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RADIATION PROTECTION AT SYNCHROTRON RADIATION FACILITIES*

James C. Liu [1] and Vaclav Vylet [2]

1. Stanford Linear Accelerator Center, MS48, P. O. Box 4349, Stanford, CA 94309, USA
2. OESO/DUMC Box 3155, Duke University, Durham, NC 27710, USA

Abstract

A synchrotron radiation (SR) facility typically consists of an injector, a storage ring, and SR beamlines. The latter two features are unique to SR facilities, when compared to other types of accelerator facilities. The SR facilities have the characteristics of low injection beam power, but high stored beam power. The storage ring is generally above ground with people occupying the experimental floor around a normally thin concrete ring wall. This paper addresses the radiation issues, in particular the shielding design, associated with the storage ring and SR beamlines. Normal and abnormal beam losses for injection and stored beams, as well as typical storage ring operation, are described. Ring shielding design for photons and neutrons from beam losses in the ring is discussed. Radiation safety issues and shielding design for SR beamlines, considering gas bremsstrahlung and synchrotron radiation, are reviewed. Radiation source terms and the methodologies for shielding calculations are presented.

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INTRODUCTION

There are many synchrotron radiation (SR) facilities around the world that provide synchrotron light for various types of research and the study of basic and applied science. A current SR accelerator facility typically consists of an injector, a storage ring, and SR beamlines. The injector can be a linear accelerator (Linac) or a Linac followed by a synchrotron accelerator (booster), which is capable of accelerating electrons (or positrons) up to a few hundred MeV or a few GeV. The injector supplies electrons to the storage ring where the electrons can be accumulated and circulated (or stored) in bunches traveling at the speed of light up to a stored current of a few hundred mA. A storage ring is configured as a set of curves connected by straight sections. When a bending magnet in a curved section deflects the circulating electrons, synchrotron radiation is emitted tangentially to the electron path, creating a “fan” of synchrotron radiation in the median plane of the ring. Special insertion devices [(1)], called wigglers and undulators, are placed in the straight sections. An insertion device consists of a linear array of magnets with alternating polarities, which makes the electrons wiggle or undulate along the axis of the device, tremendously enhancing the energy and intensity of the synchrotron radiation emitted along the axis. Third-generation high-energy SR facilities, which utilize insertion devices intensively, are capable of producing synchrotron radiation at energies greater than 100 keV. With a storage ring vacuum pressure in the 0.5 μPa range, the lifetime of the stored beam in a modern storage ring can exceed 24 hours. Thus, a typical operational pattern consists of long periods of circulating stored beam, alternated with short injection events.

A main SR beamline guides the tangentially emitted synchrotron radiation, which passes perpendicularly through the ratchet (or transverse) wall of the ring. After which, the main SR beamline may be split into a few branch lines on the experimental floor. For experiments, mirrors (*e.g.*, made of silicon crystals with metallic coatings) are used to reflect the low energy part of the SR spectrum (pink beam), while monochromators are used to select a monoenergetic beam from the incident broad SR spectrum (white beam). There are experimental stations associated with each branch line on the floor around the outer rim of the ring concrete wall. In addition to synchrotron radiation, highly forward-peaked bremsstrahlung photons (gas bremsstrahlung) will be produced 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). The gas bremsstrahlung will also be channeled down the main SR beamline.

A typical example of a SR facility is the Stanford Synchrotron Radiation Laboratory (SSRL) at the Stanford Linear Accelerator Center (SLAC). Figure 1 shows that SSRL has an injector and a 3 GeV storage ring called SPEAR. After the removal of a large fraction of the electrons from the 2.5 MeV radio-frequency (RF) thermionic gun using a magnet chopper, the electron beam (3.1×10^9 e^- per pulse, 10 Hz) is accelerated up to 150 MeV (0.75 W) in the SSRL Linac. The beam is then taken either to the Diagnostic room (when not injecting) or to the booster for further acceleration. After a few thousand turns in the booster ring, the 760 keV RF cavities will have accelerated the beam up to 3 GeV (equal to a 15 W injection beam power, if there is no loss in the injector).

The 3 GeV electron beam (with a power of a few watts after some losses in the injector) is taken through the BTS (Booster-to-SPEAR) transport line to the SPEAR ring for on-energy injection. With an injection efficiency of 75%, the 234 m circumference SPEAR ring can be filled to a maximum stored current of 500 mA within 7 minutes. The energy loss of the circulating current due to synchrotron radiation production is replenished by a few RF accelerating cavities in the ring. The stored electron current will slowly decay, with a lifetime of ~20 h at SPEAR. In an operation day, there is generally a fresh injection (*i.e.*, from 0 mA to 500 mA stored current) and a few “top-off” injections (*e.g.*, from a few hundred mA to 500 mA). Note that the injection efficiency and the stored beam lifetime may be quite different among SR facilities. Figure 1 also shows the eleven main SR beamlines. Beamlines 1, 2, 8, and 3 are bending-magnet beamlines, beamlines 7, 10, 9, 6, 4, and 11 are wiggler beamlines, and beamline 5 is an undulator beamline.

Comparing SR facilities with other types of accelerator facilities, it is the storage ring and SR beamlines that are unique and different. The storage ring and SR beamlines are generally above ground with users and workers frequently occupying the experimental floor around the normally thin (< 2 m) concrete ring wall. SR facilities are characterized by low injection beam power (a few watts and typically no more than 10 Hz) but extremely high stored electron power. For example, at SPEAR, the relativistic electron current of 500 mA at 3 GeV is equivalent to a stored energy of only 1200 J (*i.e.*, 2.43×10^{12} stored electrons) but a stored power of 1.5×10^{9} W! The losses of injection beam, as well as stored electron energy, will affect the shielding design for a storage ring. On the other hand, the stored power and the SR beamline parameters affect the gas bremsstrahlung and synchrotron radiation and so have radiation implications for SR beamlines.

Radiation protection relevant to general electron accelerator facilities has been discussed in a companion paper of these proceedings [(2)]. An example of the radiological considerations for the injector type accelerators [(3)] and an example of the engineered, interlocked radiation safety system used to protect the workers from the prompt radiation hazards at a synchrotron facility [(4)] have also been reported. This paper will address the radiological considerations associated with the storage ring and SR beamlines. The major radiation issues reviewed are the neutron/photon doses outside the concrete shielding (wall and roof) from electron beam losses (normal and abnormal) during both the injection and stored beam operations, as well as the gas bremsstrahlung and synchrotron radiation in the SR beamlines during the stored beam operation. The related radiation source terms and associated methodology of the shielding calculations are described. The SPEAR example will be referenced to illustrate the principles and methodologies discussed.

STORAGE RING

To achieve a reasonably conservative shielding design for the storage ring, normal and abnormal electron beam losses during both the injection and stored beam operations have to be analyzed. As an example for illustration, the SPEAR operation and normal beam loss estimates [(5)] are summarized below, followed by a description of the methodology for storage ring shielding design.

Operation Schedule and Normal Beam Loss Estimates

The annual SSRL storage ring operation schedules a one month start-up prior to a 10-month scientific program. Machine development is scheduled for 1 day per week during the 10-month scientific program. Table 1 summarizes the annual SPEAR ring operation and gives a reasonably conservative estimation of the total number of electrons injected into the ring [(5)]. The 3 GeV electron beam is injected into the ring at $8.3x10^9$ s^{-1} (1.33 nA, 10 Hz, 4 W). The injection efficiency is 75%. Therefore, it will take 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 scheduled operation of the scientific program, for example, is 10 months per year, 26 days per month, and one fresh injection (0 to 500 mA) plus three "top-off" injections (313 mA to 500 mA) per day. The number of electrons injected into the SPEAR ring during the 10-month scientific program is then $1.8x10^{15}$ y^{-1}. The total number of electrons injected into the ring annually is $3.5x10^{15}$ y^{-1} (*i.e.*, 467 W h y^{-1} or 117 hours of injection at 4 W per year). Thus, the 10-month scientific program contributes about 50% while the 1-month start-up contributes nearly 40% to the total number of electrons injected into the ring annually.

All electrons injected into the ring are lost either during the short injection period or during the long stored beam period. Figure 2 summarizes the SPEAR normal beam loss scenarios [(5)]. At an injection efficiency of 75%, 25% of the injected beam (*i.e.*, 1 W) is lost during the injection period and the remaining 75% is stored (but this is slowly lost within a day).

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 (at SPEAR, 25% will be lost in the process). A reasonable estimate is 50% of the particles lost during injection (*i.e.*, 0.5 W) will hit the injection septum, which has the smallest aperture. The remaining 50% loss is equally distributed across ten limiting apertures in the ring (5 horizontal and 5 vertical, which have a small position/angle phase space) yielding ~5% loss rate at any one element. The five horizontal limiting apertures are located at: 1) the injection septum, 2) the SR mask for RF cavities, 3) the SR mask for injection septum, 4) the SR mask in the diagnostic straight, and 5) the designated stored beam dump (a special 1 m long copper device designed to intercept most of the stored beam losses). Five vertical limiting apertures are located at the insertion devices 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 (gas bremsstrahlung) 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. There will also be elastic scattering (Coulomb scattering) with residual gas in both planes with losses on the injection septum chamber and insertion device chambers. 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.

In summary (see Figure 2), the power loss rate averaged over a year for SPEAR is 38% at the beam dump, 16% at the injection septum, 3% at each of the nine limiting apertures (excluding the injection septum), and 2.4% at each of the eight QFCs. With an injection of $3.5x10^{15}$ electrons over 11 months ($1.7x10^6$ J over 7200 h), the power loss rate average over a year is 25 mW at the stored beam dump, 11 mW at the injection septum, 2 mW at each of the nine limiting apertures (excluding the injection septum), and 1.6 mW at each of the eight QFCs. These numbers constitute the normal beam loss values that can be used for the ring shielding design. It is clear that thicker and/or local shielding is needed for locations with heavy losses (*e.g.*, the beam dump and injection septum). An additional note is that, if the limiting apertures were not identified and the loss was assumed to be uniform over the 234 m long ring circumference, the average loss rate would then be 0.3 mW m^{-1}. As shown in the next section, a ring shielding design based on this uniform line source model can underestimate the wall thickness that is needed for higher local beam losses occurring at limiting apertures.

Note that, during the short 7 minutes 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 radiation level 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 normal loss of 50 mW at an aperture is observed outside the ring wall during injection, the dose rate from a normal average 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} (almost immeasurable). However, because of the relatively high injection efficiency for SPEAR (75%), 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 (< 50%), the injection losses may dominate the integrated doses.

In addition to the above normal beam losses, abnormal beam losses should be considered in the shielding design. Abnormal beam losses are most likely due to beam mis-steering (*e.g.*, a mis-match between the beam and ring lattice, RF trip, loss of magnet power supply, *etc*) and less likely due to interlocked safety system failure (*e.g.*, the current limiting devices fail and a beam is injected at a power higher than normal) [6, 7]. Abnormal beam losses generally result in persistent high dose rates outside the ring wall during injection (if not detected and terminated) and instantaneous doses during stored beam. Since the regulations and standards in this area are not complete, it is the SR facility’s responsibility to carefully identify which abnormal beam loss scenarios are likely or credible, to define the dose limits against which the shielding is designed, and to implement the mitigation measures for the credible scenarios. For example, at SSRL [4], a shielding design limit of 4 mSv h^{-1} is required for the case of a beam loss at any single point at the full injection beam of 15 W (a power equivalent to the maximum current limited by three interlocked toroids in the Linac). This is called the mis-steering case. In addition, a limit of 250 mSv h^{-1} is required for a point loss of injection beam at 45 W (the maximum credible beam power from the Linac, assuming all three toroids fail). This is called the system-failure case. In both cases, reliable measures (preferably interlocked means) to detect and terminate the radiation hazards are also required. Since the average power for a normal beam loss at a limiting aperture (excluding the injection septum and stored beam dump) is 2 mW and the corresponding limit is 1 μSv h^{-1}, it is clear that the SPEAR shielding design is dictated by the mis-steering case.

Ring Shielding Design

Any beam loss in the ring will create an electromagnetic shower in the ring components, producing bremsstrahlung photons and neutrons [8]. These photons and neutrons generally dictate the ring shielding design. The implication of gas bremsstrahlung and synchrotron radiation on ring shielding design is much less significant and, thus, is discussed in the section for SR beamlines (below).

Due to the low average power (a few mW) losses at most places around the ring, a storage ring generally has thin concrete walls and roof. Locations with heavy losses, *e.g.*, the injection septum and the stored beam dump at SPEAR, have thicker walls and/or additional local shielding (*e.g.,* lead). For example, SPEAR has 60 cm thick concrete lateral walls and 90 cm thick concrete ratchet walls, but the concrete wall near the injection septum section is 120 cm thick. The ratchet wall is made thicker, because the bremsstrahlung photons from a beam loss in the ring are very forward-peaked toward, and hit nearly perpendicularly, the ratchet wall. On the other hand, the forward-peaked radiations from the ring will hit the lateral wall at a glazing angle and, thus, experience a thick concrete attenuation along the radiation direction on the lateral wall (at least 3 m in case of SPEAR). Another shielding constraint for storage rings is the need for straight penetrations in the ratchet walls for SR beamlines. Shielding blocks placed in and near the beamlines, *i.e.*, the injection stopper and shadow wall at SSRL, may be necessary to shadow these penetrations from forward bremsstrahlung and neutrons generated in the ring. Therefore, ray trace studies are important for the ratchet wall and penetration shielding design, particularly when local heavy-metal blocks are used to complement the ratchet wall shielding. Obviously the inherent shielding provided by the ring and beamline components should also be considered.

The analytic code, SHIELD11 [2,9], developed at SLAC for shielding design at electron accelerators, calculates the photon and neutron dose equivalent rates outside a shield wall from a cylindrical target hit centrally at its front face by electrons. The dose rates are clearly functions of the material and size of the target, the material and thickness of the wall, as well as the distances and relative angles between the target, wall and dose point. The SHIELD11 code has limitations, *e.g.*, the length and radius of the target have to be larger than a certain minimum dimension and the beam cannot hit the side of the target. Clearly the actual geometries for beam losses in different parts of the ring may not be the same as the SHIELD11 standard geometry. For complex geometries or to gain better accuracy, the more time-consuming Monte Carlo approach using well-known codes such as EGS4 [10], FLUKA [11] and MCNPX [12] can be used for shielding calculations. For example, the radiation profile over the SPEAR roof from a beam hitting the inner side of a thin vacuum chamber at shallow angles was calculated using FLUKA [7]. A Monte Carlo approach, including the consideration of magnetic transport, has also been suggested and successfully used to calculate the dose over the roof from beam loss in the ring at the European Synchrotron Radiation Facility (ESRF) [13].

To illustrate the storage ring shielding design, the lateral dose equivalent rates for various concrete shielding cases were calculated using SHIELD11 and are shown in Table 2. The typical ring component is simulated with an iron target cylinder of 2” radius and 12” length. A 3 GeV electron beam hits the center of the target’s front face. The inner surface of the lateral wall is 1 m from, and parallel to, the beam direction. A few observations from the example calculations are worth mentioning:

1) For a concrete wall up to 90 cm thick, the photon dose exceeds the neutron dose. However, for a 150 cm thick concrete wall, measurements [14] show that the dose is dominated by neutrons with an equilibrium spectrum, *i.e.*, neutrons above 20 MeV contribute about 50% to the total neutron dose equivalent. For SPEAR, a non-equilibrium neutron spectrum exists and

neutrons above 20 MeV contribute less than 20% to the total neutron dose equivalent [14].

2) The maximum dose rate outside a 60 cm thick concrete wall (the SPEAR case) is 0.3 mSv h^{-1} W^{-1}. Thus, the maximum dose rate is 0.6 μSv h^{-1} from a normal loss of 2 mW at an aperture during stored beam mode. The annual dose to an individual who occupies the area outside the wall over a period of 2000 h y^{-1} would be 1.2 mSv, slightly higher than the annual regulatory dose limit of 1 mSv for the general public and non-radiation workers. Statistics show that a SSRL user, at most, occupies the experimental floor no more than 760 hours per year and, therefore, would receive a dose less than 0.5 mSv.

3) During SPEAR injection, the 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 power 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 a dose rate of 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 alarm/trip threshold of 0.1 mSv h^{-1} for the interlocked area radiation monitors placed around the SPEAR ring.

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

5) A stored beam loss of the full 500 mA at a point with a 60 cm thick wall, which is generally an abnormal and unlikely event, would produce a maximum integrated dose of 0.1 mSv. 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 SPEAR, 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.

SYNCHROTRON RADIATION BEAMLINE

There are two categories of SR beamlines: hard x-ray (> a few keV), which generally is at a line-of-sight path to the stored beam, and vacuum ultra-violet/soft x-ray (VUV) beamlines. The experimental stations at x-ray beamlines are lead- or iron-shielded enclosures (called hutches), which are large enough for experimenters to access. On the other hand, the VUV or soft x-rays, arising from SR reflected from mirrors at large angles, is so soft that the experiment has to be performed inside a vacuum container. Thus, the vacuum chamber beampipe itself can easily attenuate and contain the VUV light.

Safety Considerations for a SR Beamline

Using an x-ray beamline at SSRL as an example, Figure 3 illustrates the main principles of radiation safety considerations for SR beamlines. During injection, thick heavy-metal injection stoppers have to be inserted into each main beamline to block the injection beam, in case the beam is accidentally directed into the beamline. Coupled with the collimator and shadow walls near the beamline, these stoppers also protect workers/users from secondary radiation (emitted tangentially from the ring under both injection and stored beam losses) channeling through the SR beamline to the hutches. The injection stoppers are generally located at the front end of the main beamline, which is inside the storage ring wall. To protect the injection stoppers from potential SR damage, a water-cooled movable mask is also inserted upstream of the injection stoppers to absorb the intense synchrotron radiation.

There are metal hutch shutters in front of each hutch on every x-ray branch line. During stored beam operation, the hutch shutters (or the injection stoppers) have to be inserted into the beamline to intercept gas bremsstrahlung and SR when the hutch is in an accessible state. For each VUV beamline, there is one shutter followed by an isolation valve. These two components perform a similar function to the two hutch shutters in the x-ray beamline. It is required to use at least two injection stoppers and two hutch shutters for each SPEAR beamline. However, there are facilities using only one injection stopper and one hutch shutter (*e.g.*, Advanced Light Source and National Synchrotron Light Source) by requiring multiple position-sensing microswitches for each stopper and shutter.

In addition, there are two kinds of beamstops (physical devices generally fixed in the beamline) used at SSRL: the bremsstrahlung beamstop and the white light beamstop. To contain gas bremsstrahlung, there are bremsstrahlung beamstops located along the axis of the main beamline in the median plane of the ring. When mirrors or monochromators deflect synchrotron light horizontally or vertically, local bremsstrahlung beamstops behind these devices may be needed to stop gas bremsstrahlung if the downstream area is not shielded. When the SR is directed onto monochromator crystals, a monochromatic beam is offset from the direction of the main beam. If the white light were to pass through the crystals, the white light beamstop would block it and protect beamline components downstream. The white light beamstop also prevents non-monochromatic SR from accidentally penetrating into a downstream hutch, if the hutch shielding is not adequate for the white light.

For equipment protection and to terminate the associated radiation hazard, there are disaster monitors (burn-through monitor) mounted in front of the hutch shutters and the white light beamstops for high power beamlines. If an upstream component fails, the x-ray beam will hit the disaster monitor, heating and eventually melting its wall, resulting in a drop of its internal gas pressure. A fast pressure loss would trigger the stored beam termination by removing the RF acceleration and inserting two thin scatters (18ST1 and 18ST2 in Figure 3), while a slow pressure loss will only close off the individual beamline by inserting its two injection stoppers.

Figure 4 shows an example of how the above radiation safety devices (injection stoppers, hutch shutters, bremsstrahlung beamstop, and white light beamstop), as well as the hutch wall and beampipe shielding, are used in a typical SSRL beamline. In addition to mirrors and monochromators, there are obviously other components in a beamline that serve to define the SR quality for an experiment. For example, the water-cooled fixed SR masks protect stationary beamline components from high-power SR damage and define an aperture for the SR. Slits or "comb masks" are used to intercept portions of, or all of, the SR fan. These beamline components will generally intercept not only synchrotron radiation but also gas bremsstrahlung. Scattered photons, as well as photoneutrons induced by gas bremsstrahlung, need to be considered in the SR beamline shielding design. The hutch walls and beampipes need to be thick enough to attenuate the scattered radiation from these components.

Whether it is the scattered gas bremsstrahlung or scattered SR that will dictate the shielding design depends on the characteristics of the individual beamline and its layout, as well as the storage ring parameters. For example, with the SSRL storage ring and its typical SR beamline parameters, the longitudinal thickness of the two hutch shutters is dictated by gas bremsstrahlung [(15)]. For the SSRL optical hutch (11-0 in Figure 4), it is the scattered gas bremsstrahlung from the comb mask and white light beamstop (behind the disaster monitor) that dominate the 0.476 cm thick lead hutch wall shielding design [(16)]. For the monochromatic hutches (11-1 and 11-2), it is the scattered synchrotron radiation from a small experimental sample inside the hutch that dominates the hutch wall shielding design. For the insertion device beamlines at ESRF, the 28 mm thick lead wall of the hutch is dictated by scattered gas bremsstrahlung [(13)].

Injection Beam and Stored Beam Losses

Under normal operation, beam losses of injection and stored beams occur in the ring and secondary radiation can either channel into the main SR beamline or pass through the hole for the beampipe in a ratchet wall. For abnormal beam losses, it may be assumed that either the injection beam or stored beam can accidentally channel into the main beamline. The injection stoppers, coupled with the lead collimators around the beamline and the shadow walls positioned on the side of the beamline (shown in Figure 4), should be thick and large enough to attenuate and block any radiation from the ring from passing through the beamline penetration in the ratchet wall. If this is properly accomplished, the dose rates in the experimental area for all credible beam loss scenarios will be acceptable. Analytic codes (*e.g.*, SHIELD11) or Monte Carlo methods can be used to estimate the sizes of the stopper, collimator, and shadow walls that are needed for both injection and stored beam losses.

Problems with beamline penetrations in the ratchet walls are escalated if the facility uses the “top-off” injection mode. In this mode, stored beam operation is not interrupted to allow injection. Instead, the stored charge is replenished by frequent (or continuous) injections as required, while SR beamlines are open. In this case there are no injection stoppers to protect against zero-degree bremsstrahlung from beam losses in the ring or against mis-steering of electrons into the SR beamlines. Substantially high radiation levels could be produced behind the ratchet wall. Consequently, the “top-off” mode will likely require a more conservative approach to shielding design, coupled with a higher degree of redundancy in safety systems.

Currently each SR facility may have its own “credible beam loss” scenarios and corresponding dose limits. Thus, this is one of the areas in which the SR community should develop a more consistent and sound approach. For example, at SSRL, no injection (fresh or “top-off”) is allowed without the injection stoppers being inserted into the beamlines. The thickness of the two injection stoppers, each a minimum of 18 cm thick lead (or equivalent material with a length of 32 radiation length) at a minimum distance of 2.4 m from the 90 cm thick ratchet wall, is dictated by the abnormal beam loss scenario in which the allowed injection beam of 15 W hits the first stopper, or the second stopper if the first stopper fails to go in [(17)].

However, the Advanced Photon Source (APS) allows “top-off” injection (fresh injection is not allowed) without inserting the two injection stoppers. This was allowed only after determining that, under specific stored current and injection energy conditions during the “top-off” mode, it is not credible for the injection beam to be accidentally directed down a beamline [(18)].

Gas Bremsstrahlung

The gas bremsstrahlung source term has been studied intensively by many authors [(19-26)]. The main characteristics of the gas bremsstrahlung source term are that it has nearly a 1/k energy spectrum (k is the photon energy), it is highly forward-peaked (angular distribution with a characteristic angle of 0.511/E in radians, where E is the electron energy in MeV), and the dose is proportional to $\sim E^{2.5}$, the stored current, as well as the mass thickness of the air column in the ring section that electrons pass through. Therefore the problem of gas bremsstrahlung is more acute for long insertion devices at high-energy, high-current storage rings.

Ray trace studies need to be performed to ensure that any gas bremsstrahlung ray from the ring will be blocked by at least one or more components along the SR beamline. Obviously, if the beamline layout allows, it is preferred that gas bremsstrahlung be blocked before the ratchet wall so that any scattered radiation is further shielded by the ring wall.

For radiation protection purposes, the secondary radiation coming out of the downstream and lateral sides of any beamline component hit by gas bremsstrahlung is also of interest. Clearly the most accurate method of estimating radiation doses associated with gas bremsstrahlung is using Monte Carlo codes to model the gas bremsstrahlung source and beamline components as accurately as possible (see reference [(17)] for an example). However, this Monte Carlo approach may not be feasible or available. In addition, there are cases in which crude and conservative calculations using analytic methods (described below) are sufficient. This is particularly true when considering the fact that one of the largest errors in estimating gas bremsstrahlung hazards arises from the difficulty in measuring the vacuum pressure in a long straight section, whose uncertainty could be a factor of 2-3 [(24,25)].

Formulae for estimating the gas bremsstrahlung source term at zero degrees have been developed based on results from many EGS4 and FLUKA calculations [(21,22,24)]. However, several factors need to be considered before applying these results to estimate the longitudinal thickness of, say, a hutch shutter. First, since gas bremsstrahlung is highly collimated and forward-peaked before it hits any beamline target, the so-called zero-degree source term is strongly dependent on the dose-scoring area over which the calculation was made [(22,24)]. Secondly, the size, angular divergence, and actual curved trajectory of the stored beam in the air path, which were not considered in the referenced calculations above, will also affect the calculated zero-degree dose rate. Thirdly, gas bremsstrahlung is energetic enough to produce an electromagnetic shower in the target. Thus, the build-up of the dose to its shower maximum within the target needs to be considered in estimating the required longitudinal thickness of the target. After correcting the source terms with these factors, it is conservative and appropriate to use the Compton minimum of the attenuation coefficient of a material (*e.g.*, 24 g cm^{-2} for lead) for the estimation of gas bremsstrahlung attenuation (after shower maximum) in both longitudinal and lateral directions of a target [24].

The secondary photon radiation on the lateral side of a target depends on the transverse size of the target (the smaller the target, the larger the leakage of photons). For a large target with sufficient self-attenuation (radius larger than 4 Moliere lengths, *i.e.*, $R/X_m>4$), the lateral dose is larger at backward angles (> 90 degrees) [24]. In that case, the maximum secondary photon dose rate on the lateral side, calculated using EGS4, can be used for estimation within a factor of 3 [24].

For a small target, the lateral photon dose is larger at forward angles. A crude method for photon dose estimation in this case is described as follows. Gas bremsstrahlung is a thin-target bremsstrahlung process and, thus, the fractional energy transferred from an electron to the photons, dE/E, is equal to the ratio of the thickness, t, to the radiation length of the target, *i.e.*, $dE/E = t/X_o$. Therefore, the fractional energy (or power) transferred from the circulating electrons to gas bremsstrahlung 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 stored power of the circulating electrons (500 mA at 3 GeV) at SPEAR is 1.5 $x10^9$ W. Assuming that the air path is 5 m and the vacuum pressure is 0.5 μPa (equivalent to a mass thickness of $2.9x10^{-12}$ g cm^{-2}), the ratio of the air path to air's radiation length is then $7.9x10^{-14}$. Thus, the power transferred from the circulating electrons to bremsstrahlung photons is $1.2x10^{-7}$ kW. The normalized gas bremsstrahlung power is thus 100 nW mA^{-1} μPa^{-1} m^{-1}, to be compared with the value of 156 nW mA^{-1} μPa^{-1} m^{-1} that was measured in the SPring8 beamline 11XU [26].

The normalized bremsstrahlung power can then be used to estimate the secondary photon dose rate at forward angles from a target (with a Moliere length of X_m) using the following 3 steps:

1) the fraction of incident energy (U/E_o) which escapes radially from a cylinder of radius R is calculated using the formula $U/E_o=0.8exp(-3.45R/X_m)+0.2exp(-0.889R/X_m)$ [27],
2) the normalized leakage power is then $100U/E_o$,
3) assume that the leakage power is in the form of leakage photons with an average energy of 1 MeV [23] (whose fluence-to-dose equivalent conversion factor is $5x10^{-6}$ μSv cm^2) and the photons radiate isotropically from the target, the normalized photon dose rate at 1 m laterally from a small target (H_g in μSv h^{-1} mA^{-1} μPa^{-1} m^{-1}) is calculated as $H_g =0.09U/E_o$.

It has been found that the dose rates given by this simple approach for an undulator line at SSRL agree with the measurements and EGS4 calculations [24] within a factor of 2-3.

A method for estimating the neutron dose rate from gas bremsstrahlung hitting a target was also developed [24] based on similar principles. The estimated results agree with measurements within a factor of 2 [24-26]. The approach is described as follows. The neutron yields for thick target materials hit by high-energy electrons (*e.g.*, $1.7x10^{12}$ s^{-1} for a tungsten target hit by a 1 kW electron beam) are available from Swanson [8]. Thus, the neutron yield from, *e.g.*, a tungsten hutch shutter hit by a gas bremsstrahlung power of $1.2x10^{-7}$ kW, is $2x10^5$ s^{-1}, which results in an isotropic neutron fluence rate of 1.6 cm^{-2} s^{-1} at a distance of 1 m away from the target. Using a maximum fluence-to-dose equivalent conversion factor of $3.2x10^{-10}$ Sv cm^2 for giant resonant neutrons, the above fluence rate corresponds to a neutron dose equivalent rate of 1.8 μSv h^{-1}. The neutrons from quasi-deuteron and photopion reactions, which are less than

10% of the total neutron dose equivalent, are ignored in the above estimation. Note that when the neutron dose rate is normalized to the gas bremsstrahlung power, the result (0.015 Sv h^{-1} W^{-1} at 1 m from a tungsten target) is comparable with the APS-measured value of 0.024 Sv h^{-1} W^{-1} [25].

The three independent photoneutron measurements [24-26] indicate that the neutron dose equivalent rate at 1 m from a beamline target could be around 1 μSv h^{-1} for high-energy SR facilities. The photon dose rate estimation and measurements [24] also gave similar levels. Therefore, the exposure to personnel near a beamline from gas bremsstrahlung is not necessarily insignificant when compared to the dose rate outside the ring wall from normal beam losses inside the ring.

Synchrotron Radiation

The energy, intensity and angular characteristics of synchrotron radiation have been described in detail [1,28]. For radiation safety purposes, it is useful to know a few special SR characteristics. First, synchrotron radiation from both bending magnets and wigglers have 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 the shielding design. Secondly, the vertical opening angle of the synchrotron radiation is very narrow (it has the same characteristic angle as that of gas bremsstrahlung; 0.17 mradian 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 gas bremsstrahlung, ray trace studies need to be performed to ensure that any synchrotron radiation ray from the ring will be blocked by at least one or more components along the SR beamline. Thirdly, the polarization nature of the synchrotron radiation would cause asymmetric scattering from a target. Fourth, since an insertion device may be tunable, *i.e.*, the magnetic field strength is adjustable by changing the gap, the most conservative synchrotron radiation source term based on the smallest gap of an insertion device should be used in the beamline shielding design.

Synchrotron radiation is substantially less penetrating than gas bremsstrahlung. However, modern storage rings can generate synchrotron light of extremely high intensity and high energy [29], which may dictate the hutch and beampipe shielding design [30]. For monochromatic hutches, it is generally the scattered synchrotron radiation that dominates the hutch wall shielding design (*e.g.*, photons in high-energy harmonics for hutch 11-2).

Due to the complicated SR energy spectrum and the fast-changing attenuation coefficients of materials for photons < 100 keV, a "back-of-the-envelope" estimation similar to that described above for gas bremsstrahlung is not available for synchrotron radiation shielding design. However, two easy-to-use analytic codes specifically designed for synchrotron radiation beamline design are available: PHOTON [31] and the more recent STAC8 [32,33]. Adapted from PHOTON, STAC8 provides more accurate results, since it considers the undulator sources in addition to the dipole and wiggler sources, the angular dependence of coherent scattering and incoherent scattering, the linear polarization effects, target self-shielding, and the photon buildup factors. STAC8 has been validated to give conservative results by comparing against EGS4 and measurements at SPring8 beamlines [33]. Again, a Monte Carlo approach is more suitable for complex geometries. Two examples of synchrotron radiation calculations using EGS4, illustrating the SR spectrum and angular sampling techniques for a dipole source and the normalization of Monte Carlo calculated results, have been reported [34], while FLUKA has also been used successfully to design SPEAR beamlines [15,16].

In addition to the hutch wall and beampipe shielding, attention should be paid to synchrotron radiation streaming through ventilation and cable penetrations in the hutch, as well as groundshine under the hutch doors [33], in particular for insertion device beamlines at third-generation light facilities.

MISCELLANEOUS ISSUES

Free-Electron Laser Facilities

The above discussions for radiation implications of gas bremsstrahlung and synchrotron radiation on SR beamline safety design are for storage ring facilities. There are fourth-generation light facilities that utilize the Self-Amplified-Spontaneous-Emission (SASE) process to generate coherent synchrotron radiation with much higher brightness and shorter pulses than third-generation sources [29]. These free-electron laser facilities typically produce synchrotron radiation from the single pass of an electron beam, provided from a high-energy Linac, through a long undulator. For example, the free-electron laser facility at SLAC, the Linac Coherent Light Source (LCLS) [35,36], plans to use a 15 GeV, 1.4 kW (0.1 μA) electron beam and a 120 m long undulator (actually operated in a transition range between wiggler and undulator). Due to the ultra low emittance of the electron beam, the SASE process will produce significant coherent x-ray emission at only the fundamental and harmonic wavelengths, in addition to the spontaneous synchrotron radiation. It is illustrative to compare the gas bremsstrahlung and synchrotron radiation from the LCLS (Linac-based) with that from a typical undulator beamline (5 m long and 0.5 μPa) at the 3 GeV, 500 mA SPEAR (ring-based), as shown in Table 3.

For the gas bremsstrahlung dose source term, the effect from the significantly higher current at SPEAR (which gives the high 1.5×10^9 W stored power) outweighs slightly the combined effects from the higher energy, longer undulator length, and poor vacuum pressure at LCLS.

It is not straightforward to compare synchrotron radiation between SPEAR and LCLS, since every beamline at a storage ring has its own characteristics of intensity and energy of synchrotron radiation due to different magnetic field strength, period length, and number of periods. However, if it is assumed that the magnetic field strength and period length are the same for the undulators at SPEAR and LCLS, the synchrotron radiation power from a SPEAR undulator would be 3-4 orders of magnitude higher than that from LCLS (see the last row in Table 3). At SPEAR, the total radiated power for synchrotron radiation is between a few kW for an undulator up to a few hundred kW for a wiggler. On the other hand, the average power of synchrotron radiation at LCLS is only 2.7 W, while the SASE process only increases the total power by 10%, *i.e.*, the SASE gain = 1.1 in Table 3 [35]. However, due to its higher beam energy, the critical energy of the LCLS synchrotron radiation is much higher than that of SPEAR and thus the SR from LCLS is more penetrating. Though the average power from LCLS is much lower than that at SPEAR, its peak power is significantly higher due to the SASE process.

Consequently, the radiation damage and protection issues are much more severe and challenging at LCLS.

Radioactivation of Air and Soil, and Noxious Air

Due to the low beam power nature, 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 [37,38]. However, when a high-power synchrotron radiation beam, *e.g.*, a white light beam, can travel in a long air path inside a hutch, the resulting ozone concentration should be estimated [37], and mitigation measures, such as forced ventilation, should be considered.

Muon Radiation

The highly forward-peaked muon radiation is rarely a safety consideration for SR facilities operated at less than 1 GeV. The MUON89 analytic code [39], which can calculate muon fluence at zero degrees, gives a muon dose rate of 0.02 mSv h^{-1} W^{-1} 1 m downstream from a heavy-metal target hit by a 3 GeV electron beam. Since the 3 GeV muon range is about 7 m in concrete, there may be minor muon dose concern (albeit local) at high-energy SR facilities, if the facility has an operation mode of parking the high-energy beam in a thick target (*e.g.*, a Faraday cup before injection) for a long period. If needed, the simple muon dose estimation method in Swanson [8] can also be used to provide conservative results.

Skyshine Radiation

Among the sources contributing to off-site doses from a SR facility, skyshine radiation is probably the dominant one. Both measurements and calculations [38] indicate that, for a 3 GeV, 1 W electron beam hitting the SPEAR lead Faraday cup (0.6 m under a 61 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 boundary). Since there is a total of 467 W h y^{-1} of injected particles for SPEAR (see Table 1), the annual skyshine neutron dose at 100 m is 4 μSv y^{-1}, if the neutron production 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 (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, thus, 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}. Therefore, high-sensitive neutron detectors are needed in order to measure these skyshine neutrons. Additionally note that, for SR facilities with the same beam parameters but without ring roof shielding, the corresponding skyshine neutrons would be 100 times higher.

Radiation Detection

The stored beam circulates at an orbital frequency of 1.28 MHz at SPEAR. Both gas bremsstrahlung and synchrotron radiation are produced in a train of pulses with a frequency between the orbital frequency and the ring RF frequency (358 MHz for SPEAR), depending on the number of RF buckets being filled. Thus, gas bremsstrahlung and synchrotron radiation are quasi-continuous. However, radiation from injection beam losses in the injector and storage ring is pulsed (10 Hz at SSRL) and its pulsed effect on radiation detectors should be recognized.

CONCLUSIONS

There are more and more third-generation and even fourth-generation synchrotron light facilities being built around the world. Radiation protection for SR facilities is similar to that of other electron accelerator facilities. However, the radiation safety considerations and shielding design associated with storage rings and synchrotron radiation beamlines present unique and often challenging tasks. A careful analysis of normal beam losses in the ring and identification of credible abnormal beam losses in the ring and beamlines are crucial steps for a sound safety design. Analytic tools (albeit with limitations) are available for rough and quick estimations of the photon and neutron doses from beam losses, as well as radiation concerns from gas bremsstrahlung and synchrotron radiation around the SR beamlines. Monte Carlo codes are obviously better and more accurate for the more complicated calculations.

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LIST OF CAPTIONS FOR FIGURES AND TABLES

Table 1. Annual SPEAR operation schedule and number of electrons injected into the ring

Table 2. SHIELD11-calculated maximum dose rate outside the lateral concrete wall, whose inner surface is 1 m away from a cylindrical iron target of 2” radius and 12” length, hit by a 3 GeV electron beam centrally on the front face.

Table 3. Comparison of gas bremsstrahlung source term and synchrotron radiation power between SPEAR and LCLS.

Figure 1. A schematic layout of SSRL, which shows the injector (the Linac and the booster synchrotron) and the SPEAR storage ring. Eleven main synchrotron radiation beamlines are also shown (B: bending magnet, W: Wiggler, U: undulator).

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

Figure 3. Main radiation safety items in a SSRL x-ray beamline.

Figure 4. Shielding considerations for a typical synchrotron radiation beamline.

	Operation Schedule	Number of Electrons	Electron Fraction
Start-Up	Continuous injection [1] at 4 W, 3 hours/day, 14 days/month	$1.3x10^{15}$	37%
Scientific Program [2]	2.1 fills/day of 0 to 500 mA, 26 days/month, 10 months/y	$1.8x10^{15}$	51%
Machine Development	3 fills/week of 0 to 500 mA, 4 weeks/month, 10 months/y	$0.4x10^{15}$	12%
Sum	11 months per year	$3.5x10^{15}$ y^{-1}	100%

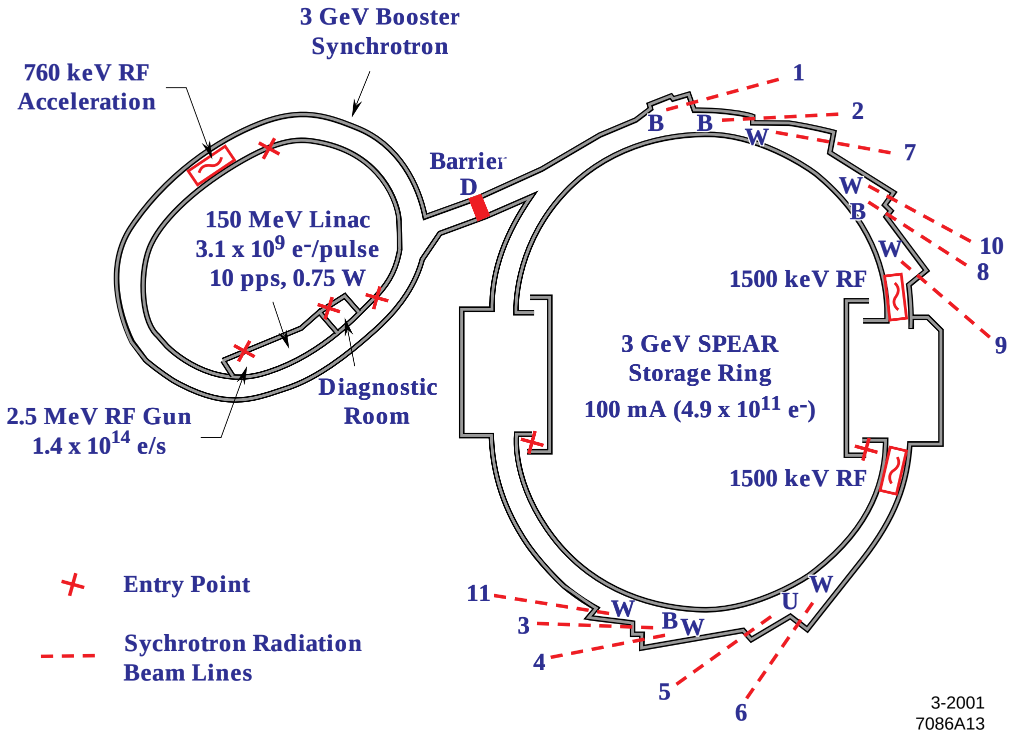
1) Injection beam is 1.33 nA ($8.3x10^9$ s^{-1} at 10 Hz) and 3 GeV, equivalent to 4 W.
2) Equivalent to one fresh injection (0 to 500 mA) and three "top-off" injections (313 mA to 500 mA) per day. 500 mA is $2.43x10^{12}$ e^- and, thus, the number of electrons injected per fill is $3.24x10^{12}$ (at an injection efficiency of 75%). Each fresh fill takes 6.5 minutes.

Maximum Dose Rate ($mSv\ h^{-1}$ per W)	Lateral Concrete Wall Thickness				Maximum Dose Rate outside a 60 cm thick Lateral Concrete Wall ($\mu Sv\ h^{-1}$)		
	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.

Parameters and Ratios	Beam Energy (GeV)	Beam Current (mA)	Undulator Length (m)	Vacuum Pressure (μPa)	SASE Gain	Sum
SPEAR Undulator	3	500	5	0.5	1	---
LCLS	15	0.0001	120	500	1.1	---
SPEAR/LCLS Ratio of Gas Bremsstrahlung Dose	$(3/15)^{2.5}$	$5x10^6$	0.04	0.001	---	3.5
SPEAR/LCLS Ratio of Synchrotron Radiation Power	$(3/15)^2$	$5x10^6$	0.04	---	1/1.1	7300

1) Assuming the magnetic field strength and period length are the same for SPEAR and LCLS undulators.



3 GeV Booster
Synchrotron
760 keV RF
Acceleration
Barrier
D
150 MeV Linac
3.1 x 10^9 e^-/pulse
10 pps, 0.75 W
Diagnostic
Room
2.5 MeV RF Gun
1.4 x 10^14 e/s
3 GeV SPEAR
Storage Ring
100 mA (4.9 x 10^11 e^-)
1500 keV RF
1500 keV RF
1
2
7
10
8
9
11
3
4
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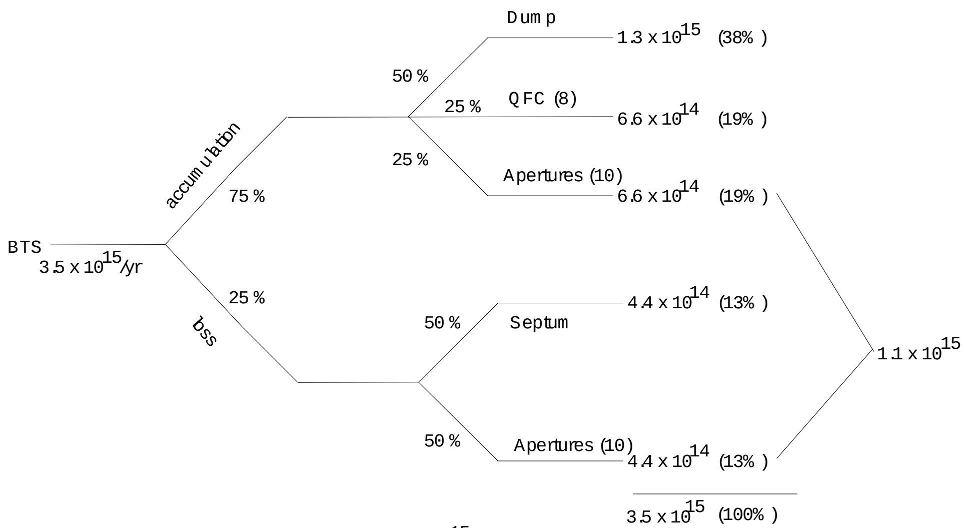


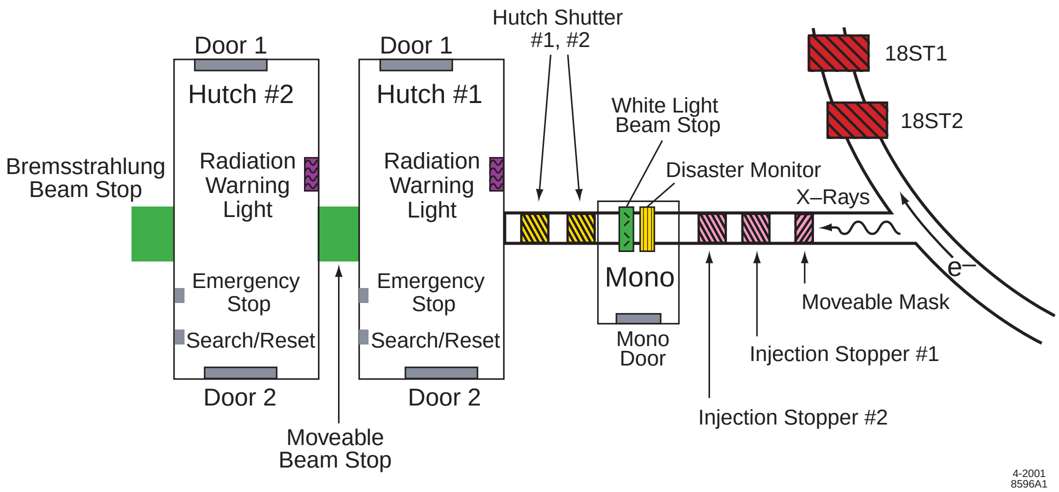
Dump: 1.3×10^{15} /yr

Each Aperture (10): 1.1×10^{14} /yr

Each QFC (8): 8.3×10^{13} /yr

Septum (10): 4.4×10^{14} /yr

General Double Hutch HPS Schematic



RSS for SR Line