (i.e., SR from an ID or bend without interacting with any component), which can demand up to 1-cm-thick lead shielding at SSRL (a few cm of lead at ultra-high x-ray lines).
2) Pink light (i.e., photons specularly reflected from a mirror at a certain angle) and the Compton light (photons scattered from a mirror or monochromator in all directions): These lights can demand up to a few-mm-thick lead shielding at SSRL. Depending on the beam parameters and beamline configuration, e.g., the solid angle subtended by the target

3) Mono light (mono-energetic photons from a monochromator), which can be further divided into two types: unfiltered mono light (mono light without a mirror reflection) and filtered mono light (mono light with a mirror reflection). Filtered mono light at SSRL only needs up to a few-mm-thick iron shielding. Note that a multi-layer monochromator has a wider band pass and, thus, higher beam intensity and thicker shielding need than those for ordinary silicon monochromator.

Most optics hutches are white light hutches, while some optics hutches are pink light hutch (when there is a mirror in alcove). Most experimental hutches are mono light hutches. The SSRL wiggler beamline BL11 in Figure 3 has a white light optics hutch BL11-0 and three experimental hutches: BL11-1 (a filtered mono light hutch), BL11-2 (an unfiltered mono light hutch in the end of the central line), BL11-3 (a filtered mono light hutch, not shown in figure), and two transport pipes between hutches.

The SSRL undulator BL5 (47) has a white light optics hutch BL5-0 and three VUV transport pipes, e.g., the BL5-1 section upstream of single grating monochromator (SGM) is a pink light beampipe and the section downstream of SGM is a filtered mono light beampipe. Note that the SGM acts like a combination of mirror and monochromator in that both the zero-order pink light and VUV mono lights will be reflected from the SGM. Therefore, the downstream of SGM needs consider both pink light and mono light in beampipe shielding design. The VUV beamlines also have view ports that are used by beamline physicists/engineers in beamline tuning and their shielding requirements should be examined. The general safety issues and shielding design for pink and VUV beamlines are also summarized in a report (42).

Using standard and conservative beam-target-shield geometries in the analytic STAC8 code (48) or Monte Carlo codes, shielding needs for white light, pink/Compton lights, and mono light can be calculated. STAC8 is recommended for SR dose calculations as it is specifically designed for SR beamline shielding design and its use is easier than Monte Carlo codes. For example, STAC8 can generate wiggler and undulator source spectrum with user input of electron beam energy, magnetic field, number of poles, and fan width. STAC8 can calculate pink beam, Compton-scattered beam, and mono beam. STAC8 takes into account of the an-isotropic Compton scattering, SR linear polarization effect, target self-shielding, and build-up factors in the shield. The STAC8 has been benchmarked with measurements and the FLUKA and EGS4 calculations (49).

Generic SR shielding calculations using STAC8 and FLUKA have been performed for SSRL beamlines (40). The ambient dose rates as a function of scattering angle from a conservative inclined Si target and the shielding thickness were calculated for white light (41), pink/Compton lights (42), and mono light (43). Figure 4 shows an example of the calculated curves for SSRL white light beamlines with 5 critical energies between 3.1 and 12.2 keV for lateral shielding determination. These families of “normalized” attenuation curves allow the estimation of the shielding requirements for beamlines with similar critical energies using a simple linear scaling of the number of ID poles and the horizontal fan width of the white light hitting the target, as well as a scaling of distance using the inverse square law.

In addition to the hutch wall and beampipe shielding, attention should be paid to SR streaming through ventilation and cable penetrations on the hutch walls, as well as groundshine under the hutch doors, in particular for high-power, high-critical-energy white light hutches.

SR Thermal Protection

The SR beam has very high power density to burn through components that are not properly cooled. It is essential to ensure every component that may be hit by SR is properly cooled if it cannot take the heat load indefinitely. In general, the white light and pink light have high power densities that warrant thermal protection, while the mono light downstream of a monochromator presents no thermal damage issue.

SR ray trace study shall be performed for every beamline to ensure that all possibly mis-steered rays are properly contained in all operational modes. SSRL ray trace study requires that 1) the SR source size is limited by interlocked stored beam orbit envelope, 2) the possible mirror angles are limited by hard stops or interlocked limit switches, and 3) the pink light reflected from a mirror in all possible angles are contained. When white light or pink light is directed onto monochromator, the monochromatic beam is offset from the direction of the in-coming beam. If the downstream section is not properly protected for non-monochromatic beams and shielded, a SR beam stop is placed behind the monochromator (see Figure 3) to block the beam in case the monochromator is mis-placed (this protection principle also applied to pink light after a mirror). SR ray trace study also allows the identification of potential targets to be considered for shielding analysis. The SSRL ray trace methodology is described in a report (46).

Coolant interlock to prevent burn-through and vacuum interlock to detect burn-through shall be part of the engineered radiation safety system, if the burn-through event has personnel safety implications.

Gas Bremsstrahlung (GB)

As summarized before (14), the GB source term has been studied extensively in the literature. The GB source term has three characteristics:

1) The energy spectrum is $1/k$, where k is the photon energy up to the electron beam energy. Therefore, the high-energy GB photons can create electromagnetic shower in beamline components and is much more difficult to shield than SR. It is conservative and appropriate to use the minimum of the Compton cross section (5) of a material (*e.g.*, 24 g cm^{-2} for lead) for the estimation of GB attenuation. Neutron produced from the GB shower may also need to be considered.
2) The GB intensity is highly forward-peaked with an angular characteristic angle (the angular width of the forward bremsstrahlung flux at half intensity) $\theta_c = 0.511/E$ (in radians), where E is the electron energy in MeV. Therefore, the GB shielding tends to be along the beamline central axis and is thicker in forward angles. A typical 6-m-long straight section at SPEAR3 ring has a 3-m-long ID. Along the 3-m wiggling path, a GB fan is created with a horizontal width dependent on the ID's deflection parameter K. In the remaining 3-m straight section, the GB is produced in a very small angular cone with the characteristic angle θ_c (0.511/3000 = 0.17 milliradian for SPEAR3). Therefore, the actual GB power profile from an ID straight as a function of horizontal angle has a peak at 0-degree (from the θ_c effect) and tails at both ends (from the K effect) (50). This may have implication for GB shielding design, as shown later.
3) The un-attenuated GB dose rate is strongly dependent on the dose-scoring area over which the calculation or measurement was made, as well as the size, angular divergence, and actual curved trajectory of the stored beam in the air path. In general, the GB dose rate source term is proportional to $\sim E^{2.5}$, the stored beam current, as well as the mass thickness of the air

column in the ring section that stored beam passes through. Therefore, the GB problem is more acute for long insertion devices at high-energy, high-current storage rings.

Shielding for Primary GB

The primary GB, i.e., the GB that has not interacted with any material, has very high dose rate, up to a few Sv h^{-1} at zero-degree (51). Therefore, the beamlines need to have GB safety components (see Figure 3) such as collimators, hutch shutters, and GB beam stops (up to 25-cm-thick lead for SPEAR3 ID beamlines) that can provide enough longitudinal and lateral attenuation for any primary GB rays. The sufficient coverage shall be demonstrated with GB ray trace study, which assumes that: 1) a GB source size the same as the ring vacuum chamber size, 2) the GB ray is not affected by optical components, and 3) the GB ray is terminated until it is blocked with sufficient GB safety components (46,52). The safety component design for primary GB is described in a SLAC report (44).

GB Scattered from Beamline Components

The secondary photons and neutrons coming out of the downstream and lateral sides of any beamline component (e.g., masks, slits, mirrors, monochromators) hit by GB may need shielding. As a minimum, the shielding for the first optical element hit by primary GB from ID beamlines in the median plane and central axis needs to be considered.

The most accurate method of calculating radiation doses associated with GB is using Monte Carlo codes to model the GB source and beamline layout as accurately as possible. However, this Monte Carlo approach may not be practical or available. In addition, there are cases in which conservative estimation using analytic methods (described below) is sufficient.

This is particularly true, considering the fact that one of the largest errors in estimating GB hazard arises from the difficulty in measuring the vacuum pressure in a long straight section, whose uncertainty could be a factor of 2-3.

The GB source term and shielding can be estimated using the following analytical method:

1) GB is a thin-target bremsstrahlung process and, thus, the fractional energy transferred from the stored beam to the bremsstrahlung photons, dE/E, is equal to the ratio of the target thickness t to the radiation length X_o of the target material, *i.e.*, $dE/E = t/X_o$ (4,5). Therefore, the fractional energy (or power) transferred from the circulating electrons to GB photons is t/X_o, where t is the mass thickness of the air path length and X_o is 36.818 g cm^{-2} for air. For example, the SPEAR3 stored beam power is = 500 mA x 3 GeV= 1.5 $x10^9$ W. With an 6-m-long ID straight and a vacuum of 0.13 μPa (10^{-9} torr), the air mass thickness is $9x10^{-13}$ g cm^{-2}, and the t/X_o is $2.5x10^{-14}$. Thus, the power transferred from stored beam to GB in a SPEAR3 ID beamline is 38 μW. This is one of the highest GB powers of all current SR facilities. The normalized GB power is 0.1 μW mA^{-1} μPa^{-1} m^{-1}, which is in good agreement with the SPring8 measurement of 0.16 μW mA^{-1} μPa^{-1} m^{-1} (53). The dipole source (15-cm-long bending length at SPEAR3) is much shorter than an ID source and, thus, the GB in bend beamlines does not present a scattered GB concern, but its primary GB still needs to be considered (e.g., up to 20-cm-thick lead for collimators, hutch shutters, and GB beam stops in a SPEAR3 bend beamlines).
1) The above GB power can be used to calculate the scattered GB dose rates with the following steps:

a. According to SHIELD11 results, the laterally scattered dose rates at 1 m for an electron beam hitting a thick iron target (5-cm radius, 30-cm long) are 15 μSv h^{-1} mW^{-1} photons and 12 μSv h^{-1} mW^{-1} neutrons (also see the column 2 of Table 3).

b. With equal beam power, GB photons will give similar dose results as an electron beam. Therefore, with 38 μW of GB hitting a thick iron target, the scattered dose rates at 1 m are 0.6 μSv h^{-1} photon and 0.5 μSv h^{-1} neutron.

Other analytic methods can also estimate the scattered GB photon and neutron dose rates from a thin target such as mirror or monochromator (14), which should give higher dose rates than a thick target (radius larger than 4 Moliere lengths). These analytic methods give scattered GB dose rates that are in good agreement with the measurements (within a factor of 2-3) (54,55), considering the vacuum uncertainty and the target size/geometry effects. In any case, the total laterally scattered GB dose rate at 1 m is likely to be a few μSv h^{-1} (53-55), which could be higher than the 1 mSv y^{-1} beamline shielding design limit. Therefore, for modern high-energy, high-stored-current facilities, up to 5-cm-thick lead shielding (providing attenuation up to a factor of 10) may be needed for laterally scattered GB in an ID beamline, particularly for the first optical component hit by primary GB. For small hutches where distance does not offer much dose reduction, local shielding for scattered GB at forward angles (up to 10-cm-thick lead at 20-50 degrees) may also be needed.

The analytic method can only estimate shielding at 50-100 degrees. A generic GB shielding design method has been developed to estimate shielding at all angles (45). The method utilizes FLUKA-calculated curves for the photon and neutron dose rates as a function of lead shielding thickness at polar angles from 0-degree to 90-degree from GB hitting 3 types of targets: an inclined 1-m-long Si mirror (a typical beamline GB target), a 2.5-cm-cube copper (a shower maximum target), and a 2.5x2.5x15 cm^3 Cu block (simulating a long mask).

The facility's choice of the hutch shielding depends on the beamline characteristics and layout, and the storage ring parameters. For example, for the SPEAR3 optics hutch (11-0 in Figure 3), the hutch wall thickness is determined by SR and local shielding is added for scattered GB. For the ESRF ID beamlines, the 28-mm-thick lead hutch wall is dictated by scattered GB (31).

A medium-energy ring like SSRL tends to have more wigglers (which have high deflection parameters K) than other high-energy or low-energy rings (56). To maximize the benefit of wiggler beamlines, there are generally 2-3 branch lines in a beamline. Therefore, the optical components in the optics hutch of a wiggler beamline may be so close to each other such that the integration of GB shielding into the beamline layout becomes difficult. Therefore, it is imperative that the GB, as well as SR, shielding design be considered in the early beamline design stage.

Due to the low electron beam power, the production of radioactive nuclides in the air and soil, as well as noxious gases, from beam losses in the injector and storage ring are generally not considered safety issues (57). However, when a high-power SR beam, *e.g.*, a white light beam, travels in a long air path inside a hutch, the resulting ozone concentration may need to be estimated (57), and mitigation measures such as forced ventilation considered.

Bremsstrahlung from Injection and Stored Beam Losses in Ring

In addition to SR and GB, forward-angle bremsstrahlung from stored beam and injection beam (during top-off mode) losses at a ring aperture may channel into a beamline, which should be considered in the beamline shielding. FLUKA calculations (58) show that the fraction of bremsstrahlung power coming into the out-of-alcove beamline to the power loss at an ring ID aperture (called bremsstrahlung fraction hereafter) varies between 10^{-6} and 10^{-1}, heavily depending on the beamline's cone of sight to the ring aperture, which is governed by the ring and beamline aperture layout and configuration. Measurements at SRRC and SSRL (59,60) give a bremsstrahlung fraction of 0.5% and up to a few percents, respectively, for ID beamlines.

The bremsstrahlung fraction is crucial to the dose estimation on the experimental floor. For example, For a SPEAR3 ID beamline with an average stored beam loss of 2 mW at its ring aperture and a bremsstrahlung fraction of 1%, the bremsstrahlung power onto to the floor is 20 μW, which is comparable with the GB power. Note that this bremsstrahlung from stored beam losses (which is beamline dependent) cannot be differentiated from the GB (which is not beamline dependent). Long-term measurements using sensitive detectors during SPEAR3 stored beam operation (60) show that local lead shielding installed for GB is not sufficient for a few ID beamlines and additional lateral shielding of up to 5-cm-thick lead is needed to cope with the additional bremsstrahlung from stored beam losses.

SPECIFIC SAFETY ISSUES FOR TOP-OFF INJECTION

Normal Operation

For top-off mode, the forward bremsstrahlung from injection beam losses at ring apertures should be considered for beamline shielding design, particularly when injection efficiency is poor. Therefore, analysis and measurements for top-off mode (58,60) should be conducted to ensure that instantaneous dose rate and integrated dose around optic hutches during top-off injection are acceptable. Controls for injection beam lattice and optics may be needed to maintain good injection.

Due to the shorter lifetime near the maximum current, the trickle charge injection mode will inject more than that for non trickle charge mode, e.g., SPEAR3 trickle charge mode injects up to 4.5×10^{15} electrons per year into the ring, 30% more than the non trickle charge operation (61). This increase needs to be considered in both the ring and beamline shielding designs.

For a facility upgraded to higher stored current and/energy, it is important to consider that the total electrons injected into the ring or the integrated dose measurement results at lower current/energy should be scaled up with the current and energy, as well as the reduced lifetime (59-61). For example, SPEAR3 upgrade from 100-mA infrequent injection to 500-mA trickle injection requires an increase of a factor of about 20 (5 from current and 4 from lifetime).

Controls and Mitigation for Mis-steered Injection Beam

As mentioned earlier, during top-off injection, the injection beam needs to be prevented from being mis-steered into a beamline and possibly onto experimental floor to create significant hazard. Injection beam trajectory study is needed to demonstrate that, under certain machine bounding conditions, such abnormal injection events are very unlikely (62,63). Interlocked safety systems shall then be installed to monitor and/or limit the machine bounding conditions. All SR facilities require, as a minimum, a stored current interlock which allows top-off injection only when stored current is above a threshold (17). Interlocks for injection beam energy, injection beam current and/or injection losses are very common (17,59,63). Adding a permanent magnet in the frontend to deflect the injection beam mis-steered into the beamlines near the injection region have also been used (59,64).

Most SR facilities install fixed radiation detectors next to the first optical element that the bremsstrahlung may hit to monitor/limit the integrated dose and/or dose rate from stored beam and top-off injection beam, which are generally low (< 1 mSv/year). Coupled with the very low frequency of trickle charge injection, the measurement of doses from top-off and stored beam losses generally has to be relied on sensitive detectors under long-term measurements.

SPECIFIC SAFETY ISSUES FOR 4th GENERATION X-RAY FEL FACILITY

The 4th generation FEL facilities utilize the self amplified stimulated emission (SASE) process to generate FEL with a much higher brightness and shorter pulses with unprecedented peak power than the 3rd generation sources. The storage ring based FEL facilities which utilize optical cavities (mirrors) for FEL production are not described here, as their safety issues are similar to those of the 3rd generation SR facilities. What discussed here are the 4th generation FEL facilities, which are Linac-based FEL facilities producing VUV or x-ray FEL, in addition to spontaneous SR, from the single pass of high-energy electron beam (tunable energy, high current, and extremely low emittance) through an undulator that is typically longer than the FEL saturation length. For example, the SLAC Linac Coherent Light Source (LCLS), the world's first x-ray FEL, uses an electron beam (3-17 GeV, 5 kW maximum) and a 120-m-long undulator to generate FEL in the x-ray and VUV range (65).

It is illustrative to compare the SR, FEL and GB from LCLS with those of SPEAR3. A SPEAR3 ID beamline generates a maximum of a few kW/mradH of SR (critical energy 12 keV) and a GB power of 38 μW. The LCLS undulator generates only a maximum of 2.5 W of SR (critical energy 155 keV maximum), 0.3 W of FEL (fundamental 8 keV maximum), and a GB power of 1.2 μW (0.13 mPa and 150-m long straight) (66). Therefore, LCLS has much less shielding demands for SR, FEL and GB. However, the Linac-based FEL facilities present several unique safety issues.

The first issue is illustrated in Figure 5, which shows that the electron beam, after passing through the undulator (not shown here), is bended down by electromagnets to the main beam dump. The FEL and SR will channel into the Front End Enclosure (FEE), which has a FEL diagnostic section (FEE is similar to the first optic hutch of a storage ring facility). The FEL is then directed by one of the mirror systems in FEE to one of the 3 photon beamlines in Near Experimental Hall (NEH). The LCLS operations have continuous electron beam losses at collimators and electromagnets, as well as temporary beam losses from very thin devices (beam finding wires, wire scanners, etc) being inserted in undulator section. These beam losses will create forward-angle muons and zero-degree bremsstrahlung that need to be considered for FEE and NEH shielding design (68). When 20 W is lost at the first electromagnet (BYD1), the dose rate in FEE immediately downstream of Wall #1 (120-cm iron and 90-cm concrete) is 0.01 mSv h^{-1}. Furthermore, the zero-degree bremsstrahlung entering FEE via beampipe (calculated to be 35 to 1450 mW, depending on uniform or point loss pattern) can hit and create shower at the first collimator and mirror, resulting in a dose rate of a few μSv h^{-1} downstream of Wall #2 (90-cm iron and 90-cm concrete) in NEH. The facts that the radiation in FEE and NEH is dominated by muons and the whole beam loss geometry is complicated warrant the use of Monte Carlo codes, instead of analytic codes, for more accurate calculations in order to derive reasonably conservative shielding requirements. In addition, an extensive set of active and passive safety systems needs to be used to prevent the electron beam from being mis-steered into the FEE. A set of collimators has to be installed also in FEE to block the zero-degree bremsstrahlung from directly entering the NEH, due to the very small off-set between the FEE line and NEH hard x-ray line. The 5-kW electron beam on the beam dump has also been heavily shielded such that it does not create much radiation in FEE as well as the activation of air and soil surrounding the dump pit (69,70). The radiation measurements in FEE during the electron beam commissioning are in agreement with the Monte Carlo calculations (71).

The 2nd issue is about the thermal stress caused by the extremely high FEL peak power (due to its much shorter pulse of ~100 fs) that normal coolant for SR is not useful. Based on the FEL ray trace study, LCLS has installed extensive sets of B_4C disks with burn-through monitors or collimators with air attenuators as passive absorbers to contain the FEL (67). Vacuum pressure interlocks in photon beamlines are also a mitigation option.

The hutch and beamline safety design for FEL and SR are similar to those of 3rd generation facilities. One of the unique hazards is the high peak power laser experiment that can be conducted only in FEL facilities, not in 3rd generation facilities, as such experiment can create x rays from plasma induced by high-power laser (72).

OPERATIONAL SAFETY PROGRAM

Examples of synchrotron facilities' operational radiation safety programs have been reported for SSRL accelerators (73) and beamlines (74). Only some key aspects of the programs are summarized in this section.

Operation Authorization

The hazards, mitigation measures (shielding and interlocked safety systems), operation envelope (e.g., allowed beam energy and current, and integrated beam particle numbers that can be delivered to different areas of accelerator complex) and safety envelope (e.g., maximum credible beam energy and current) should be specified in the facility's safety assessment document. Those relevant to accelerator or beamline operations, such as shielding, safety system annual certification and periodic tests, operation envelope, etc., should also be specified in the operation authorization document, which are approved by facility management, Operations group and safety professional.

Accelerator physics studies at SSRL are grouped into three categories: studies with normal injection (e.g., stored beam study), studies with poor injection (e.g., optimization of injection or stored beam lattice), and studies with zero injection efficiency (e.g., ring RF off or kickers mis-matched); the latter needs approval and mitigation measures unless the associated hazards have been shown to be known, stable and acceptable. Some facilities do not allow top-off accelerator physics study without additional safety controls other than those in top-off operations for user runs.

Role, Responsibility and Training

Similar to those for the accelerator operators, beamline physicists and engineers at SSRL and LCLS, who design, construct, commissioning, tune and/or operate a photon beamline, need radiation safety training to understand the basic radiation protection, beamline characteristics, hazards, shielding and safety systems, and configuration control. Each beamline has a beamline engineer responsible for its beamline safety and operation authorization. The beamline duty operators have sufficient training to perform their safety functions on the experimental floor such as verifying the completeness of safety measures and readiness of beamline operation, searching the optic hutches, allowing beam to be brought to a beamline, conducting regular radiation survey, etc. The SR facilities are generally designed such that minimal safety training is needed for outside users.

Commissioning

Because commissioning of accelerators and beamlines generally involves more frequent injection, intentional beam mis-steering, and uncertain machine performance (which lead to higher losses), the plans for personnel dose controls (e.g., special access control, beam limiting, etc.) and radiation measurements (both active and passive) have to be developed to govern the commissioning process. The radiation dose results and commissioning process should be reviewed and revised as the commissioning achieves various milestones. The performance of accelerators, beamlines, and interlocked safety systems may need to be verified or calibrated during commissioning. The commissioning results should be incorporated into the establishment of the final operational safety controls and radiation measurements for routine operation.

Start-up after a long down may pose similar, though less, safety issues.

Radiation Measurements

The stored beam circulates at an orbital frequency of 1.28 MHz at SPEAR3. Both SR and GB are produced in a train of pulses with a frequency that is a multiple of orbital frequency (but no more than the ring RF frequency: 358 MHz for SPEAR3), depending on the number of RF buckets being filled around the ring. Thus, SR and GB pulses are quasi-continuous. However, radiation from injection beam losses in the injector and storage ring, as well as radiation at Linac-based FEL facilities, is pulsed at much lower rates (10 Hz at SSRL and 120 Hz at LCLS), and its pulsed effect on active radiation detectors should be recognized.

Radiation measurements around photon beamlines should consider the low-energy (a few keV to tens of keV) nature of SR and FEL, as well as the potentially narrow beam nature for a leakage radiation measurement.

CONCLUSIONS

There are many SR and FEL facilities in the world and radiation protection for these facilities is similar to that of other types of electron accelerator facilities, except in the areas of storage ring and photon beamlines (which has SR and GB hazards). FEL facilities also have unique high peak power FEL thermal stress issue and zero-degree radiation issue. A careful analysis of normal beam losses in the ring and identification of credible abnormal beam losses in the ring and photon beamlines is the first crucial step of a sound safety design. Analytic tools (albeit with limitations) are available for rough estimations of the photon and neutron doses from electron beam losses, as well as mitigation for SR and GB in beamlines, though Monte Carlo codes may be the desired tools for complicated geometry problems. Because most SR and FEL facilities have similar design and dose control goals as well as similar beam parameters and operation modes, it is desired and useful for SR/FEL accelerator community to have consistent radiation safety policies and practices, and experience from peer facilities should be consulted when practical.

REFERENCES

1. http://lightsources.org/cms/
2. Robinson, A. and Plummer B. Scientific needs for future x-ray sources in the USA, white paper. SLAC National Accelerator Laboratory, Stanford, CA, SLAC-R-910 (2008).
3. Winick, H. Synchrotron radiation sources: a primer. World Scientific, New Jersey (1995).
4. Swanson, W. P. Radiological safety aspects of the operation of the electron linear accelerators. International Atomic Energy Agency, Vienna, IAEA Technical Report No. 188 (1979).
5. Swanson, W. P. and Thomas, R. H. Dosimetry for radiological protection at high-energy particle accelerators. The Dosimetry of Ionizing Radiation, Vol. III, Ch. 1, edited by Kase, K. R. et al., Academic Press, Inc., Orlando, FL (1990).
6. Vylet, V. and Liu, J. C. Radiation protection at high energy electron accelerators. Radiat. Prot. Dosim. 96(4), 333-344 (2001).
7. Rokni, S., Cossairt, J. D. and Liu, J. C. Radiation shielding at high-energy electron and proton accelerators. SLAC National Accelerator Laboratory, Stanford, CA, SLAC-PUB-13048, Dec. 2007. Health Physics Society Professional Development School “Topics in Accelerator Health Physics”, Jan. 31-Feb. 2, 2008, Oakland, CA, Medical Physics Publishing, Madison, WI (2008).

8. Rokni, S., Fasso, A. and Liu, J.C. Operational radiation protection in high energy physics accelerators. This issue.

9. Ipe, N. E. and Liu, J. C. Shielding and radiation protection at the SSRL 3 GeV injector. SLAC National Accelerator Laboratory, Stanford, CA, SLAC-PUB-5714 (1991).

10. Liu, J. C., Ipe, N. E. and Yotam, R. Radiation safety system at the Stanford Synchrotron Radiation Laboratory. Proceedings of the 1st International Workshop on Radiation Safety at Synchrotron Radiation Sources, Argonne, IL, April 23-24 (2001).

11. Liu, J. C., Bull, J., Drozdoff, J., May, B. and Vylet, V. Radiation safety systems for accelerator facilities. Radiat. Prot. Dosim. 96(4), 429-439 (2001).

12. Liu, J. C., Vylet, V. and Walker, L.S. Engineered and administrative safety systems for the control of prompt radiation hazards at accelerator facilities. SLAC National Accelerator Laboratory, Stanford, CA, SLAC-PUB-13048. Health Physics Society Professional Development School “Topics in Accelerator Health Physics”, Jan. 31-Feb. 2, 2008, Oakland, CA, Medical Physics Publishing, Madison, WI (2008).

13. Vylet, V. Safety systems. This issue.?

14. Liu, J. C. and Vylet, V. Radiation protection at synchrotron radiation facilities. Radiat. Prot. Dosim. 96(4), 345-357 (2001).

15. Vylet, V. and Liu, J. C. Synchrotron facilities and free electron lasers. SLAC National Accelerator Laboratory, Stanford, CA, SLAC-PUB-13049, Dec. 2007. Health Physics Society Professional Development School “Topics in Accelerator Health Physics”, Jan. 31-Feb. 2, 2008, Oakland, CA, Medical Physics Publishing, Madison, WI (2008).

16. Berkvens, P., Holbourn, M., Ryder, R., Pruvost, J. B. and Colomp, P. Design and practices at four European synchrotron radiation facilities. Radiation Meas. 41(2), S202-S206

(2007).

17. Liu J. C., Rokni, S., Asano Y., Casey, W., Donahue, R. and Job, P. Comparison of design and practices for radiation safety among five synchrotron radiation facilities. Radiation Meas. 41(2), S206-S220 (2007).

18. Corbett, J., Evans, I., Guerra, E., Hettel, R. and Safranek, J. Electron beam loss estimates for SPEAR3. SLAC National Accelerator Laboratory, Stanford, CA, SSRL-ENG-NOTE-M371, April 5 (2001).

19. Ipe, N. E. Radiological considerations in the design of synchrotron radiation facilities. SLAC National Accelerator Laboratory, Stanford, CA, SLAC-PUB-7916 (1999).

20. Stanford Linear Accelerator Center, Stanford. Radiation safety systems technical basis document. SLAC National Accelerator Laboratory, Stanford, CA, SLAC-I-720-0A05Z-002-R003 (2008).

21. Liu, J. C., Rokni, S., Khater, H. and Mao, S. Summary of radiation safety design for SPEAR3 ring. SLAC National Accelerator Laboratory, Stanford, CA, RP Note 03-07 (2003).

22. Liu, J. C., Rokni, S., Khater, H. and Mao, S. Radiation safety design for SSRL SPEAR3 ring. SLAC National Accelerator Laboratory, Stanford, CA, RP Note 03-05 (2003).

23. Khater, H., Liu, J. C. and Rokni, S. Radiation safety design for SSRL storage ring. Radiation Meas. 41(2), S172-S178 (2007).

24. Nelson, W. R. and Jenkins, T. The SHIELD11 computer code. SLAC National Accelerator Laboratory, Stanford, CA, SLAC-R-737 (2005).

25. Nelson, W. R., Hirayama, H. and Rogers, D. W. O. The EGS4 code system. SLAC National Accelerator Laboratory, Stanford, CA, SLAC-265 (1985).

26. Fasso, A., Ferrari, A., Ranft J. and Sala, P. R. FLUKA: a multi-particle transport code. CERN-2005-10, INFN/TC_05/11, SLAC-R-773 (2005).

27. Waters, L. S. (editor), Monte carlo n-particle transport code system for multi-particle and high energy applications, version 2.7. Los Alamos National Lab., Los Alamos, NM, LA-UR-08-07182 (2008).

28. Liu, J. C., Khater, H. and Rokni, S. FLUKA calculations of source terms and attenuation profiles for generic shielding design of SPEAR3 ring. SLAC National Accelerator Laboratory, Stanford, CA, RP Note 02-20 (2002).

29. Bauer, J., Guetersloh, S., Khater, H., Liu, J. C., Prinz, A. and Rokni, S. Process and requirements for radiation safety analysis of SPEAR3 ring ratchet wall, lateral wall and frontend safety components. SLAC National Accelerator Laboratory, Stanford, CA, RP Note 05-20, Rev. 2 (2007).

30. Liu, J. C., Fasso, A. and Roesler, S. Evaluation of SPEAR3 roof shielding. SLAC National Accelerator Laboratory, Stanford, CA, RP Note 01-03 (2001).

31. Berkvens, P. Radiation safety issues of synchrotron radiation sources, an overview. Proceedings of the 1st International Workshop on Radiation Safety at Synchrotron Radiation Sources, Argonne, IL, April 23-24 (2001).

32. Taniguchi, S., Sasaki, M., Nunomiya, T., Iwase, H., Yonai, S., Nakamura, T., Rokni, S., Liu, J. C., Roesler, S. and Kase, K. Neutron energy and time-of-flight spectra behind the lateral shield of a high-energy electron accelerator beam dump, part I: measurements. Nucl. Instru. Methods A503, 595-605 (2003).

33. Roesler, S., Liu, J. C., Rokni, S.H. and Taniguchi, S. Neutron energy and time-of-flight spectra behind the lateral shield of a high-energy electron accelerator beam dump, part II:

34. Vylet, V., Liu, J. C., Rokni, S. H. and Thai, L. X. Measurements of the neutron spectra at the Stanford Linear Accelerator Center. Radiat. Prot. Dosim, 70(1-4), 425-428, (1997).

35. Liu, J. C., Fasso, A., Mao, S., Nelson, W. R., Seefred, R. and Sit, R. Environmental impact from accelerator operation at SLAC. Proceedings of 1999 Symposium on Environmental Monitoring Techniques, Kaohsiung, Taiwan, March 18-19, 1999. SLAC National Accelerator Laboratory, Stanford, CA, SLAC-PUB-8085 (1999).

36. Liu, J., Mao, S., Roesler S. and Rokni S. Radiation safety design for SPEAR3 beamline frontend. SLAC National Accelerator Laboratory, Stanford, CA, RP Note 03-01 (2003).

37. Rabedeau, T. SPEAR3 Beamline in-alcove radiation shielding. SLAC National Accelerator Laboratory, Stanford, CA, SSRL M417, Rev. 1 (2003).

38. Liu, J. C., Fasso, A., Prinz, A. and Rokni, S. Radiation safety design for SSRL wiggler beamline 11. SLAC National Accelerator Laboratory, Stanford, CA, RP Note 04-05 (2004).

39. Prinz, A., J. C., Khater, H., Fasso, A., and Rokni, S. Shielding design for synchrotron radiation beamlines at SSRL. Proceedings of the 4th International Workshop on Radiation Safety at Synchrotron Radiation Sources, Saskaton, Canada, 75-80 (2007).

40. Liu, J. C., Fasso, A., Khater, H., Prinz, A. and Rokni, S. Generic radiation safety design for SPEAR3 beamlines. Radiation Meas. 41(2), S156-S162 (2007).

41. Liu, J. C., Khater, H., Prinz, A. and Rokni, S. Generic synchrotron radiation shielding design for SPEAR3 white light hutches. SLAC National Accelerator Laboratory, Stanford, CA, RP Note 03-08 (2003).

42. Prinz, A., Liu, J. C. and Khater, H. Generic synchrotron radiation shielding design for

43. Fasso, A. and Liu, J. C. Attenuation of scattered monochromatic synchrotron radiation in iron and lead. SLAC National Accelerator Laboratory, Stanford, CA, RP Note 03-20 (2003).

44. Khater, H., Liu, J. C., Prinz, A., Fasso, A. and Rokni, S. Primary gas bremsstrahlung shielding requirements for SPEAR3 beamlines. SLAC National Accelerator Laboratory, Stanford, CA, RP Note 03-09 (2003).

45. Prinz, A., Liu, J. C., Khater, H. and Rokni, S. Shielding for scattered gas bremsstrahlung for SPEAR3 beamlines. SLAC National Accelerator Laboratory, Stanford, CA, RP Note 03-10 (2003).

46. Rabedeau, T. SSRL Beam line documentation requirements for radiation physics. SLAC National Accelerator Laboratory, Stanford, CA, SSRL Engineering Note M580 (2008).

47. Prinz A., Liu J. and Rokni, S. Radiation safety design for SSRL undulator beamline BL5. SLAC National Accelerator Laboratory, Stanford, CA, RP Note 04-03 (2004).

48. Asano, Y. A Study on radiation shielding and safety analysis for a synchrotron radiation beamline. Japan Atomic Energy Research Institute, Ibaraki, Japan, JAERI-Research 2001-006 (2001).

49. Liu, J. C., Fasso, A., Prinz, A., Rokni, S. and Asano, Y. Comparison of synchrotron radiation calculations between analytical codes (STAC8, PHOTON) and monte carlo codes (FLUKA, EGS4). Radiat. Prot. Dosim. 116(1-4), 658-661 (2005).

50. Rabedeau, T. Insertion device beam line off-axis primary gas bremsstrahlung power. SLAC National Accelerator Laboratory, Stanford, CA, SSRL memo (2005).

51. Ferrari, A., Pelliccioni, M., and Sala, P. R. Estimation of fluence rate and absorbed dose rate due to gas bremsstrahlung from electron storage rings. Nucl. Instru. Meth. B83, 518-524 (1993).

52. Advance Light Source (ALS), ALS beamline design guide. Lawrence Berkeley National Laboratory, ALS-PUB-3114 (1998).

53. Asano, Y. Measurements of photoneutron spectrum due to gas bremsstrahlung at SPring8 insertion device beamlines. Proceedings of the 1st International Workshop on Radiation Safety at Synchrotron Radiation Sources, Argonne, IL, April 23-24 (2001).

54. Liu, J. C., Nelson, W. R. and Kase, R. K. Gas bremsstrahlung and associated photon-neutron shielding calculations for electron storage rings. Health Phys. 68(2), 205-213 (1995).

55. Pisharody, M., Semones, E., and Job, P. K. Dose measurements of bremsstrahlung-produced neutrons from thick targets. Nucl. Instru. Meth. A430, 542-558 (1999).

56. Asano, Y. and Liu, J. C. Shielding design aspects of SR beamlines for 3 GeV and 8 GeV class synchrotron radiation facilities. Radiation Meas. 41(2), S194-S199 (2007).

57. Moe, H. J. Advanced Photon Source: radiological design considerations. Argonne National Laboratory, APS-LS-141 (1989).

58. Liu, J. C., Bauer, J., Fasso, A., Prinz, A. and Rokni, S. Radiation safety analysis for SSRL top-off operations. SLAC National Accelerator Laboratory, Stanford, CA, RP Note 07-23 (2008).

59. Sheu, R. J., Liu, J. and Wang, J. P. Radiation safety analysis for top-up operation at NSRRC. Proceedings of the 3rd International Workshop on Radiation Safety of Synchrotron Radiation Sources, SPring8 Document A-2005-002 (2004).

60. Bauer, J., Liu, J. C., Prinz, A. and Rokni, S.??. SLAC National Accelerator Laboratory, Stanford, CA, RP Note 09-? (2009).

61. Hettel, R. and Corbett, J. Electron beam loss estimates: top-off mode. SLAC National Accelerator Laboratory, Stanford, CA, SSRL-ENG-NOTE M569, Rev. 1 (2008).

62. Emery, L. and Borland M. Analytical study of top-off safety for the APS. Proceedings of 1999 Particle Accelerator Conference, New York, 2939 (1999).

63. Terebilo, A., Bozorg-Chami, B., Corbett, J., Hettel, R., Huang, X., Padilla, M., Rabedeau, T., Safranek, J., Schmerge, J., Wermelskirchen, C., Yotam, R., Bauer, J., Liu, J. C. and Prinz, A. Summary report on SEPAR3 top-off injection: hazards and mitigation. SLAC National Accelerator Laboratory, Stanford, CA, SSRL-ACC-PHYS-NOTE 007 (2009).

64. Liu, J. C. and S. Rokni, S. Radiation safety design for SPEAR3 SLM beamline. SLAC National Accelerator Laboratory, Stanford, CA, RP Note 02-01 (2005).

65. Stanford Linear Accelerator Center. LCLS design study report. SLAC, Stanford, CA, SLAC-R-521, UC-414 (1998).

66. Rokni, S. Liu, J. and Mao. S. Calculation of gas-bremsstrahlung for the LCLS undulator. SLAC National Accelerator Laboratory, Stanford, CA, RP Note 02-03 (2002).

67. Stefan, P., Bionta, R., Arthur, J. and March, D. Beam containment in the LCLS Front End Enclosure. LCLS Engineering Specification Document 1.5-135 (2009).

68. Santana, M., Fasso, A., Sanami, T., Mao, S., Liu, J. and Rokni, S. Shielding design for the LCLS BTH and undulator. SLAC National Accelerator Laboratory, Stanford, CA, SLAC-PUB-12697 (2007).

69. Sanami, T. and Mao, S, Radiation safety evaluation for engineering implementation of the LCLS 5 kW electron dump and shielding. SLAC National Accelerator Laboratory,

Stanford, CA, RP Note 07-17 (2007).

70. Sabourov, A., Liu, J., Santana, M. and Mao, S. Linac Coherent Light Source (LCLS) radiological environmental impact analysis report. SLAC National Accelerator Laboratory, Stanford, CA, RPD Report (2008).

71. Santana, M., Mao, S., Liu, J., Bauer, J and Allan, J. Radiation survey during the commissioning of the LCLS electron beam line from the BTHW to the main beam dump. SLAC National Accelerator Laboratory, Stanford, CA, RP memo RP-RPG-090113-MEM-02 (2009).

72. Kruer, W.L. The Physics of Laser Plasma Interactions, Addison-Wesley (1988).

73. Khater H. and Liu, J. C. Results of dose control and measurement plan applied for SPEAR3 commissioning year (FY04). Radiation Meas. 41(2), S163-S171 (2007).

74. Prinz, A., Liu, J. C., Allan, J., and Khater, H. Operational radiation safety program for SSRL beamlines. SLAC National Accelerator Laboratory, Stanford, CA, SLAC RP Note 05-01 (2008).

LIST OF CAPTIONS FOR TABLES AND FIGURES

Table 1. Key storage ring parameters for four US synchrotron light facilities.

Table 2. Annual SPEAR3 operation schedule and number of electrons injected into the ring.

Table 3. Maximum dose equivalent rate outside the lateral concrete wall from a standard iron target hit by 3-GeV electron beam calculated with SHIELD11.

Figure 1. SSRL with the injector (the Linac and the booster synchrotron), SPEAR3 storage ring, and photon beamlines (B: dipole, W: wiggler, U: undulator).

Figure 2. Annual normal beam loss estimates for SPEAR3 storage ring operation.

Figure 3. A typical layout of a SSRL hard x-ray beamline (wiggler BL11) to illustrate the radiation safety aspects of a photon beamline.

Figure 4. The maximum ambient dose rate from an inclined Si mirror as a function of lead shielding thickness for SSRL white-light beamlines with 5 critical energies between 3.1 and 12.2 keV for lateral shielding determination.

Figure 5. Radiation levels in LCLS FEE and NEH from 20-W electron beam loss at the first electromagnet at the dump line.

Parameter	**Low-energy ALS**	**Medium -energy SSRL**	**Medium -energy NSLS-II**	**High-energy APS**
Injection Beam Power (W)	1.5	4	0.75	20
Ring Circumference (m)	197	234	792	1104
Stored Beam Energy (GeV)	1.9	3	3	7
Stored Current, I (mA)	400	500	500	100
Stored Energy (J)	500	1200	4060	2578
Stored Beam Power, Ps (MW)	760	1500	1500	700
Design Lifetime, τ (h)	8	10	3	54
Typical Straight Length (m)	6	6	6.6	15
GB Power from Straight (μW)	19	38	42	44
Ring Floor Shielding Limit (mSv y^{-1})	2	1	5	5
Beamline Shielding Limit (mSv y^{-1})	1	1	1	1
Site Boundary Dose Limit (mSv y^{-1})	0.1	0.05	0.05	0.1

1) As of Jan. 2009.

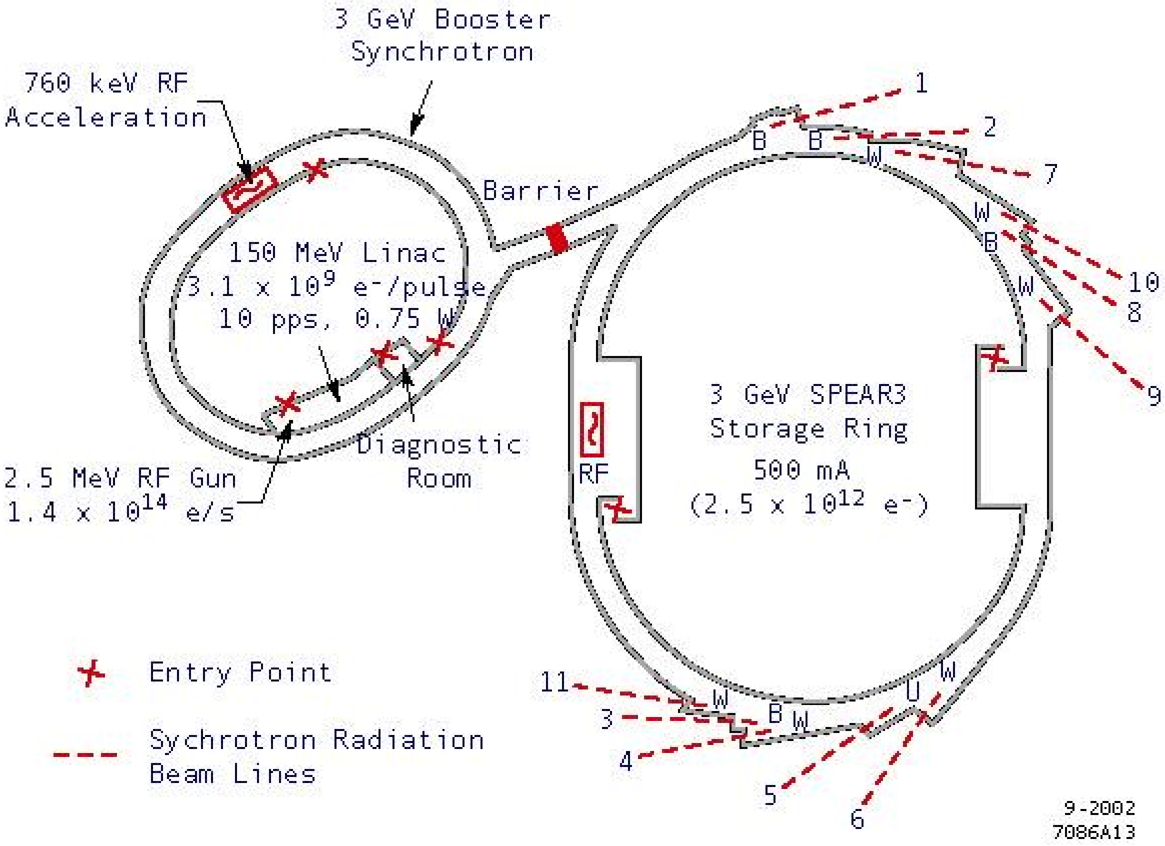
2) Occupancy of 2000 h y^{-1} on the floor and 7200 h y^{-1} at site boundary is generally assumed.

	Operation Schedule	**Number of Electrons**	**Electron Fraction**
Start-Up	Continuous injection [1] at 4 W, 3 hours/day, 14 days/month	1.3×10^{15}	37%
Science Program [2]	2.1 fills/day of 0 to 500 mA, 26 days/month, 10 months/y	1.8×10^{15}	51%
Accelerator physics	3 fills/week of 0 to 500 mA, 4 weeks/month, 10 months/y	0.4×10^{15}	12%
Sum	11 months per year	3.5×10^{15} y^{-1}	100%

1) 3-GeV, 4-W injection beam is 1.33 nA (8.3×10^{9} s^{-1} at 10 Hz).
2) From one fresh injection (0 to 500 mA) and three refill injections (313 mA to 500 mA) per day. 500 mA is 2.43×10^{12} e^{-} and, thus, the number of electrons injected per fill is 3.24×10^{12} (75% injection efficiency). Each fresh fill takes 6.5 minutes.
3) Trickle charge injection increases the number of electrons from 3.5×10^{15} to 4.5×10^{15}.

Maximum Dose Rate (μSv h^{-1} per mW)	**Thickness of Lateral Concrete Wall at 1 m from Loss Point**				**Maximum Dose Rate outside 60 cm thick Lateral Concrete Wall (μSv h^{-1})**		
	0 cm	60 cm	90 cm	120 cm	2 mW Loss	50 mW Loss	0.3 mW m^{-1} Line Loss
Photon	15	0.2	0.03	0.005	0.4	10	0.1
Neutron	12	0.1	0.02	0.007	0.2	5	0.1
Total	27	0.3	0.05	0.012	0.6	15	0.2

1) All are point loss situations, except the last column, which is for a line source.
2) A stored beam loss of 500 mA (1200 J) at a point results in a maximum dose of 0.1 mSv outside 60-cm-thick concrete wall.


3 GeV Booster Synchrotron
760 keV RF Acceleration
150 MeV Linac
3.1 x 10^9 e-/pulse
10 pps, 0.75 W
Barrier
Diagnostic Room
2.5 MeV RF Gun
1.4 x 10^14 e/s
3 GeV SPEAR3 Storage Ring
500 mA
(2.5 x 10^12 e-)
RF
B
B
W
W
B
W
W
B
W
U
W
1
2
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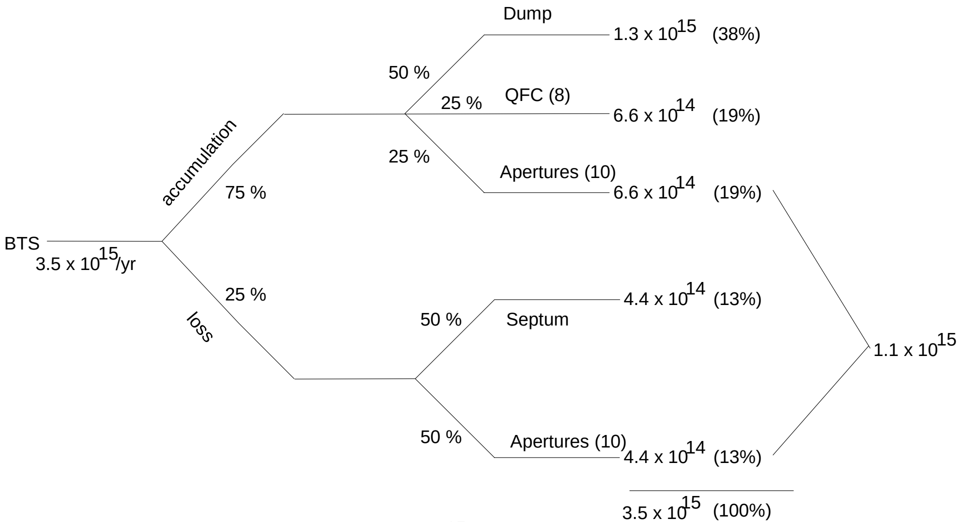
Entry Point
Sychrotron Radiation Beam Lines
9-2002
7086A13



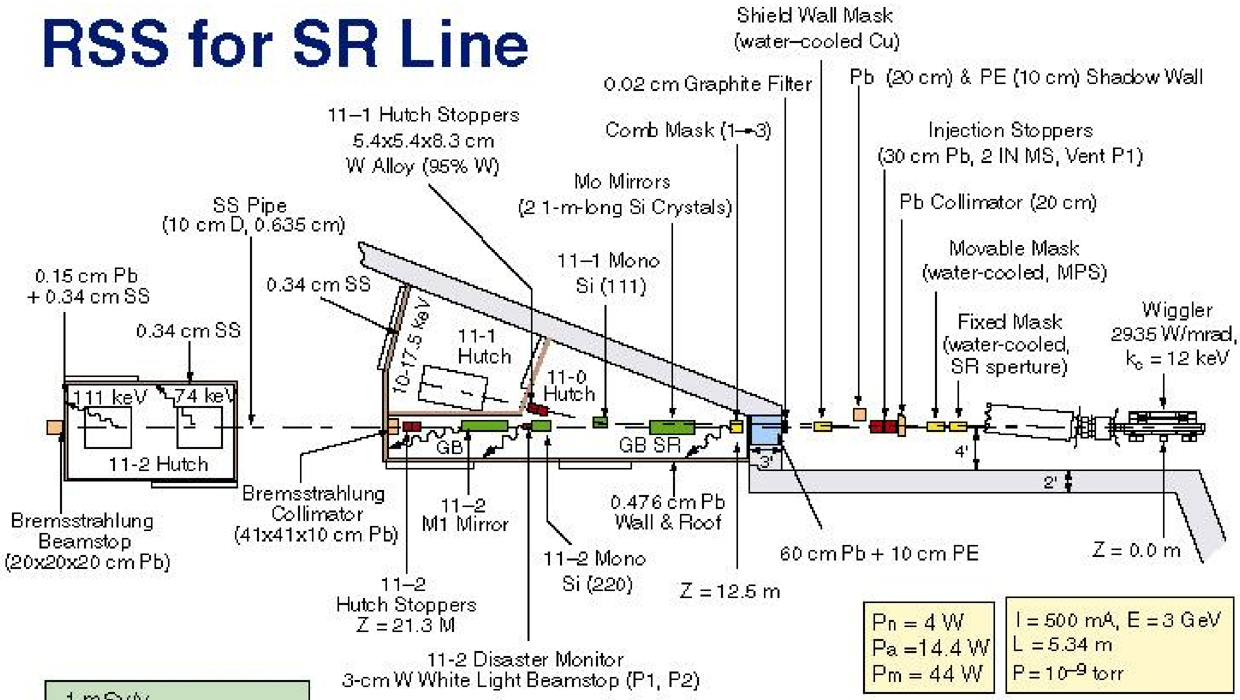
Dump: 1.3×10^{15} /yr

Each Aperture (10): 1.1×10^{14}/yr

Each QFC (8): 8.3×10^{13}/yr

Septum (10): 4.4×10^{14} /yr

RSS for SR Line

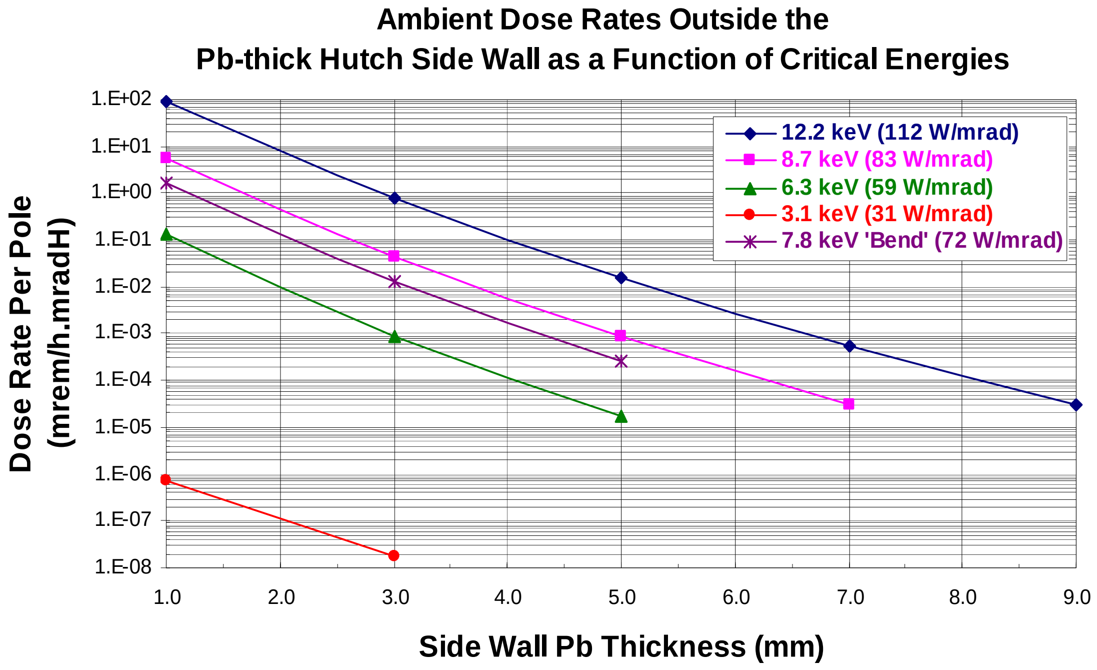


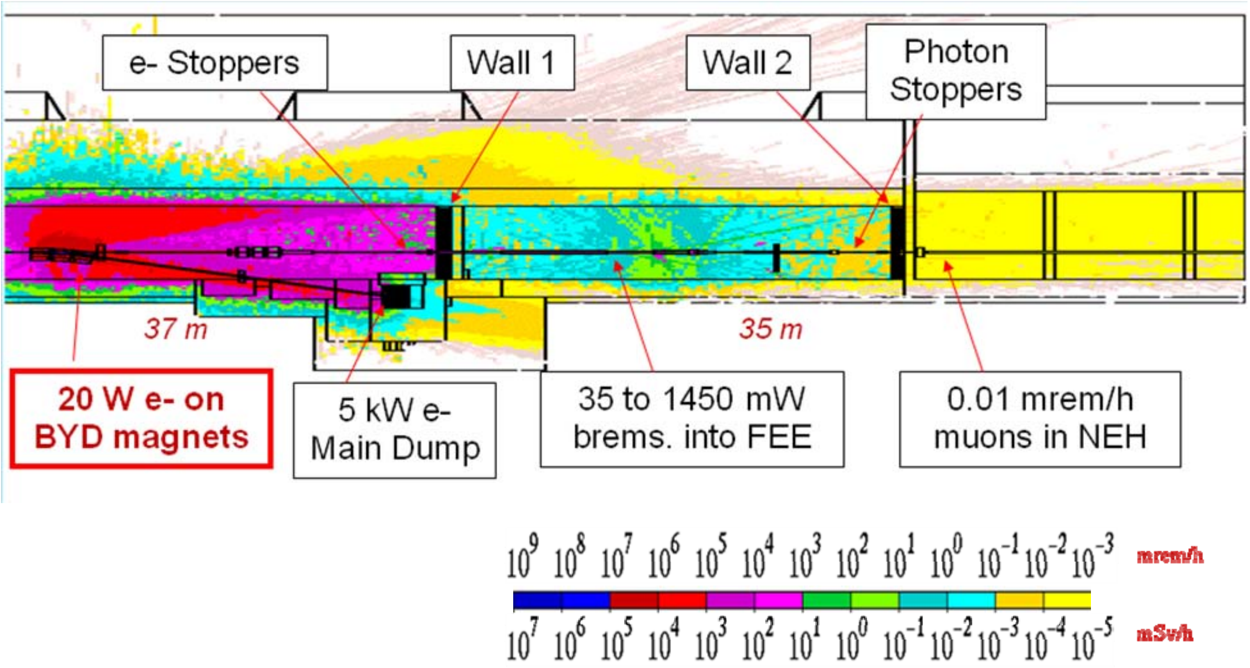
Pn = 4 W
Pa =14.4 W
Pm = 44 W

I = 500 mA, E = 3 GeV
L = 5.34 m
P = 10^{-9} torr

1 mSv/y
4 mSv/h
1 µSv/h for SR & GB

Pa loss at ring or 1st IS
I loss at ring or SR line


Ambient Dose Rates Outside the
Pb-thick Hutch Side Wall as a Function of Critical Energies
Dose Rate Per Pole (mrem/h.mradH)
Side Wall Pb Thickness (mm)
1.E+02
1.E+01
1.E+00
1.E-01
1.E-02
1.E-03
1.E-04
1.E-05
1.E-06
1.E-07
1.E-08
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
12.2 keV (112 W/mrad)
8.7 keV (83 W/mrad)
6.3 keV (59 W/mrad)
3.1 keV (31 W/mrad)
7.8 keV 'Bend' (72 W/mrad)


e- Stoppers
Wall 1
Wall 2
Photon Stoppers
37 m
35 m
20 W e- on BYD magnets
5 kW e- Main Dump
35 to 1450 mW brems. into FEE
0.01 mrem/h muons in NEH
10^9 10^8 10^7 10^6 10^5 10^4 10^3 10^2 10^1 10^0 10^-1 10^-2 10^-3 mrem/h
10^7 10^6 10^5 10^4 10^3 10^2 10^1 10^0 10^-1 10^-2 10^-3 10^-4 10^-5 mSv/h