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RADIOLOGICAL CONSIDERATIONS IN THE DESIGN OF SYNCHROTRON RADIATION FACILITIES

N. E. Ipe
Stanford Linear Accelerator Center
P. O. Box 4349
Stanford, California 94309
(650) 926-4324

ABSTRACT

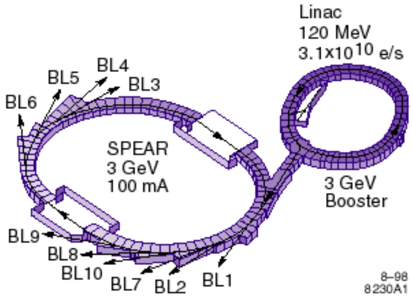
As synchrotron radiation (SR) facilities are rapidly being designed and built all over the world, the radiological considerations should be weighed carefully at an early stage in the design of the facility. This necessitates the understanding and identification of beam losses in the machines, especially the storage ring. The potential sources of radiation are photons and neutrons from loss of injected or stored beam, gas bremsstrahlung and synchrotron radiation. Protection against radiation is achieved through the adequate design of the shielding walls of the storage ring and the synchrotron radiation beam lines. In addition safety systems such as stoppers and shutters provide protection in the forward direction for entry into the experimental enclosures. Special care needs to be exercised in the design of SR experimental enclosures to minimize radiation leakage through penetrations and gaps between doors and walls, and doors and floors.

I. INTRODUCTION

Synchrotron radiation (SR) has become a valuable tool in several areas of science and technology because of its high intensity, brightness, broad spectral range, collimation, polarization, etc. At SR facilities experimenters spend a major portion of their time working in close proximity to beam lines, experimental enclosures, and the storage ring shielding walls. Hence, in order to ensure that dose rates on the experimental floor are as low as reasonably achievable, the radiological considerations should be weighed carefully at a very early stage in the design of the facility. This clearly necessitates a good understanding and identification of beam losses in the machines.

A typical SR facility consists of an electron or positron injector, a storage ring and the SR beam lines. Figure 1 shows a schematic of the Stanford Synchrotron Radiation Laboratory (SSRL). The injector is composed of a 120 MeV electron linear accelerator (linac) and a 3 GeV booster synchrotron. The maximum intensity in the linac is limited to 3.1 x 10^{10} e^-/s by three current toroids. The electron bunches are injected into the booster synchrotron where they are accelerated to 2.3 GeV, and then transported to the storage ring SPEAR. The beam energy is ramped up to 3 GeV in SPEAR. Currently SPEAR is capable of storing circulating currents up to 100 mA. Special bending magnets and focussing magnets (quadrupoles) guide the beam as the electrons move at nearly the speed of light around the storage ring maintained at a vacuum of 0.133 μPa (10^{-9} torr). The electrons radiate SR as they are being deflected in the fields of storage ring magnets or special magnets called insertion devices (IDs) which are placed in the straight sections of the storage ring.

Figure 1. Schematic of SSRL



II. SOURCES OF SYNCHROTRON RADIATION

Charged particles emit electromagnetic radiation whenever they undergo acceleration. When the electron kinetic energy is low compared with its rest mass energy m_0c^2 (m_0 = rest mass of electron, c = velocity of light) the radiation is emitted in all directions [1]. At electron energies well above m_0c^2, the amount of energy radiated increases rapidly and is confined into a sharp forward cone with a vertical half opening angle given by the natural emission angle $1/\gamma$ ($\gamma = E/ m_0c^2$ where E is the electron or positron energy)[1]. For an electron energy of 3 GeV, the half opening angle is 170 μrad. The bending magnet creates a fan of radiation which is swept around as the particles move in a circular trajectory, thus acting as a sweeping searchlight. The vertical half opening angle remains small.

An ID consists of a series of short magnets with alternating magnetic fields, which cause the particles either to wiggle or undulate as they pass through the device. Wigglers produce very intense, energetic radiation over a wide range of x-ray energies, while undulators yield radiation of selected energy with high brightness. In a wiggler the angular deflection produced by the magnetic poles is large compared with the natural emission angle of the synchrotron radiation. The magnet is designed so that alternating deflections cancel out, thus resulting in no net bending. Therefore, wigglers can be placed in the straight sections of the storage ring because they hardly disturb the orbit. Due to incoherent superposition the synchrotron radiation emitted is in a continuous spectrum similar to that from a bending magnet with the same field strength. However, the brightness (number of photons per second per unit solid angle per unit source area) is 2N times that from a bending magnet where 2N is the number of magnetic poles. The half opening angle is given by K/γ where K is much greater than 1. K depends on the period length λ and the magnetic field strength B. In an undulator the angular deflection is much smaller than the natural angle of emission at each pole so that the small angular divergence of the synchrotron radiation is not significantly affected. The half opening angle is given by K/γ where K is less than 1. Coherent interference of radiation from different paths of the trajectory (emission from co-linear source points) results in a spectrum that is enhanced at certain wavelengths. There is an N^2 increase in brightness compared to the bending magnet.

For bending magnets and wigglers the smooth spectrum is defined by a single parameter called the critical energy. The critical energy ε_c is the energy above which (and below which) half the total SR power is radiated. The on-axis critical energy is given by $\varepsilon_c = 0.665B(T)E_0^2(GeV)$, where B is the magnetic field strength in Tesla and E_0 is the primary beam energy in GeV. At the first glance it may appear that the critical energy is proportional to E_0^2 and indeed this is true for wigglers. For bending magnets however, the critical energy is proportional to E_0^3 because the bend radius in the storage ring is fixed. As E_0 increases, B must be increased in order to keep the primary beam in the same orbit. This dependence is a very important consideration in the shielding design of the SR beam lines. If there is an energy upgrade for the storage ring, the shielding for the beam lines will have to be re-evaluated because of the shift in the synchrotron radiation spectrum to higher energies.

Insertion devices are tunable, that is the gap width can be varied. As the gap width decreases, B increases, ε_c increases and the SR spectrum shifts to higher energies. The above mentioned fact is another important consideration in the shielding design for two reasons. First, the SR beam line shielding design should be based on the narrowest achievable gap width which in turn results in the highest energy SR spectrum. The second reason is that the ID vacuum chamber may become the limiting aperture in the storage ring, and hence is a potential location of beam loss during injection. For example, at the Advanced Photon Source (APS), the shielding design for the storage ring incorporated a 20 % loss in the transition region between the insertion device and storage ring vacuum chambers [2].

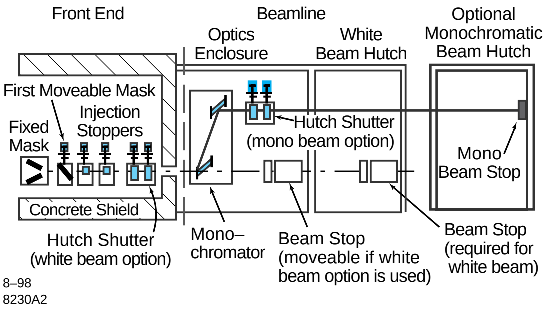
One of the desirable properties of synchrotron radiation is its high polarization[1]. The electric field vector of the emitted radiation is in the direction of instantaneous acceleration, i.e., in the orbital plane. Thus the synchrotron radiation from horizontal bending magnets is linearly polarized in the orbital plane. The polarization becomes elliptical and eventually circular with opposite helicity as one moves out (above and below) of the orbital plane. For wigglers and undulators which have magnetic poles confined to a single plane, the alternating poles cancel the elliptical polarization out of the plane, and the radiation is linearly polarized everywhere. For IDs with helical magnetic fields the radiation is elliptically polarized. For synchrotron radiation that is linearly polarized, scattering in the plane of polarization is negligible. This again is an important consideration in shielding design. During radiation surveys performed outside SR experimental enclosures, the radiation measured at the orbital plane will be minimal, but will increase as one moves away from the orbital plane.

III. SYNCHROTRON RADIATION BEAM LINES

Figure 2 shows the schematic of a model SSRL SR beam line. The SR beam lines are transported to the experimental floor through penetrations in the ratchet shaped storage ring shielding walls. The portion of the

SR beam line within the storage ring is referred to as the front end. The typical components of a beam line are fixed and moveable masks, injection stoppers, hutch shutters, filters, valves, slits, monochromator (mono), beam stops, etc. The injection stoppers in the front end are closed during normal injection, to provide protection primarily in the forward direction on the experimental floor, from radiation originating from beam losses in the storage ring, and accidental transportation of primary beam down the SR beam line.

Fig 2. Schematic of an SSRL Beam Line



A typical beam line may consist of an optics enclosure, a white beam hutch (WBH), a beam transport line and a monochromatic (mono) beam hutch (MBH). The entire SR beam known as the white beam can be transported to the WBH, or if desired a monochromator can be used in the optics enclosure and a mono beam can be transported to the MBH. The white beam is far more intense than the mono beam.

IV. BEAM LOSSES IN THE STORAGE RING

The beam losses in the injector and storage ring should be carefully studied because of their impact on the shielding of the facility. Papers related to this subject can be found in the literature [3, 4]. Only the beam losses in a storage ring will be addressed in this paper.

A. Stored Beam

The stored current in a storage ring decays with a finite lifetime τ_0, where τ_0 is the time taken for the current to decay to 1/e of its initial value. The lifetime varies from 1 to 100 hours and depends on the operating conditions. Particles can be lost from the stored beam due to elastic (Coulomb) scattering and inelastic collisions (bremsstrahlung) with the residual gas molecules in the vacuum chamber [1]. Other loss mechanisms include multiple small angle scattering (intra beam scattering) and large angle scattering (Touschek effect) within a bunch. There are also loss mechanisms unrelated to scattering such as the “quantum effect” (electrons being lost from the rf acceptance due to the emission of a high-energy SR photon). In general, the Touschek effect is the limiting factor on lifetime for low-energy (< 1 GeV) storage rings while scattering effects from residual gases is the limit on lifetime for high-energy rings. Instabilities in the storage ring can lead to catastrophic losses.

B. Normal Injection and Topping Up

In order to replenish the stored beam, new particles have to be injected into the storage ring. Injection generally takes place when the current has decayed to about 40 % of its initial value (normal mode) or in the topping up mode (where the current is kept close to its maximum value with frequent short injections). For example, during normal injection in SPEAR, the injection stoppers (Fig. 2) are closed to protect individuals on the experimental floor. This mode of injection has the disadvantage of producing variable heat loads in the storage ring as well as on the optical components in the SR beam lines, thus affecting both the stability of the stored beam and the properties of the optical components [1]. Further, the time averaged photon flux for a given experiment is reduced. The topping up mode eliminates these disadvantages, but its major drawback is that the injection stoppers may have to remain open, all the time. This raises serious concerns since the individuals occupying the experimental floor are no longer adequately protected against radiation produced by the primary beam. Any facility intending to use the topping up mode must first determine whether it is possible to transport a portion of the electron beam down the SR beam line. If the electrons strike any beam line component an electromagnetic shower could be produced. In most cases the SR beam line shielding is not adequate enough to provide protection in the event of the above mentioned scenario. The following beam loss scenarios and their consequences need to be analyzed to ensure that it is safe enough on the experimental floor:

1) Rf trip during injection -- beam spirals inwards. *Can electrons scattered upstream at small angles be transported down the SR beam line?*

2) Power supply to bend magnets trips during injection -- beam spirals outwards. *Can a portion of the electron beam be transported down the SR beam line?*

3) Bend magnets are off or have low magnetic fields prior to injection, or a bend magnet is shorted. *Can a portion of the electron beam be transported down the SR beam line?*

4) Mis-steering of beam during injection. *Is it possible to steer portion of the electron beam down the SR beam line?*

5) Steering magnets set at wrong fields, or power supply to steering magnets trips or quadrupole is shorted. *Is it possible to steer a portion of the electron beam down the SR beam line?*

Possible solutions include but are not limited to the use of:

a) permanent magnets/interlocked magnets downstream of SR exit port in the storage ring to deflect the charged particle beam into a shielded dump;
b) interlocked detectors (average current toroids, position monitors, etc.) that turn off the beam if the primary beam is detected in the SR beam lines;
c) interlocked relay which monitors shunt current in bend magnets;
d) interlocked radiation monitors;
e) interlocked current monitors to detect sudden loss of stored beam;
f) additional and directional shielding (which contains radiation within a small solid angle) for SR beam lines.

An alternate approach is to consider the use of fast injection stoppers during topping-up. Clearly the topping-up mode requires a careful study and analysis of beam losses and production of radiation on the experimental floor. In the end one must ask *Is it safe enough?*

C. Stored Beam Losses

Once a beam is stored, there are several mechanisms that can cause a beam loss. A kicker magnet is normally used to deflect the particle beam into or out of the stored beam orbit. If a fast kicker misfires, the stored beam gets kicked out at a small angle and targets at the vacuum chamber over an extended distance. The time frame for this mechanism is of the order of microseconds. For example, in SPEAR, it takes an electron about 1 µsec to complete a revolution.

If the power supply of a bending magnet fails, the magnetic field does not decay instantaneously, but over several milliseconds. The beam would spiral outwards and be lost over about 1000 turns. The losses would be distributed around the ring. If the rf power turns off, the beam would spiral inwards. The particle would lose all its energy within a time period of about 10 milliseconds and would therefore be lost after about 100 revolutions in the vacuum chamber.

Any increase in pressure in the vacuum chamber causes increased scattering. Particles scattered at large angles will be lost from the beam. A local pressure bump will increase the probability of losing particles downstream of the bump, due to scattering.

D. Injection Losses

Injected beam losses have far more radiological consequences than stored beam losses because loss of the entire stored beam (locally or distributed around the ring) results in a small integrated dose outside the shielding walls. The injected beam losses, however, can persist for very long time periods (commissioning, mis-steering, machine physics, etc.) and may result in larger integrated doses depending upon the intensity of the injected beam. For instance, a local loss of 100 mA in an iron target of length and radius equal to 5 cm, in the storage ring SPEAR, results in an integrated dose equivalent of about 30 µSv outside the 2-foot thick concrete shielding wall. Typical injection rates in SPEAR vary from 3 to 8 x 10^9 e^- /s. A loss of 1 watt (2.1 x 10^9 e^-/s) during injection in the same iron target results in a dose equivalent of 250 µSv/h outside the shielding walls.

If there is a significant mismatch in position, angle, or energy of the injected beam, the beam will be lost in the first sector downstream of the injection point. If the mismatch is slight, the particles may be lost over a few turns. Under normal operating conditions, a mismatch in position or angle alone can cause the beam to be lost over one or several turns depending upon the degree of mismatch. For a given bending magnet field, there is one value of the electron energy for which the particle follows an ideal orbit [1]. This energy is called the synchronous energy. At a given azimuthal position, an electron that has the same energy as the synchronous particle, but is displaced in position or angle with respect to the ideal orbit, executes betatron oscillations around the orbit. These oscillations can occur either in the horizontal or vertical plane. The β function is a periodic function of the distance along the accelerator, that describes these oscillations. Thus, injection at the wrong position or angle leads to betatron oscillations. The maximum β occurs in the quadrupole magnets which are located at frequent intervals along the lattice of the storage ring. Beam losses will occur at locations where β is a maximum and therefore will be distributed around the storage ring. In addition, any limiting aperture intercepts the beam and becomes a location for beam losses.

The septum magnet is usually the first or last bending magnet of a transfer line to or from a storage ring. It is positioned very close to the aperture of the storage ring vacuum chamber in order to minimize the kicker magnet field strength and to deflect the injected beam or extracted beam with minimal effect on the stored beam . Because of the small aperture of the septum magnet, large losses can be expected at the injection and extraction septum magnets. Losses at the injection septum typically vary from about 20 to 50 % and should be considered in the shielding design of the storage ring. At most facilities, additional high- Z shielding material is placed in the vicinity of the septum magnet. Other limiting apertures are potential locations for beam loss.

Loss of rf power will cause the injected beam to spiral inwards. Failure of magnetic fields or power supply failures will result in growing betatron oscillations. Injection into a bad magnetic field could result in the beam being lost in less than 1 turn. Any off-energy injection could have the same effect.

If the momentum of a particle changes, the bending radius of the dipole magnet changes and the closed orbit also changes. A particle whose energy differs from the reference value, follows a different orbit and beam losses will occur at locations where the dispersion is a maximum. The dispersion function characterizes the trajectory of off-momentum particles. For a storage ring with horizontal bending magnets, the dispersion x(s) due to a relative change in energy $\Delta E/E$ is given by $x(s) = \eta(s)\, \Delta E/E$ where s is the distance along the orbit and $\eta(s)$ is the dispersion function. Thus, any mismatch in energy causes the beam to be lost at locations where the dispersion is a maximum. Dispersion occurs only in the horizontal plane as long as there are no vertical bends.

Mis-steering of the beam (due to improper settings of magnets etc.) can also cause beam losses. Abnormal operating conditions include losing rf power, losing power supply to the magnets, shorting of magnets etc.. The associated beam losses in each of these cases should be analyzed.

Ray traces should be done for the various beam loss scenarios. Both normal and accidental beam losses should be considered. It is vital to “contain” the primary beam, so that it does not directly strike the shielding for reasons explained in the next section. If the optics in the storage ring is being re-designed, it is important to keep in mind the inherent shielding provided by the iron in the bending magnets and quadrupole magnets of the storage ring. If C-shaped magnets are used, and the open end of the magnet points to the outside of the storage ring, additional localized shielding may be required to reduce the radiation from beam losses to acceptable levels. Also, it is prudent to add high-Z shielding material (such as lead) at the exit of each magnet to minimize radiation from beam losses due to a magnet trip or out of tolerance current conditions in the magnet, as has been done at SPEAR.

V. POTENTIAL SOURCES OF RADIATION ON THE EXPERIMENTAL FLOOR AND MITIGATING MEASURES

The potential sources of radiation on the experimental floor are photons and neutrons from loss of injected or stored beam, gas bremsstrahlung and synchrotron radiation. Synchrotron radiation is not a problem outside the thick shielding walls of the storage ring, however it has to be considered in the design of the beam lines and experimental enclosures. Inside the storage ring, the high-energy photons, neutrons and synchrotron radiation can contribute to radiation damage of the storage ring components. Particularly sensitive are electronics, CCD cameras, cables, and permanent magnets used for IDs. High level dosimetry can be used to assess doses to sensitive devices.

Activation of components is not a major problem at storage rings because of the low beam powers (few watts) associated with injection and stored beam. Typically injection takes place once a day in SPEAR and lasts for 5 to 15 minutes. Minor activation can be expected at locations of beam loss. Measurement of activation immediately after shut down provides a quick indication of where the beam losses occur.

A. Photons and Neutrons

As the electrons are being guided to their final destination, they may scrape the vacuum chamber or strike machine components producing a cascade of photons, electrons and positrons known as an electromagnetic shower. The average or characteristic angle of photons and electrons emitted (by bremsstrahlung and pair production) is given by $\vartheta_c = 1/\gamma = m_0c^2/E_0$, where m_0c^2 is the rest mass of the electron and E_0 is the energy of the electron or positron. This angle is so small that the shower is peaked in the forward direction. However, there is a lateral spread in the shower due to Coulomb scattering of the electrons and Compton scattering of the photons. The shower contains photons of all energies up to the primary particle energy. The photon spectrum has a $1/k^2$ distribution for thick targets and 1/k distribution for thin targets, where k is the photon energy.

A small fraction (0.2 %) of the bremsstrahlung energy in the shower goes into the production of hadrons including neutrons, protons and pions. There are three neutron production mechanisms: giant resonance neutrons (GRN) below 30 MeV, neutrons between 30 and 140 MeV from the quasi-deuteron process, and neutrons released as a product of pion production at photon energies above 140 MeV [5]. Neutrons will be produced in any material struck by the electron beam or bremsstrahlung beam above threshold energies that vary from 10-19 MeV for light nuclei and 4-6 MeV for heavy nuclei (exceptions are ^{2}H and ^{9}Be, which have threshold energies of 2.22 and 1.67 MeV, respectively). At low photon energies the GRN dominate because of the large number of low-energy photons in the shower and the relatively large cross sections at these low energies. The GRN have an average energy of a few MeV and are produced almost isotropically. The cross section for quasi-deuteron process is about an order of magnitude below the GRN cross section. Above photon energies of 140 MeV, the cross section rises again due to photopion production and goes through a number of resonance peaks. These peaks are only a fraction of the giant resonance cross sections, however the neutrons released as a product of pion production are more energetic and therefore more penetrating than the GRN. These neutrons are more forward peaked than the GRN neutrons. For shield thicknesses greater than about 2 m of concrete, these neutrons dominate and continually regenerate a field of lower energy neutrons and neutron capture gamma rays.

If the target that the electron or positron strikes is very thin, the shower can be propagated in subsequent targets, which is another important consideration for shielding design. Whenever there is a potential for the beam to strike a thin target, and the shielding in the forward direction is not thick enough, local shielding (high-Z material like lead) can be added to provide a thick target in the proximity of the beam pipe. Thus the propagation of the shower in the shielding walls is prevented and the beam is "contained". The photon dose rate in the forward direction from a thick target is approximately proportional to E_0^2I, where I is the beam current. At 90^0 the photon dose rates are proportional to E_0I. Thus, in storage rings the ratchet (transverse) shielding walls are usually thicker than the lateral walls. Protection against photons and neutrons can be achieved through the adequate design of the storage ring shielding walls and the use of additional localized shielding in areas where beam losses are expected. In addition a system of collimators and injection stoppers should be designed to ensure that there is no direct line-of-sight to the experimental floor, through the penetrations in the storage ring ratchet wall. At SPEAR lead shadow masks are used in the front end.

High-Z materials are more effective in shielding photons, while hydrogenous materials such as concrete and polyethylene are more effective in shielding GRN neutrons. For example, 2.54 cm of lead reduces the photon dose equivalent by about a factor of 3. Thirty centimeters of concrete reduces the photon dose and GRN dose equivalent by factors of about 5 and 10, respectively. Since the bending magnets provide some shielding in the vertical direction, the roof of some of the storage rings such as SPEAR are thinner than the lateral walls. However in these cases careful studies should be performed to determine the impact of skyshine. The lateral concrete walls of SPEAR are 61 cm thick. The roof is 61 cm thick in some areas and 30. 48 cm thick in other areas. The ratchet walls are 91.48 cm thick in some cases. In cases where the ratchet walls are 61 cm thick additional localized shielding has been installed.

B. Gas Bremsstrahlung

Gas bremsstrahlung is produced by the interaction of the primary stored beam with residual gas molecules (H_2, CO, CO_2, CH_4, etc.) or ions in the storage ring vacuum chamber. It is produced in a narrow cone, with a characteristic emission angle of $1/\gamma$. Gas bremsstrahlung becomes very important for straight sections in the storage ring, since the contribution from each interaction adds up to produce a narrow mono-directional beam which travels down the SR beam line along with the SR. The forward directed gas bremsstrahlung can be stopped with injection stoppers and beam stops. Both GB and SR can scatter off any beam line component that they strike. Scattered GB requires far greater shielding thicknesses (tenth value layer is ~5.08 cm of lead) than SR (tenth value layer = few mm of lead depending upon the critical energy) because it is more penetrating. The gas bremsstrahlung can develop an electromagnetic shower in any target that it strikes. In addition it can produce neutrons in any target when the photon energy is greater than the threshold for photoneutron production.

According to Ferrari et. al [6] the maximum dose equivalent rate in the forward direction is proportional to $E_0^{2.67}ILP/(d(L+d))$, where I is the stored beam current, L is the length of the straight section, P is the pressure in the straight section and d is the distance from the end of the straight section to the point of interest. This expression is valid for $E_0 < 1$ GeV. Using this expression and assuming it is still valid at higher energies, the ratio of gas bremsstrahlung dose rates at different facilities can be obtained. The gas bremsstrahlung dose rate at the APS (L=15 m) is about 61 times higher that that at SSRL (L= 5.0 m). While the SSRL WBH and optics enclosures have been shielded primarily for scattered SR, the equivalent APS enclosures have been shielded primarily for scattered GB [7].

Since the GB dose rate increases with the pressure, a serious radiological concern is the loss of vacuum in the storage ring. However, it has been shown that the pressure in the straight section cannot rise indefinitely because the stored beam lifetime decreases with increasing storage ring pressure [8]. The maximum gas bremsstrahlung dose equivalent rate D_{max} is given by $D_{max} = C\tau_0 D_{oL}/L$, where C is the circumference of the ring, τ_0 is the beam lifetime at an average pressure of $P_{0,}$ D_{oL} is the dose equivalent rate at the same pressure and L is the length of the straight section. It is also important to note that the pressure in the storage ring will be higher than the design value ($\sim 10^{-9}$ torr) during the commissioning and early stages of machine operation. The composition of the residual gas also changes with time.

Gas bremsstrahlung calculations can be carried out using analytical methods or Monte Carlo methods. With analytical methods, the forward directed dose equivalent rates can be calculated. However, from the literature, it is not always clear as to what the area is over which the dose equivalent rate is calculated. It has been shown that the area over which the dose rate has been calculated is very critical, since the gas bremsstrahlung is very forward peaked [8]. Further if the dose is scored in a 30 cm thick tissue phantom, one finds that the dose rates reach a maximum at the back of the phantom because of the shower process taking place within the phantom. Thus the depth in the phantom at which the dose equivalent rate is calculated is also important.

Analytical methods are not very useful when one is interested in determining the thickness of a beam stop that would attenuate the dose equivalent rates to acceptable levels, for two reasons. The gas bremsstrahlung will shower in the stop, and hence a simple attenuation coefficient cannot be used. Further, the dose equivalent rate peaks at the front surface of the phantom because the bremsstrahlung has already created an electromagnetic shower in the stop [8].

It is also difficult to determine scattered gas bremsstrahlung dose equivalent rates with analytical methods. In addition to the reasons mentioned above, the dose equivalent rates will depend on the target material, dimensions and geometry. If the target is thick enough, the bremsstrahlung will produce a shower in the target. If the target is thin, the bremsstrahlung can scatter or propagate the shower in subsequent targets. Monte Carlo methods should be used to determine forward directed and scattered gas bremsstrahlung dose equivalent rates. Codes like EGS [9] and FLUKA [10] can be used to simulate the actual geometry and one can have a high confidence in the results provided that the statistics is good. For the reasons mentioned above, all possible scattering targets should be identified and scattered gas bremsstrahlung calculations should be performed on a case by case basis.

In the literature one finds that instead of scoring energy deposition while performing gas bremsstrahlung Monte Carlo calculations, sometimes fluence is scored. The maximum fluence to dose equivalent conversion factors published by Rogers are then used to obtain a “conservative’’ estimate of dose equivalent [11]. These conversion factors are the maximum dose equivalent per unit fluence for broad parallel beams of monoenergetic photons incident on a 30-cm-thick slab of ICRU tissue. The use of this technique can lead to erroneous results because the gas bremsstrahlung beam is a narrow beam. The scattered gas bremstrahlung beam is a diverging beam consisting of a spectrum of photons. Since the maximum dose equivalent occurs at different depths depending on the energy, one assumes that the use of these conversion factors leads to a conservative estimate of dose equivalent. However, it has been shown that the use of these conversion factors does not yield conservative estimates of scattered gas bremsstrahlung dose equivalent rates because these conversion factors (for photons) do not account for dose deposited by charged particles emanating from the target.

Optical enclosures, white beam hutches and white beam transport lines should be shielded for scattered gas bremsstrahlung [12]. The back walls of the enclosures and hutches will usually require additional shielding in a localized area to protect against scattered gas bremsstrahlung from the bremsstrahlung stops and other targets within the enclosure. White beam transport lines will also require additional shielding or collimators in locations where there are limiting apertures or solid scatterers within the transport line. Mono beam hutches and beam transport lines do not usually require shielding against scattered gas bremsstrahlung because the gas bremsstrahlung travels in the median plane of the storage ring. The mono beams are offset from the median plane.

The possibility of producing neutrons should also be carefully analyzed. Usually neutron production may not be a significant problem unless the pressure in the straight section increases.

C. Synchrotron Radiation

The direct synchrotron radiation can be shielded with shutters and stops. Since synchrotron radiation can scatter off beam line components, the hutches and transport lines have to be shielded against scattered synchrotron radiation. Codes using analytical methods such as PHOTON and STAC8 can be used for shielding calculations [13, 14]. These codes are easy to use and yield quick results. However, it is important to understand and account for the limitations of the codes.

PHOTON is a computer program developed at the National Synchrotron Light Source and calculates dose in the following sequence: calculation of photon flux as a function of energy and vertical opening angle of the synchrotron radiation beam, attenuation by filters, a scattering process, and conversion from flux to dose after attenuation through a shield wall. In PHOTON the scattered photon spectrum is calculated by assuming that the scatterer is an isotropic point source Further the total angle integrated Compton cross section is used. However, Compton scattering is not isotropic, but is forward peaked. Forward scattering increases with increasing photon energy. Thus PHOTON will overestimate scattering at large angles and underestimate scattering at small angles. Therefore the shielding thickness calculated by PHOTON for the 90^0 direction will not be sufficient for scattering at the small angles. Typically, the dose rates peak at angles between 40 and 50^{0} outside the enclosures. PHOTON uses the narrow beam attenuation coefficient and does not include build up factors. It does not account for the polarization dependence of scattering. For synchrotron radiation polarized in the horizontal plane, there will be no scattering in the plane of polarization for a point source. However, since the beam has a finite size, there will be some minimal scattering in the plane of polarization. Hence, PHOTON will overestimate the dose in the horizontal plane, but will underestimate dose in the vertical plane. In PHOTON, the target is assumed to be at normal incidence. Therefore PHOTON cannot be used for inclined targets, nor for reflection from a mirror. No consideration is given for electron-photon beam interactions, finite source size or horizontal beam distribution. PHOTON was primarily developed for bending magnets but can be used to obtain a conservative estimates of dose for wigglers and undulators. PHOTON2 is a modified version of PHOTON that calculates the wiggler spectrum using the proper wiggler horizontal beam distribution[15].

STAC8 is a modification of PHOTON which includes the angular dependence of coherent scattering and incoherent scattering. It includes build up factors and linear polarization. It cannot be used for an inclined target or for reflection from a mirror. STAC8 includes undulator sources. Calculations performed with STAC8 show agreement with EGS within a factor of 1.25 to 2.13 for angles between 10 and 90^0. Overall STAC8 provides a conservative estimate of dose.

Monte Carlo codes can also be used for SR shielding calculations.

For the hutch shielding scattering from a solid target that could be located anywhere along the beam line, should be considered. For beam transport line shielding, scattering from a solid target and scattering from air (for loss of vacuum) should be considered [13]. Collimators or localized shielding can be used for scattering from a solid target.

The transmission of higher harmonics (higher in energy, lower in intensity) must be considered in the shielding design of mono beam lines as their contribution will dominate the dose outside the shielding [13] . Mirrors may sometimes be used in the front end or optics enclosure to obtain “pink beam” (reflected white light). A word of caution must be interjected at this point about pink beam SR lines. Mirrors are characterized by a “cut off”, which is loosely defined as the energy below which the mirror does not reflect much useful photon flux (to the user). However, there is still sufficient photon flux at the higher energies which dominate the dose outside the shielding.

The hutches at SSRL have been shielded primarily for scattered SR, and the back walls are usually thicker than the lateral walls because Compton scattering (of SR) is more peaked in the forward direction. At APS the back walls have also been shielded for scattered GB. The BL9 WBH has been shielded with 0.5 cm of lead, laterally. The optics hutches are normally shielded with lead varying from 0.63 cm (median plane) to 0.31 cm. Monochromators at SSRL are normally enclosed in shielded enclosures (0.95 cm of steel). The MBH are also shielded with 0.31 cm of steel. The shielding of the beam transport lines vary depending upon the critical energy

In the design of SR facilities, special attention should be paid to penetrations in the walls and gaps under the doors, of the enclosures to ensure that scattered SR does not reach the experimental floor. Openings into the hutches should not have a direct line-of-sight to the beam pipe. The penetrations should be designed so that radiation scatters at least twice before reaching the outside of the hutch through the penetration. Outside openings should not point towards occupiable areas and should not be positioned at beam height. All gaps and openings around cables should be minimized. Penetrations may pose more of a radiation hazard for white beam hutches. Penetrations can be effectively shielded by using shielded box-type enclosures around the penetrations both inside and outside the experimental hutches as has been done at the European Synchrotron Radiation Facility (ESRF).

Gaps between doors and walls should be minimized. An overlap should be provided between the door and the wall greater than10 times the gap between the door and the wall. An insert can be used between the door and the wall to minimize the radiation streaming through the gap.

Gaps between doors and floors should be minimized. A high-Z insert such as lead can be used under the door to reduce groundshine. Alternatively a sill or threshold with an overlap of 10 times the gap width may be used. However, fixed sills may pose trip hazards and complicate movement of equipment into and out of the hutch. In such a case a retractable sill that can be moved up when the hutch door is opened may be preferred. Other options include recessing the door in grooves which are lined with high-Z material or lining a portion of the floor extending from inside the hutch to outside the hutch. The latter option which has been used at both the APS and the ESRF also reduces the groundshine between the walls and the floor.

For white beam hutches where the SR is allowed to travel over large air paths, the production of ozone must be considered and engineering controls such as ventilation must be installed as needed. It is more effective to ventilate the ozone at the point of production.

VI. RADIATION SAFETY SYSTEMS

In addition to shielding, other radiation safety systems such as the Beam Containment System (BCS) and the Personnel Protection System (PPS) are used at SSRL for radiation protection. The Personnel Protection System (PPS) prevents unauthorized or accidental entry into the beam housing. The PPS includes a system of stoppers which are inserted when entry into an area located downstream of the stopper, is required. The BCS limits the beam power. The PPS and BCS for the SSRL injector have been described elsewhere [16].

Since the shielding for a storage ring is based upon losing a certain fraction of the nominal beam power the beam power should be limited to the allowed beam power. At SSRL this is achieved by using three average current toroids in the linac which limit the electron intensity to 3.1×10^{10} electrons/sec. These toroids are interlocked to the BCS such that the beam is turned off if excess current is detected in any toroid. Radiation detectors are also located in areas where beam losses are expected, so that if radiation levels exceed a preset level, the beam is turned off.

Protection against photons and neutrons produced by the interaction of the beam with storage ring components, is achieved through the adequate design of the storage ring shielding walls and the use of local shielding. In addition during injection (Fig. 2), the moveable mask and the two injection stoppers are closed. The moveable mask absorbs the SR heat load, while the injection stoppers together with a set of collimators (not shown) provide protection in the forward direction from GB, white beam and radiation originating from losses in the storage ring. The injection stoppers should be designed such that in the event that the entire electron beam is transported accidentally down the SR beam line, (in the front end) and strikes the stoppers, the radiation levels in the experimental areas are within some acceptable limits. Most of the injection stoppers at SSRL are made of lead 30 to 44 cm thick. During stored beam conditions, the WBH shutters provide protection against GB and white beam (WB) during entry into the hutch. In the mono beam mode, the MBH shutters provide protection against the mono beam. The thickness of these shutters varies depending upon the critical energy (E_c) of the beam line. For instance BL-9 has WB shutters that are made of Cu of thickness 14 cm (E_c = 11.97 keV). During WB operation the white beam stop located in the median plane provides protection in the forward direction against both GB and WB (Fig. 2). The stops are made of lead of thickness 20 cm and are protected with a burn-through monitor (BTM) which is a pressurized gas-filled chamber connected to a pressure switch. A water-cooled copper plate which absorbs the SR heat load is placed in front of the BTM. In the event that the water is lost and the SR is intense enough to burn a hole in the copper plate and the BTM, the BTM trips the beam off. The mono beam stop provides protection against the mono beam.

VII. CONCLUSIONS

The radiological considerations in the design of SR facilities include a thorough understanding and analysis of beam losses. Shielding and radiation safety systems need to be considered in the early stages of the facility design. The topping-up mode of injection requires careful analysis to ensure that radiation safety is not jeopardized in any way.

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