# Radiation Safety Design for SPEAR3 Ring and Synchrotron Radiation Beamlines

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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 users and workers occupying the experimental floor around a normally thin concrete ring wall. This paper addresses the radiation safety issues associated with the SPEAR3 [f1] storage ring and SR beamlines. Normal and abnormal beam loss analyses for injection beam and stored beam, as well as typical storage ring operation, are described. Ring wall (lateral, roof and ratchet) shielding design for photons and neutrons from beam losses in the ring chamber and beamline frontend is discussed. Radiation safety issues and shielding design for SR beamlines, considering both gas bremsstrahlung and synchrotron radiation hazards, are also presented.

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## INTRODUCTION

SSRL (Stanford Synchrotron Radiation Laboratory) has upgraded its storage ring to a 3rd generation storage ring in 2003, called SPEAR3 (3-GeV and 500-mA). SSRL is a division of SLAC (Stanford Linear Accelerator Center) and, thus, the SLAC safety policies and practices apply to SPEAR3 design. The reports describing general consideration and approach for radiation safety design for synchrotron radiation facilities have been published [1,2]. This paper will address the radiation safety design and requirements specifically for the SPEAR3 storage ring and synchrotron radiation (SR) beamlines. The major radiation issues discussed are the photon/neutron doses outside the concrete shielding (lateral wall, roof and ratchet wall) from electron beam losses (normal and abnormal cases) under both the injection and stored beam operations, as well as the SR and gas bremsstrahlung (GB) in the SR beamlines during the stored beam operation. The related radiation source terms, associated methodologies of the shielding calculations, and the shielding/safety requirements are described. The safety design for the SSRL injector (150-MeV Linac and 3-GeV Booster) is addressed elsewhere [3,4].

## OVERVIEW OF RING SAFETY DESIGN

Figure 1 shows the layout of injector, SPEAR3 ring and current SR beamlines. Two mazes in East Pit and West Pit allow interlocked-controlled access into the SPEAR3 ring. Inherited from the SPEAR2 ring concrete walls, the 234-m-circumference SPEAR3 ring has 2'-thick lateral wall and 1'-thick roof. The ratchet wall is either 2' or 3' thick. At the injection section, the outer lateral wall is 4' thick and the roof is 2' thick. The minimum distance from ring chamber to the outer lateral wall is 1.2 m, 1.8 m to the inner lateral wall, and 1 m to the roof. Currently there are 16 ratchet walls with 11 main beamlines around the outer ring wall. The inner ring is not occupied frequently, except that the SPEAR Control Room (Building 117) is located near the ring center. The ring shielding design goal is to have the floor areas as a non-RCA (Radiological Controlled Area) so the users are not required to wear personal dosimeters.

Figure 2 gives the standard cell in an arc section of the SPEAR3 ring, showing a quadruple between two C-shaped gradient dipoles. SPEAR3 has a thin copper antechamber/chamber design and 36 C-shaped dipoles (openings toward the outer lateral wall), instead of the H-shaped bends for SPEAR2. Due to the 500-mA upgrade and the loss of SPEAR2 dipole self-shielding, it is expected that local shielding is to be added to each beam loss aperture.

Figure 3 shows the radiation safety items located in each alcove: a copper movable mask (MM) to protect the two injection stoppers (lead or Hevimet), a lead/polyethylene (Pb+PE) collimator, a 12"Pb+6"PE shielding around the beampipe in the ratchet wall hole, and 6"Pb+6"PE shadow walls placed at strategic locations near the ring chamber. The shadow walls are primarily used to intercept the secondary radiation generated from beam losses in the ring chamber that may otherwise pass through the beampipe hole in the ratchet wall. In this regard, the collimator can be viewed as one of the shadow walls. In addition, a lead wall on the ratchet wall surface (or lead skirts around shadow walls) can be used to augment the ratchet wall if the concrete ratchet wall itself is not thick enough. This is the case for 2'-thick ratchet walls, which have additional 1" lead on its surface.

The safety aspects of top-up mode of ring operation have not been analyzed and, thus, the movable mask and the two injection stoppers are required to be in (via interlock) during ring injection. Beamlines can be opened only during stored beam mode. Therefore, the boundary of safety design between ring and beamline is the 2nd injection stopper in the frontend. In this report, the frontend refers to the beamline section that is upstream of last injection stopper. Note that the GB and SR safety design for the section of the SR beamline between the last injection stopper and the ratchet wall is to be included in the beamline design.

For the ring safety design, the radiation levels and shielding requirements for the lateral wall (and roof) and ratchet wall from both the normal and abnormal beam losses in the ring chamber and frontend components have been studied [5-14]. The annual skyshine doses from normal beam losses to an individual at SSRL buildings, SLAC user lodge, and SLAC site boundary were also calculated [9,10].

Because SPEAR3 was built with existing SPEAR2 ring wall, the layout condition for every ratchet wall is not uniform around the ring. Instead of designing every ratchet wall, studies [5-7] were made to develop generic methodologies and requirements for the in-alcove safety components that can be applied to all ratchet walls.

The SPEAR3 ring safety design will be summarized as follows:

1) Beam Containment System (BCS) and Personnel Protection System (PPS),
2) Annual normal beam losses of both injection beam and stored beam in 28 identified physical apertures in the ring and the BTS line, given by SSRL physicists,
3) Mis-steered loss of the Allowed Injection Beam Power of 5-W at any point in the ring chamber and the frontend components,
4) Shielding design limits at SLAC and design criteria used for SPEAR3 ring for both normal and abnormal beam loss conditions,
5) Shielding requirements for lateral wall and roof from both normal and abnormal beam losses in ring chamber and in frontends,
6) Generic shielding requirements for ratchet wall from mis-steered injection beam losses in ring chamber and frontends. In this case, the generic methodology is described, but the actual implementation of safety requirements for every ratchet wall, which was reviewed through beamline layout and ray trace studies, is not given here.
7) Summary of shielding and safety requirements at 5-W/500-mA operation.

## BEAM CONTAINMENT SYSTEM (BCS) AND PERSONNEL PROTECTION SYSTEM (PPS)

At SLAC, BCS (e.g., shielding and beam limiting devices) is used to control and keep radiation away from people while PPS (equivalent to access control system) is used to control people away from radiation hazard. The details of active parts of BCS and PPS for SSRL have been described before [15] and an overview is shown in Figure 4 and described below.

SPEAR3 ring has a nominal injection beam of 3 GeV, 4 W (at 10 Hz), and a maximum stored current of 500 mA (1200 J). The Allowed Injection Beam Power (Pa) is set at 5 W, limited by three Average Current Monitors (ACMs) in the BTS (Booster to SPEAR3) line. The stored beam current is monitored and limited by 2 types of BCS devices: DCCTs and BPMs in the ring. There will be four LIONs (Long Ion Chambers, one per quadrant) inside the ring that will be used to detect and terminate any abnormal injection beam losses. The LION trip point is set at a level a few times higher than the normal beam loss of 0.05 W at each aperture during injection. There are also 17 SLAC-made BSOICs (tissue-equivalent ion chamber with a keepalive source) to detect the radiation levels around the SPEAR3 outer ring wall. The ring BSOIC trip point is set at 10 mrem/h to terminate injection by activating the BTS beam stoppers.

When there is a PPS violation in the ring, the four RF cavities in the West Pit will be shut off immediately to terminate stored beam hazards. In addition, two Al mechanical ring stoppers (ST1 and ST2) are to be inserted into the S1 straight section downstream of West Pit. The Al ring stoppers can also be used to purposely abort the stored beam during routine operation when needed. On the other hand, the three PPS stoppers to stop the injection beam from Booster to SPEAR3 ring are the two mechanical stoppers in the BTS line (ST1 and ST2) and the ejection septum in Booster ring.

For those beamlines that are not yet qualified for 500-mA operation, the related movable mask and 2 injection stoppers will be interlocked or padlocked to be in whenever the stored current is more than 100 mA. Therefore, all frontends have to be qualified for 500-mA operation prior to ring operation, but SR beamlines may not need to be. Figure 4 also shows that there are two hutch shutters for each x-ray beamlines.

## BEAM LOSS SCENARIOS FOR RING SAFETY DESIGN

The following 3 beam loss scenarios (normal, mis-steered and system-failure) were considered for ring safety design [16-22]:

1) Normal beam losses around the ring during both the injection and stored beam operations. Figure 5 shows the 28 limiting apertures (8 QFCs, 7 insertion devices, 7 SR masks near West Pit, 3 injection kickers, injection septum, stored beam abort dump, and ring stoppers) around the ring identified as normal beam loss points [20]. The septum, beam abort dump, ring stoppers, as well as the Faraday cup and PR2 profile monitor in the BTS line, are the four high-loss points, while the remaining apertures are low-loss points. Figure 6 summarizes the normal beam loss analysis [17]. With the one-month start-up and 10-month scientific program schedule, a total of $3.5 \times 10^{15}$ $e^-$/y is to be injected into the ring with an injection beam power of 4 W (3-GeV, 10 Hz) and an injection efficiency of 75%. During the 7-min injection period, an instantaneous power loss of 0.05 W occurs at each aperture, except the septum (which has 0.5 W) and ring stoppers (which remains open during injection and do not see injection beam loss, i.e., 0 W). When averaged over a period of 7200 h/y, the loss of both the injection and stored beams is equivalent to an average loss of 2 mW at each low-loss aperture. For high-loss points, a safety factor of 2 was applied to the beam loss amounts. Thus, the average loss is 47 mW at the beam abort dump, 16 mW at the septum, and 13 mW at the ring stoppers. Note that normal beam losses do not occur in the frontend.
2) Mis-steered loss of the Allowed Injection Beam Power of 5 W at any point in the ring chamber at a maximum horizontal angle of 1-degree [18] as well as at any point in the frontend section [22].
3) Loss of the Allowed Injection Beam Power of 5 W in one of the injection stoppers during the system-failure conditions when the movable mask or the first injection stopper fails to be inserted into the beamline during injection.

## SHIELDING DESIGN LIMITS AT SLAC AND THE CRITERIA USED FOR SPEAR3 RING

Table 1a shows the SLAC shielding design limits and guidance. SLAC requires that an individual entering a RCA needs to wear a dosimeter and should be classified as GERT or RWT. The shielding design limit for normal beam losses is generally 1000 mrem/y for RCA and 100 mrem/y for non-RCA (an occupancy of 2000 h/y is generally assumed). The shielding design limit for general public from all SLAC facilities due to skyshine is 10 mrem per 7200 h. For abnormal beam losses, the guidance is 400 mrem/h for mis-steered cases and the limit is 25 rem/h for system-failure cases (which involve the failures of any interlocked device).

Based on the SLAC limits and practical considerations for SSRL, Table 1b gives the criteria used for SPEAR3 ring shielding design under the three types of beam loss scenarios. The limit for normal beam losses is set at 100 mrem per 1000 h. This was set based on the SSRL statistics that the maximum occupancy of SSRL users on the floor is 700 h/y. With this shielding design value of 0.1 mrem/h outside the outer ring wall for a normal beam loss of 2 mW at a low-loss aperture, this is equivalent to a normalized dose limit (NDL) of 50 mrem/h/W. The corresponding shielding design value outside the inner ring wall is 800 mrem per 2000 h (i.e., 0.4 mrem/h), because the area is occupied infrequently. The design value on top of roof is 3000 mrem per 2000 h (average 1.5 mrem/h), because the roof is to be fenced off (with lock) without access during ring injection. The SPEAR Control Room is a non-RCA, but the operators are RWT and they wear dosimeters.

For mis-steered beam losses, the SLAC guidance is 400 mrem/h outside the ring wall. However, this guidance was raised to 1200 mrem/h because of the extensive use of interlocked radiation detectors around the ring (e.g., BSOICs and LIONs). Furthermore, to allow the radiation level for some mis-steered injection beam losses in the frontends to be higher than 1200 mrem/h, SSRL also demonstrated [22] that the mis-steered injection beam losses in frontends are less likely to occur, though credible, when compared to the mis-steered injection beam losses in ring chamber. The mis-steered limit of 1200 mrem/h at 5 W is equivalent to a NDL of 240 mrem/h/W. The mis-steered limit for the roof was set at 3000 mrem/h, because it is fenced.

For system-failure beam losses, the SPEAR3 ring design criterion is the same as SLAC limit of 25 rem/h. The Maximum Credible Injection Beam Power (Pm) is 45 W (a system-failure case that the beam is delivered when the ACMs fail). This is equivalent to a NDL of 555 mrem/h/W.

Because the NDLs for mis-steered and system-failure cases are higher than that for normal beam loss cases, the normal beam losses would dictate the shielding design, except in situations where no normal beam losses occur (e.g., in non-aperture ring chamber points or in frontends).

Currently, there is no SLAC limit for the instantaneous dose rates during the short injection period. During SPEAR2 injection periods, the maximum dose rates were less than 1 mrem/h outside outer lateral wall, 5 mrem/h outside inner wall, and 15 mrem/h on the roof. Therefore, these SPEAR2 dose rates were used as the design goals during SPEAR3 injection. Note that the ratio between injection beam loss (0.05 W) and average beam loss (0.002 W) at a low-loss aperture is 25. Thus, when the normal loss design criterion outside the outer lateral wall is 0.1 mrem/h, it is expected that the dose rate during injection will be 2.5 mrem/h. Therefore, the radiation levels during SPEAR3 injection may be higher than those of SPEAR2. In any case, the radiation level during the injection period should be less than 5 mrem/h, or otherwise the control requirements for Radiation Area would be needed.

Table 1c shows that the shielding design criteria for annual skyshine doses due to SPEAR3 normal beam losses are set at 10 mrem per 2000 h at SSRL buildings (13 m from ring), 5 mrem per 7200 h at SLAC user lodge (100 m away), and 1 mrem per 7200 h at SLAC site boundary (300 m away). The concrete roof and the top local shielding for normal beam loss points will affect the skyshine doses.

SHIELDING AND SAFETY REQUIREMENTS

The dose calculations were made using the analytic SHIELD11 code [23] for thick target cases and the FLUKA Monte Carlo code [24,25] for thin target cases. To accommodate potential uncertainties associated with Monte Carlo simulations of the actual geometries, a safety factor of 3 was multiplied to the FLUKA-calculated dose values, unless otherwise stated. The skyshine neutron doses were calculated with the analytic SKYSHINE code [26].

Outside the thin SPEAR3 walls and roof, photon dominates over neutron (except in four high normal beam loss points, which have heavy local metal shielding). Both SHIELD11 and FLUKA results were used for lateral wall and roof calculations [9,10]. Outside ratchet wall, the radiation of concern is the forward-peaked photons and neutrons from beam losses in ring chamber or frontend components. In this case, the photon intensity varies significantly as a function of angle and depends strongly on the target geometry. Therefore, for ratchet wall shielding calculations (e.g., shadow wall, injection stopper, etc.), the FLUKA results with simulation of ring antechamber and frontend geometries were used in a generic approach [5-7].

### Shielding for Lateral Wall and Roof

<u>Normal Beam Losses in Ring Chamber [9,10]</u>

Figure 7 gives an example of shielding design and requirements using injection septum for three types of beam losses (normal annual dose, mis-steered dose rate at 5-W, and dose rate during injection) around the SPEAR3 ring. These values correspond to those in Tables 2a and 2b [10], which summarize the shielding requirements and dose rates, respectively, for lateral wall and roof from normal and abnormal beam losses in the ring chamber and BTS line. For example, Table 2a shows that the injection septum is 63”, 72”, and 40” from the inner surface of the 4’-thick outer wall, 2’-thick inner wall, and 2’-thick roof, respectively. The shielding required is 0”, 4” Fe, and 4” Fe on the side of outer wall, inner wall, and roof, respectively. The length of shield should cover 45$^{o}$ backward of the first beam loss point and 45$^{o}$ forward of the last beam loss point inside the septum. Table 2b shows that the resulting doses (at 16 mW) are 40 mrem over 1000 h/y, as well as 210 mrem and 480 mrem over 2000 h/y, respectively, outside the outer wall, inner wall, and roof. The corresponding mis-steered dose rates (at 5 W) are 12, 33, and 73 mrem/h, respectively. The corresponding dose rates during the injection period (at 0.5 W) are 1.2, 3.3, and 7.3 mrem/h, respectively. The skyshine dose from septum is 0.8 mrem/2000h at SSRL Building 130 and 0.015 mrem/7200h at SLAC site boundary.

Similar to the injection septum, the other three high normal beam loss points (stored beam abort dump, Al ring stoppers, and Faraday Cup/PR2) also need thick local metal shielding.

For 2-mW loss at a low-loss aperture like QFC, ID, and SR masks, Tables 2a and 2b show that 2” Fe (or 1” Pb) is needed on the outer lateral wall side. This requirement is dictated by the normal annual dose of 50 mrem/1000h (1.3 mrem/h outside wall and 29 mrem/h on the roof at 0.05-W during injection). The local shielding should cover a vertical angle of $\pm 30^o$. FLUKA calculations [14] also show that the length should cover 1' upstream and 2' downstream of the beam loss point (e.g., the middle of a QFC, the beginning and/or the end of an ID).

Section G4 of the ring is located immediately downstream of the septum. According to experience from SPEAR2 and other SR facilities, this section tends to have more normal beam losses than other ring sections. Therefore, it was assumed that Section G4 has a normal beam loss of 4 mW.

The inner ring has an annual dose of 795 mrem/2000h from beam abort dump. The Controlled Room, where RWT operators occupy frequently, has 20 mrem/2000h with the distance factor considered. With the roof and required top local shielding, the total skyshine dose is 9.3 mrem/2000h at SSRL Building 130, 3.4 mrem/7200h at SLAC user lodge, and 0.3 mrem/7200h at SLAC site boundary. These are within the design criteria.

It is also recognized that the credit of any self-shielding (e.g., magnet and chamber components) may be taken in replacement of the required shielding. However, the self-shielding must be demonstrated and they should be easily verifiable.

<u>Mis-steered Injection Beam Loss in Ring Chamber [9,10]</u>

In addition to normal beam losses in apertures, abnormal loss of injection beam of Pa = 5 W could occur at any point in the ring chamber, e.g., in the bare straight sections and the gaps between any two thick components. The worst case is that the 3-GeV injection beam is mis-steered to hit the thin 0.7-cm Cu antechamber wall with a maximum horizontal angle of $1^o$ [18]. The FLUKA results shows that, if without shield, the dose rate for 5-W loss at a thin 0.7-cm Cu target is 500, 285, and 2850 mrem/h outside the outer wall, inner wall, and roof, respectively (see Table 2b). The levels are lower than the respective limits. Therefore, no shield for lateral wall and roof is required for mis-steered beam loss at a thin target in the ring chamber.

<u>Mis-steered Injection Beam Loss in Frontend [7]</u>

FLUKA simulations with frontend geometries for bend and ID beamlines (similar to Figure 3) were used to calculate the dose rates outside the lateral walls and roof. Table 3 shows that, for 3-GeV electron beam hitting a frontend component, the maximum dose rate outside the lateral wall is 1080 mrem/h at 5 W. There will also be a leaf-shaped zone on the roof with a maximum of 5550 mrem/h at 5 W, which is higher than the roof limit of 3000 mrem/h. This was granted because of the following 3 arguments: 1) the mis-steered injection beam losses in a frontend are not likely, 2) roof is fenced off, and 3) credit of BSOICs and LIONs.

## Shielding for Ratchet Wall

Outside ratchet wall, the radiation of concern is the forward-peaked photons and neutrons from beam losses in ring chamber or frontend components. Generic approach for ratchet wall shielding calculation was used and, thus, the implementation of safety requirements was reviewed for every ratchet wall afterwards via comprehensive ray trace studies.

<u>Source Terms and Attenuation Lengths</u>

With the geometry of 3-GeV electron hitting a 0.7-cm Cu antechamber wall at $1^o$, the source terms, as well as the associated attenuation lengths in concrete, lead, and polyethylene, have been calculated with FLUKA as a function of angle relative to the beam direction [5].

Figure 8 shows the normalized dose equivalent (mrem/h/W at 1 m) source term profiles for photons (top figure) and neutrons (bottom figure) between 0 to 100 degrees for three beam-target situations with concrete shield. Note that the 0.7-cm Cu target produces the highest photon and neutron dose rates.

Figure 9 shows examples of the dose equivalent attenuation profiles in concrete at various angles for photons (top) and neutrons (bottom) from 3-GeV beam hitting the thin Cu plate. The 180-cm-thick concrete shield starts at a simulated radius of 600 cm. The first and 2$^{nd}$ attenuation lengths were then derived from the attenuation profiles as a function of angle and material [6].

Normal and Mis-steered Beam Losses in Ring Chamber [6]

With the source terms and attenuation lengths, the dose at any angle and shield thickness can be calculated via ray trace study. Data sheets using the Excel program (which incorporates the pre-calculated source terms and attenuation lengths) were developed to calculate the corresponding dose rates [6]. The generic shielding requirements for 3' or 2' ratchet walls were then developed by studying their worst geometry cases (i.e., the one with the shortest distance between the ratchet wall and ring source point) [6].

Figure 10 shows the in-alcove geometry of the worst 2' ratchet wall case. Ray trace studies were made for 16 source points (SA to SK, as well as synchrotron radiation masks denoted by stars) and 5 dose points outside ratchet walls (OF to OJ). The source points ID, SE, and SL are normal beam loss points while the others are mis-steered beam loss points. Two heights at each dose point were studied: the ray at median plane (to examine the thickness and width of shadow walls, as well as their locations) and the ray that just skims over the 12"-tall shadow wall.

Table 4 summarizes the dose rates outside 2' ratchet wall. With 1" lead shielding on the 2'-thick ratchet wall, the mis-steered doses are within the limit of 1200 mrem/h at 5 W, while the normal doses are not (a factor of 3 too high). However, each normal beam loss point requires 2" Fe local shielding alongside the aperture, which was not considered in these calculations. Therefore, the 2' ratchet wall with 1" Pb should be acceptable. 2' concrete wall plus 1" Pb is equivalent to a 3'-thick concrete wall without lead, for the purpose of shielding photon radiation. Note that the limit-approaching rays have angles < 10 degrees and they just skim over the shadow wall. In addition, over 90% of the doses are from photon radiation in those cases. Therefore, additional 1" lead can provide a factor of 3 that is needed for dose reduction.

The ray trace studies have also shown that there are some self-shielding of ring components, particularly when the ray is off the median plane. Since the self-shielding was not considered in the dose calculations, the multiplication factor of 3 for the FLUKA dose results was not applied in this case.

The shielding requirement of concrete ratchet wall from beam losses in ring chamber is summarized in Table 5. 1" lead wall is needed on the surface of 2' ratchet wall (no need of lead for 3' ratchet wall). The collimator in front of injection stoppers and the shadow walls near the ring chamber need to be at least 6"Pb+6"PE thick and 12" tall. Any secondary radiation ray from ring chamber to the beampipe hole should be blocked by either collimator or shadow walls. A shielding of 12"Pb+6"PE should surround the beampipe in the ratchet wall.

Mis-steered Injection Beam Losses in Frontend [7,13]

FLUKA with the in-alcove geometries of 2' and 3' ratchet walls (similar to Figure 3), as well as SHIELD11 for thick target cases, was used to calculate the dose rates outside the ratchet wall for mis-steered losses in a frontend. Table 3 gives the maximum dose rate of 1800 mrem/h at 5 W, exceeding the limit of 1200 mrem/h. This was granted again because of the 2 arguments: a) mis-steered injection beam losses in a frontend are not likely, and b) credit of LIONs and BSOICs.

The generic safety requirements are summarized below:

1) For 2' ratchet wall, a 1"-thick lead wall is needed. For 3' ratchet wall, no lead is needed.
2) Collimator should be at least 6"Pb+6"PE and 12" high.
3) 12"Pb+6"PE filling the hole around the beampipe in the ratchet wall is acceptable.
4) For a minimum distance of 2 m between the front face of an injector stopper and the outer surface of ratchet wall, an injection stopper thickness of 5" Hevimet (or 7" lead) is needed for $0^{o}$ dose.

Note that there are five ratchet walls that do not have SR beamlines yet and these beamlines, as well as the unused beam exit points need to be terminated with 4"-thick lead (8" wide and 4" high) shielding immediately downstream of the beamline exit point. This is to prevent the beam to hit and create shower in the concrete wall.

### Summary of Safety Design and Requirements for SPEAR3 Ring

SSRL implemented the required shielding according to two phases of operation: 1.5-W/100-mA and 5-W/500-mA. Prior to the 1.5-W/100-mA operation, all shielding are to be implemented, except the 2"-Fe shielding alongside the low-loss apertures, which will be implemented prior to the 5-W/500-mA operation.

The main dose of concern, which dictates the ring shielding design in most cases, is the integrated dose over a long period of time. The annual doses around the outer lateral wall, where users occupy frequently, from normal beam losses at the 2"-Fe shielded low-loss apertures are about 50 mrem over 1000 hours. This is to be considered together with the skyshine dose (10 mrem/2000h) and the doses from SR beamline operation, which also has a design criterion of 100 mrem per 1000 h. In addition, the dose rates during normal injection are about 2 mrem/h.

The mis-steered shielding guidance was raised from 400 mrem/h to 1200 mrem/h by taking credit of interlocked radiation detectors. In addition, to reduce the shielding need from the mis-steered injection beam losses in a frontend by 1"-Pb, it was also demonstrated that, such beam losses (though credible) are much less likely to occur, when compared to the mis-steered injection beam losses in ring chamber. The roof also has to be fenced off for no access during injection.

Figure 11 summarizes the dose rate results outside lateral wall and ratchet wall (2' wall with 1" Pb; 3' wall without Pb) for normal losses in a low-loss aperture (with 2" Fe shielding) and mis-steered beam loss of 5-W at a point.

For any new concrete ring wall design, the recommended thickness is 2' for roof, 3' for lateral wall, and 4' for ratchet wall. In that case, local shielding for low-loss apertures and the credit of BCS devices are no longer necessary.

The main shielding/safety requirements for 5-W/500-mA ring operation are:

1) Three ACMs at BTS line set to trip at 5 W and stored current interlock set at 505 mA.
2) One LION in each quadrant and 17 BSOICs around the ring walls.

3) High normal beam loss points (injection septum, stored beam abort dump, ring stoppers, and Faraday Cup/PR2) shielded locally per Table 2a.
4) 2”-thick, 3’-long Fe for each low-loss aperture (8 QFCs, 7 IDs, 7 SR masks near West Pit, and 3 injection kickers) and Section G4.
5) 1"-thick Pb for 2' ratchet walls and no shield for 3' ratchet walls
6) Roof areas of ring are fenced off and locked for no access during injection periods.
7) Shadow walls and collimator (6”Pb+6”PE) placed to block the rays from the ring to the beampipe hole for every ratchet wall.
8) Shielding (12”Pb+6”PE) surrounding the beampipe in the ratchet wall.
9) Frontend components meet the size and distance requirements.
10) Lead block (8”x4”x4”) downstream of each unused beamline exit port.

## OVERVIEW OF BEAMLINE SAFETY DESIGN

A beamline takes the SR light from the source, an insertion device (ID) or a bend magnet, in the ring through an optical hutch (downstream of the ratchet wall) into experimental stations. Along each beamline, there are optical elements defining the SR ray envelope, as well as beam quality and quantity for experiments. The optical components include apertures (masks/slits), mirrors, and monochromators (hereafter called monos). In addition to the low-energy, high-power SR, the high-energy, low-power GB also channels into the beamline. The SR hazard is generally mitigated with hutch wall shielding (or beampipe with lead wrap in case of VUV line). On the other hand, the GB hazard is mitigated with safety components (i.e., collimators, hutch shutters, beamstops, and local shielding around the optical components that are hit by GB).

When compared to other light sources, SPEAR3 is a medium-energy light source and tends to have more wigglers, which have high deflection parameters K. To maximize the use of wiggler, there are generally 2-3 branch lines in a beamline. Therefore, the optical components in the optical hutch may be close to each other and this may causes difficulty in shielding layout, if the safety design has not been considered early in the beamline design stage.

As many SPEAR2 beamlines need to be upgraded in a limited time, generic methodologies and the rules for both SR and GB hazards have been developed using conservative, standard beam-target-shield geometries for the radiation safety design of SPEAR3 beamlines. Detailed shielding data needed for generic methodologies are available in 5 references [27-31] while the methodologies and rules were described in detail in [32]. The following will summarize the safety considerations, methodologies, and design rules.

## CONSIDERATION AND METHODOLOGIES FOR BEAMLINE DESIGN

There are three SR light categories in SPEAR3 beamline design:

1) White light (SR from the source that has not interact with any component),
2) Pink light (a surface effect that photons specularly reflected from a mirror) and Compton light (a bulk effect that photons Compton-scattered from a mirror or mono in all directions), and

3) Mono light (mono-energetic photons from a monochromator). This is further divided into unfiltered mono light (mono light without a mirror reflection) and filtered mono light (mono light with a mirror reflection).

The GB hazards are divided into two categories:

1) 0-degree GB that needs to be intercepted with beamline safety components, and
2) Scattered GB from optical components that need to be shielded with local shielding.

To develop the methodologies and rules needed for generic beamline design, studies have been made using the analytic STAC8 code [33] and FLUKA for the following radiation issues:

1) SR doses from white light hitting a beamline component or an experimental sample [27],
2) SR doses from both the pink light and Compton light hitting a beamline component (or beampipe) or an experimental sample [28],
3) SR doses from mono light hitting an experimental sample [29],
4) 0-degree GB, which determines the requirements for safety components in terms of their longitudinal thicknesses and lateral extensions [30],
5) Scattered doses from GB hitting an optical component [31].

### 1) Scattered SR Doses from White Light Hitting a Target

The SPEAR3 SR beam parameters as of Jan. 2004 are shown in Table 6 [34]. All bend beamlines (BL1, BL2, BL3, and BL8) have the same critical energy of 7.8 keV. Among all seven ID beamlines, BL11 is expected to produce the highest levels of SR radiation, due to its highest critical energy (Ec=12.2 keV), the high power per horizontal fan width (3029 W/mradH), and its wide fan width (8.9 mradH) out of the source.

Figure 12 shows the beam-target-shield geometry used in STAC8 to calculate the shielding needs for scattered SR in a white light hutch [27]. Two types of targets were used: a Si disc (0.2-degree-inclined, d = 2 cm, r = 6 cm) and a perpendicular Cu disc (d = 0.5 cm, r = 0.5 cm). The ambient dose equivalent rates as a function of scattering angle outside the shielding wall for SR beams with various critical energies and power levels (W/mradH) were calculated. The build-up effect in shield was considered but the polarization effect was not considered.

Figure 13 gives one example of the calculated results: dose rate outside the lead side wall for five SPEAR3 SR beams hitting the Si disc (top) and Cu disc (bottom). The dose results are normalized to the SR power per mradH with a single pole. Since the polarization effects are not considered, the side wall results can be applied to roof also. An inclined silicon target produces a slightly higher dose rate than a perpendicular copper target. It was also found that Si targets with small inclined angles produce higher dose rate than targets with large inclined angles.

The SR scattering at forward angles is more angular-dependent than lateral direction. Therefore, the downstream (back) wall shielding results are shown as a function of angle. For example, Figure 14 shows the dose rate outside the lead downstream wall, for 5 angular ranges, for BL11 SR beam hitting a perpendicular Cu target.

These figures and others [27] form a family of curves, which allows one to design the shielding for white light hutches with the same critical energy, using a scaling of the number of poles and the horizontal fan width of the white light hitting the target, as well as a scaling of distance between target and dose point using the inverse square law.

**2) Scattered SR Doses from Pink and Compton Lights Hitting a Target**

For shielding design purposes, the SSRL pink lights were divided into two different energy groups: hard x-ray pink light (Pt-coated mirror at an inclined angle of $0.16^o$ with a cut-off of 23 keV) and soft x-ray pink light (also called VUV, Pt-coated mirror at $2.5^o$ with a cut-off of 1.5 keV).

Figure 15 shows the diagram of the STAC8 geometry in the scattered SR dose calculations for either pink or Compton light hitting a target. The white light hits the mirror (located in alcove in this case), generating the pink light, which then hits a target in the downstream hutch (called pink light hutch). At the same time, some Compton lights scatter from the mirror will also hit the target (limited by apertures with a linear opening half-angle, to be defined in STAC8 inputs). Therefore, the STAC8-calculated Compton dose results have to be scaled to the actual solid angle (e.g., with the square of actual linear half-angle) obtained from the SR ray trace drawing.

The forward and lateral scattered doses from both the pink and Compton lights hitting an optimum target (i.e., $0.16^o$–inclined Si disc) have been calculated as a function of shielding thickness for various SPEAR3 SR lights [28]. Figure 16 shows an example of the pink light dose results, while Figure 17 shows an example of the Compton light dose results. It was found that, in the SSRL cases of hard x-ray pink light, both pink and Compton lights need to be considered in shielding design, and in case of soft x-ray pink light, only Compton lights need to be considered.

**3) Scattered SR Doses from Mono Lights Hitting a Target**

The Si mono light is divided into two groups: Si(111) series and Si(220) series. The energies and intensities of the mono light for the two series are shown in Table 7. The common target in a mono-light experimental hutch is the experimental sample and, thus, the $0.16^o$-inclined Si disc was used as an optimum target (also see Figure 15). Dose calculations outside the hutch wall (iron or lead) were performed using FLUKA [29].

Figure 18 shows an example of the FLUKA-calculated mono-scattered dose rates for the iron side wall from all lines of the mono light series Si(220). An equilibrium attenuation length exists at thick shield, which corresponds to photons at 74 keV. It was found that in most cases the photons at energies between 60 and 90 keV dominate the shielding design. In the case of downstream wall for unfiltered mono light, the 111-keV photons may dictate the shielding design at forward angles.

In the mono hutch design, the horizontal fan width, the number of poles, and the magnetic field strength should be used to adjust the FLUKA-calculated dose. If the mirror is always in, the case of filtered mono light applies and the mirror reflectivity R can be used to scale down the photon intensity. Note that, when a multi-layer mono is used, the broader band pass compared to that of double Si mono should be considered.

**4) Zero-Degree GB Issues For Beamline Safety Components**

The actual SPEAR3 ID straight section is about 5.4 m, but in the GB calculations, the air length was assumed to be 6-m-long (3-m-long wiggler and 3-m straight), giving a GB power of 0.038 mW at a vacuum pressure of 1 ntorr. The bend has a 15-cm-long bending length. In either case, the zero-degree GB dose rate is very high. Therefore, the goal of safety components are to provide enough longitudinal thickness and lateral coverage to block all potential GB rays so that the high forward-angle doses are reduced to acceptable levels.

Figure 19 shows a diagram illustrating the GB ray trace method to determine the safety component requirements (collimators, 2 hutch shutters, beamstops) in terms of longitudinal thickness (t) and lateral extension (L) requirements. Both issues are related to the Physical Envelope of the GB ray trace. The Physical Envelope is defined by the physical size of the ring chamber (limited by apertures) [35] and the collimators (≥ 6" Pb) or the fixed mask (≥ 15" Cu).

The longitudinal thickness of a safety component, lead or Hevimet (tungsten alloy, $\rho$ = 17 gm/cm$^3$) has been determined analytically [30] to be a function of the distance between the safety component and the downstream end of straight section. For SPEAR3, a conservative thickness can be obtained with a minimum distance of 10 m.

FLUKA was used to study the lateral extension requirements [30]. Figure 20 shows the total and photon dose rates at 30-cm and 100-cm lateral from the GB beam axis, resulting from 0.038 mW of GB hitting a lead block with 1"-Pb lateral extension. At a distance of 100 cm, 1"-lead lateral extension is sufficient for photons. However, the neutron dose, calculated to be 0.1 mrem/h, dominates the radiation level. The experience with the SPEAR2 operation and other similar facilities has not shown that neutron dose is a major issue for shielding of beamlines or hutches. Therefore, it was decided that 2"-Pb (3.2 Moliere radius) lateral extension will be sufficient for primary GB. Detailed measurements during commissioning and operation will be performed to verify the need for neutron shielding.

The above requirements refer to primary GB (PGB); rays that have not interact with any object. In many cases, the GB rays will go through some optical components and become secondary GB (SGB), which has a lower intensity than PGB. Therefore, for the safety design purpose, the SGB is defined as the GB rays that go through at least 50-cm-long mirror, 2" Cu, or 1" Pb (whose length is about 4 radiation length, more than the shower-maximum length for SPEAR3 GB spectrum). Compared to the PGB, the SGB has lesser requirements for safety components.

Table 8 summarizes the longitudinal thickness and lateral extension requirements for PGB and SGB at SPEAR3 500-mA operation.

There are cases when hutch shutters are behind or in front of the collimators or two collimators are close to each other. In those cases, the two safety components need to have a minimum overlap. FLUKA calculations have been made to show that a minimum overlap of ¼" Pb is acceptable for all cases.

**5) Scattered Doses from GB Hitting an Optical Component**

The GB generally hits an optical component before it hits a safety component. There is another type of GB ray trace envelope called the Maximum Stored Beam Orbit envelope [36], defined by the maximum orbit that a beam can be stored. The Maximum Stored Beam Orbit envelope can be used to identify the optical components hit by GB and to determine the shielding needs. However, the more conservative Physical Envelope has been used to design the optical element shielding requirements, as it was found that there was not much difference on the results. On the other hand, the MPS-interlocked Stored Beam Orbit was used in generating the SR ray trace envelope to determine the containment of the SR rays.

To calculate the shielding for primary GB hitting an optical element, FLUKA simulations were performed [31] for three different targets: an inclined mirror, a 1" Cu cube (a shower-maximum target), and a 1”x1”x6” Cu slab (to simulate a long mask). The doses are scored as a function of angle at 5 m distance from the target with an annular lead ring shield at 2.5 m

Figure 21 compares the photon source terms (i.e., no lead shield) as a function of scattering angle and at 1m from three types of target, hit by the full GB power of 0.038 mW. The forward-peaked dose profiles between the Si target and the short Cu target are similar, while the long Cu target has a lower forward dose, but a factor of 5 higher lateral dose. The $2^o$-forward photon doses from the targets are high and may need shielding even at 10 m. The lateral (>$45^o$) photon doses at 1 m are acceptable for Si or short Cu targets, but the lateral doses for long Cu target are a factor of 5 too high. The neutron doses for all 3 types of target are below the design limit.

Figure 22 shows the photon dose equivalent rate at 1 m as a function of forward angle for 6 lead shield thicknesses (0” to 5”), from GB hitting an inclined Si target. Similar figures were developed for 1-inch Cu cube and long Cu slab targets. These figures allow one to determine the forward-angle shielding needs for optical components.

Figure 22 indicates there may be a shower build-up effect, which causes the dose at thin shield higher than the doses in the no-shield case. Considering the amount of self-shielding provided by the beam line components, the shower effect will be ignored in the design and special attention will be paid to this issue during the beamline commissioning measurements.

The above calculations and shielding requirements refer to optical components hit by primary GB. When a beamline is operated with a mirror always in alcove, the SGB requirements apply. FLUKA was used to calculate the dose profiles for a two-mirror geometry, in which the PGB hits the first mirror and the SGB (passing through the first mirror) hits the second mirror 1 m downstream of the first mirror. For the 2-mirror geometry, the lateral doses at 1 m from the $2^{nd}$ mirror are ≤ 0.005 mrem/h. This is a factor of 6 lower than the 1-mirror case. Thus, no lateral shield is needed even for the SGB hitting a long Cu target. However, shielding in small forward angles still need to be evaluated in a two-mirror geometry.

## RULES FOR BEAMLINE SAFETY DESIGN

The rules for shielding design of SPEAR3 beamlines are summarized in this section and are divided into 4 categories: general rules for both SR and GB, rules for SR (white, pink/Compton, and mono), rules for GB, and recommended practices.

### General Rules

The design rules that apply to both SR and GB hazards are:

1) The dose limit of 0.05 mrem/h for SR and 0.05 mrem/h for GB (a total of 0.1 mrem/h) should be used for beamline shielding design. If the SR dose is ≤ 0.001 mrem/h, the GB limit can be raised to 0.1 mrem/h. This gives a maximum of 100 mrem/y from beamline operation for 1000 h/y occupancy on the experimental floor. Note that the dose limit on the floor from the normal electron beam losses inside ring is also 100 mrem/1000h.
2) Occupancy factor for roof can be set to 0.1 (i.e., the limit is 0.5 mrem/h), if only very infrequent occupancy can be assured via engineering means. When there are $2^{nd}$ floor on top of a hutch roof, an occupancy factor of 1 should be used.

### Rules for Synchrotron Radiation (SR)

The design considerations and rules for SR are as follows (summarized in Table 9):

1) The maximum magnetic field and maximum number of poles for an ID should be used.
2) If mirrors can be removed for a fraction of operation time, the unfiltered beam mode of operation (i.e., white light or unfiltered mono light) should be used for shielding design.
3) A shielding credit of ¼" Fe for the tanks of mirrors and monochromators in optical hutches can be considered. Thus, for white light optical hutch shielding design, the dose results for the perpendicular copper target can be used. For pink light optical hutches, the ¼" Fe gives an additional minimum attenuation factor of 4.
4) For unfiltered-mono hutches, use the results of 1 of the 2 sets of harmonics hitting a $0.16^{o}$-inclined Si disc. Scaling for the horizontal fan width, number of poles, and the magnetic field should be made to obtain the final dose results. For filtered-mono hutches, the intensity reduction from the 23-keV cut-off mirror reflectivity for hard x-ray pink light (or 1.5-keV cut-off for VUV) can be considered. For multi-layer mono, the broader band pass should be considered.
5) Polarization effect is not considered in calculations.
6) Triple (or more) Compton scattering lights are not considered in the shielding design.
7) SR ray trace based on the MPS-interlocked stored beam orbit is used to identify the potential targets and to show that all rays are properly contained by components.
8) It should be shown that components that can intercept any mis-steered SR ray can withstand the heat load indefinitely or are properly water-cooled via an engineered-interlocked system.

### Rules for Gas Bremsstrahlung (GB)

The design rules for GB are as follows (also see Table 8):

1) Two types of GB are considered: primary GB and secondary GB.
2) Two types of beamline component are considered: safety components (collimators, hutch stoppers, and beamstops) and optical components (mirrors, monochromators, and masks).
3) The GB ray trace is performed with the Physical Envelope to show that all GB rays are intercepted by safety components with sufficient thickness and enough lateral extension.
4) The length requirement of 10"-Pb can be determined with a minimum distance of 10-m between the end of ID straight and the safety component.
5) The minimum lateral extension of ID beamline safety components is 2" lead for PGB and 1" Pb for SGB (for bend beamlines, it is 1" Pb for PGB and 0.5" Pb for SGB).
6) The minimum overlap between any two near-by safety components is 1/4" lead.
7) For the PGB hitting an optical element, the FLUKA-calculated dose results for GB hitting a mirror, a 1-in Cu cube, or a long Cu slab should be used. At 1 m, no lateral shield is needed for mirror and small Cu targets. For bend beamlines, no lateral shield is needed for all types of target.
8) For the SGB hitting an optical element, the FLUKA-calculated dose results of 2-mirror geometry should be used. No lateral shield is needed for all types of target at 1 m.

### Recommended Practices

Some of the design rules were developed because of the need to accommodate the existing SPEAR2 beamline configurations. These special considerations demand more intensive calculations, deviate away from true generic approach, and create shielding verification and configuration issues. Therefore, for new or future beamline designs, it is strongly recommended that the following practices be followed:

1) The principles of conservatism, uniform specifications for same types of beamlines, simplicity of shielding verification and configuration, minimal administrative and operational control burden, and future upgrade should be observed.
2) Design a white, pink, or mono hutch wall SR shielding that is independent of detailed operation modes and beamline configurations.
3) Unify the thickness and/or dimension of all GB collimators, beamstops, and hutch shutters (e.g., 10" long for ID and 8" Pb for bends).

## CONCLUSIONS

Generic methodologies and rules for the storage ring and beamline safety design, as well as shielding design data needed for the approaches, have been developed for SPEAR3 ring and beamlines. The shielding for ring and ten beamlines (> 30 branch lines) have been designed, reviewed, and implemented successfully. The active safety systems are also implemented. Comprehensive radiation measurements made during commissioning show the levels of radiation are acceptable and the results are consistent with the design. Design practices and improvements for future ring and beamline upgrades are also recommended.

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Table 1a. Shielding design limits at SLAC.

| Beam Loss Conditions | Normal | Mis-steering | System-Failure |
|---|---|---|---|
| Radiological Control Area (RCA) | 1000 mrem/y | 400 mrem/h | 25 rem/h |
| Non-RCA | 100 mrem/y | 400 mrem/h | 25 rem/h |
| General Public (Skyshine) | 10 mrem/y | N.A. | N.A. |

1) An individual entering a RCA needs to wear a dosimeter and be classified as GERT or RWT.
2) An occupancy of 2000 h/y is assumed for workers (7200 h for skyshine).

Table 1b. Shielding design criteria for SPEAR3 ring at 5-W/500-mA.

| Area | Normal Beam Loss | Mis-steering Loss at 5 W | Normal Injection [3] |
|---|---|---|---|
| Outer Ring Wall (User Side) | 100 mrem / 1000 h (0.1 mrem/h) [1] | 1200 mrem/h [2] | 1 mrem/h |
| Inner Ring Wall (Less Occupied) | 800 mrem / 2000 h (0.4 mrem/h) | 1200 mrem/h [2] | 5 mrem/h |
| Roof (Fenced and No Access) | 3000 mrem / 2000 h (1.5 mrem/h) | 3000 mrem/h | 15 mrem/h |

1) The criterion of 100 mrem per 1000 h is set based on the maximum occupancy of 700 h/y for SSRL users on experimental floor.
2) In SPEAR3 shielding implementation, the mis-steered limit was raised from 400 to 1200 mrem/h based on the justification of the extensive use of BSOICs/LIONs in the ring.
3) The criteria for normal injection are set based on the maximum dose rates experienced during SPEAR2 operation.

Table 1c. Shielding design criteria for skyshine doses from SPEAR3 normal beam losses.

| SSRL Buildings (13 m) | SLAC User Lodge (100 m) | SLAC Site Boundary (300 m) |
|---|---|---|
| 10 mrem / 2000 h | 5 mrem / 7200 h | 1 mrem / 7200 h |

Table 2a. Shielding requirements for lateral walls and roof for beam losses in the ring chamber.

| Element | Outer Ring Side | Inner Ring Side | Top |
|---|---|---|---|
| Injection Septum<br>(4’@63”, 2’@72”, 2’@40”) | 0 | 4” Fe<br>or 2” Pb | 4” Fe<br>or 2” Pb |
| Stored Beam Abort Dump<br>(4’@78”, 2’@78”, 2’@40”) | 0 | 3” Fe<br>or 3” Pb | 3” Fe<br>or 3” Pb |
| PPS Ring Stoppers<br>(no injected beam mode)<br>(2’@60”, 2’@60”, 2’@40”) | 6” Fe<br>or 3” Pb | 2” Fe<br>or 1” Pb | 0 |
| Faraday Cup & PR2<br>(4’@25”, 2’@125”, 2’@25”) | 8” Fe<br>or 8” Pb* | 4” Fe<br>or 4” Pb* | 8” Fe<br>or 8” Pb |
| Low-Loss Apertures<br>(2’@48”, 2’@72”, 1’@40”) | 2” Fe<br>or 1” Pb | 0 | 0 |
| G4 (down beam of Septum)<br>(2’@48”, 2’@78”, 2’@40”) | 2” Fe<br>or 1” Pb | 0 | 0 |

1) Height should cover ±30° vertical angles.
2) For septum, ring stoppers and Faraday Cup, the length requirement is 45° backward of the first and 45° forward of the last beam loss points in a device.
3) For dump, low-loss apertures, and G4 section, the length requirement is 1’ upstream and 2’ downstream of the loss point (e.g., middle of a QFC or the beginning of an ID).

Table 2b. Dose rates outside SPEAR3 lateral walls and roof, as well as skyshine doses, from beam losses in ring chamber [10].[1]

| Location | Normal [2] (e/7200h) | Outer | Inner | Roof | Mis-steering | Outer | Inner | Roof | Inject | Outer | Inner | Roof | B130 13 m | Lodge 100 m | Site 300 m |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Septum | $8.8 \times 10^{14}$ (16 mW) | 40 | 210 | 480 | 5 W | 12 | 33 | 73 | 0.5 W | 1.2 | **3.3** | **7.3** | 0.8 | 0.19 | 0.015 |
| Beam Dump | $2.6 \times 10^{15}$ (47 mW) | 95 | **795** | **2000** | 5 W | 10 | 41 | 100 | 0.05 W | 0.1 | 0.4 | 1.0 | 2.5 | 0.6 | 0.048 |
| Ring Stoppers | $7.0 \times 10^{14}$ (13 mW) | **70** | **500** | 2500 | N/A | | | | N/A | | | | 1.0 | 0.2 | 0.02 |
| Faraday & PR2 | $4.1 \times 10^{15}$ (75 mW) | 15 | 110 | 460 | N/A | | | | 5 W | **0.9** | **3.6** | **15** | 1.7 | 0.4 | 0.03 |
| Apertures | $1.1 \times 10^{14}$ (2 mW) | **50** | 230 | 2300 | 5 W | 125 | 285 | 2850 | 0.05 W | 1.3 | 2.9 | 28.5 | | | |
| Section G4 | $2.2 \times 10^{14}$ (4 mW) | **100** | 460 | 1100 | 5 W | 125 | 285 | 650 | 0.1 W | 2.6 | 5.8 | 13 | 0.3 | 0.06 | 0.005 |
| Straight [3] (0.7-cm Cu target) | N/A | | | | 5 W | 500 | 285 | 2850 | N/A | | | | | | |
| | | | | | | | | | | | | Skyshine Total Dose | 9.3 | 3.4 | 0.3 |
| Dose Limit | | 100 mrem / 1000 h | 800 mrem / 2000 h | 3000 mrem / 2000 h | | 1200 mrem/h | 1200 mrem/h | 3000 mrem/h | | | | | 10 mrem / 2000h | 5 mrem / 7200 h | 1 mrem / 7200 h |

1) The shielding to achieve these dose rates are shown in Table 2a. Bolded values are the cases that require shielding.
2) The number is the annual electron normal loss at each location, given by SSRL.
3) Straight sections include bare straights and the gaps between any two thick components (like dipoles and quads).

Table 3. Dose rates from abnormal beam losses at a thin target in SPEAR3 ring.

| Dose Location | Beam Loss Location | Maximum Dose Rate (mrem/h at 5 W) | Shielding to Meet the Limit |
|---|---|---|---|
| Lateral Wall | Frontend | 1080 | None |
| Roof | Frontend | 5550 | (Note 1) |
| Ratchet Wall | Ring Chamber<br>(Note 2) | 900 for 2’ ratchet wall<br>1100 for 3’ ratchet wall | 1” Pb wall<br>None |
| | Frontend<br>(Note 3) | 1800 for 2’ ratchet wall<br>1800 for 3’ ratchet wall | 1” Pb wall<br>None |

1) Higher than the limit of 3000 mrem/h was granted because the mis-steered injection beam losses in a frontend are not likely. In addition, the roof is fenced off and the credit of interlocked radiation detectors was taken.
2) The safety factor of 3 was not applied to the FLUKA-calculated doses outside ratchet wall from beam losses in ring chamber, due to the credit of self-shielding from ring components was not considered in ray trace study.
3) Higher than the limit of 1200 mrem/h was granted because the mis-steered injection beam losses in a frontend are not likely. In addition, the credit of interlocked radiation detectors was taken.

Table 4. Dose rates outside 2' ratchet wall with 1" lead on the wall [6]

| Dose Point | Source Point | Scatter Angle (degrees) | Normalized Dose (mrem/h*W) |
|---|---|---|---|
| OF median plane | ID | 5 | 70 |
| OF over shadow wall | ID | 5 | 70 |
| OG median plane | SL | 57 | 0.5 |
| OG over shadow wall | ID | 2 | 55 |
| OH median plane | SL | 54 | 14 |
| OH above shadow wall | ID | 2 | 55 |
| OI median plane | SL | 49 | 5 |
| OI above shadow wall | ID | 2 | 55 |
| OJ median plane | SL | 36 | 20 |
| OJ above shadow wall | SE | 6 | 140 |
| OF median plane | SA | 6 | 80 |
| OF over shadow wall | SA | 6 | 80 |
| OG median plane | SL | 57 | 0.5 |
| OG over shadow wall | SA | 2 | 80 |
| OH median plane | SA | <2 | 34 |
| OH above shadow wall | SB | 6 | 90 |
| OI median plane | SK | 35 | 14 |
| OI above shadow wall | SB | 4.5 | 100 |
| OJ median plane | SK | 25 | 30 |
| OJ above shadow wall | SH | 7.5 | 180 |

1) Source points ID, SL and SE are normal loss points and the NDL is 50 mrem/h/W.
2) Other source points are mis-steered loss points and the NDL is 240 mrem/h/W.

Table 5. Shielding for concrete ratchet wall from beam losses in ring chamber [6,13].

| | |
|---|---|
| Lead on Wall | No lead on 3'-thick ratchet wall. 1"-thick Pb on 2'-thick ratchet wall. |
| Collimator | 6"Pb+6"PE thick, 12" tall, 12" wide to cover the hole in ratchet wall |
| Shadow Walls | 6"Pb+6"PE thick, 12" tall, widths and locations to cover the hole for all rays. |
| Hole Shielding | 12"Pb+6"PE around the beampipe in the ratchet wall. |

Table 6. SR beam parameters for eleven SPEAR3 main beamlines, as of January 2004 [1].

| Beamline Number | # of Poles [2] | B (T) [2] | Ec (keV) [3] | SR Power (W/mradH) [4] | Fan Width (mradH) [4] |
|---|---|---|---|---|---|
| Bend 1, 2, 3, 8 | 1 | 1.29 | 7.8 | 74 | 19.3 |
| 4 | 20 | 0.71 | 4.3 | 809 | 5.2 |
| 5 | 20 | 0.53 | 3.2 | 604 | 3.1 |
| 6 | 55 | 1.05 | 6.3 | 3388 | 2.5 |
| 7 | 20 | 0.71 | 4.3 | 809 | 5.2 |
| 9 | 16 | 2.04 | 12.2 | 1881 | 14.2 |
| 10 | 32 | 1.45 | 8.7 | 2673 | 6.6 |
| 11 | 26 | 2.02 | 12.2 | 3029 | 8.9 |

1) Stored electron beam parameters: 3 GeV and 500 mA.
2) Effective number of poles with a magnetic field of B.
3) Critical energy Ec.
4) SR power per horizontal fan width and the horizontal fan width from the source. The actual fan width into a beamline depends on apertures.

Table 7. Two groups of light energy and intensity from double monos for SSRL beamlines.

| Reflection Index | Energy (keV) | Photon Intensity (photons/sec) (500 mA, 1 mradH, 1 pole) | | Mirror Reflectivity, R |
|---|---|---|---|---|
| | | B = 2 T | B = 1 T | |
| Si(111) | 22.7 | 1.61E12 | 3.06E11 | 8.4E-1 |
| Si(333) | 68.1 | 3.60E9 | 1.70E7 | 7.4E-4 |
| Si(444) | 90.8 | 3.74E8 | 2.59E5 | 1.4E-4 |
| Si(555) | 113.4 | 2.09E7 | 2.02E3 | 3.3E-5 |
| Si(777) | 158.8 | 1.62E5 | 2.75E-1 | 1.8E-6 |
| Si(220) | 37.1 | 2.50E11 | 1.48E10 | 1.9E-2 |
| Si(440) | 74.1 | 2.51E9 | 7.18E6 | 4.7E-4 |
| Si(660) | 111.1 | 3.83E7 | 4.53E3 | 3.8E-5 |
| Si(880) | 148.2 | 6.96E5 | 3.07E0 | 3.7E-6 |

1) FLUKA mono dose results are presented for intensity at 500-mA, 1 mradH, 1 pole, 2-T magnetic field, and without mirror reflectivity.

Table 8. Longitudinal thickness, lateral extension, and overlap requirements for safety components (collimators, hutch stoppers, and beamstops) in a SPEAR3 ID [1].

| GB Type [2] | PGB | SGB |
|---|---|---|
| Longitudinal Thickness, t [3] | 10” Pb | 9” Pb |
| Lateral Extension, L [4] | 2” Pb | 1” Pb |
| Overlap, O [5] | 1/4” Pb | |

1) Ray trace study using Physical Envelope is used to define these requirements. The air length (vacuum pressure of 1 ntorr) is 6-m for an ID straight and 15-cm for a bend.
2) See text for definitions for PGB and SGB.
3) The minimum distance between safety component and the end of straight section is 10 m. For Hevimet, t is 7” for ID and 5.5” for bend. For bend beamlines, t is 8” Pb for PGB and 7” Pb for SGB.
4) For bend beamlines, L is 1” Pb for PGB and 0.5” Pb for SGB.
5) Overlap requirement between two near-by safety components applies to all cases.

Table 9. SPEAR3 beamline design for synchrotron radiation hazards.

| SR Type | White | Mirror (23 keV & 1.5 keV) | | Mono, Si(111) & Si(220) | |
|---|---|---|---|---|---|
| | | Pink | Compton | Unfiltered | Filtered |
| Hutch | Optical/Exp. | Optical/Experimental | | Experimental | |
| Target | Cu Disc | 2 Mirrors | 2 Mirrors | $0.16^{o}$ Si | $0.16^{o}$ Si |
| Key Parameters | Critical Energy, Pole Number, Fan Width | Reflectivity | Linear Half Angles | B Field | B Field, Reflectivity |
| Data | Ref 27 | Ref 28 | | Ref 29 | |

1) Maximum magnetic field and maximum number of poles for an ID should be used.
2) If mirrors can be removed, the unfiltered beam mode is used.
3) A shielding credit of ¼” Fe for the tanks of mirrors and monochromators in optical hutches can be considered.
4) For experimental hutches, the target (simulated as an optimum $0.16^{o}$-inclined Si disc) is at 100 cm from the downstream wall or 30 cm from the upstream wall.
5) In experimental hutches, additional shielding of two TVL is needed for the area of downstream wall that can be illuminated by the SR beam when samples are not in a place.
6) The SR polarization effect is not considered.
7) Triple (or more) Compton scattering lights are not considered.

## Captions of Figures

Figure 1. The SSRL layout, showing the injector (150-MeV Linac and 3-GeV Booster ring), the BTS (Booster-to-SPEAR) transport line, the 234-m-circumference, 3-GeV SPEAR3 ring and current synchrotron radiation beamlines. The red dashed line is the boundary of the SSRL buildings around the outer rim of the ring and the 2nd floor areas.

Figure 2. A standard cell in an arc section of the SPEAR3 ring, showing one QFC between two C-shaped gradient dipoles (opening toward the outer lateral wall).

Figure 3. A typical in-alcove layout for a SSRL synchrotron radiation beamline, showing five radiation safety items (movable mask, collimator, 2 injection stoppers, lead/polyethylene shadow walls, and lead/polyethylene shielding in the hole of the ratchet wall), in addition to the 2'-thick lateral wall and ratchet wall (2' or 3').

Figure 4. SPEAR3 ring active BCS devices (three ACMs in BTS line; DCCT/BPM; one LION in each quadrant; BSOICs not shown) and PPS devices (ejection septum, ST1 and ST2 in the BTS line; RF, ST1 and ST2 in ring; movable mask and two injection stoppers in each frontend; two hutch shutters for each x-ray beamlines).

Figure 5. SPEAR3 limiting physical apertures (8 QFCs, 7 insertion devices, 7 SR masks near West Pit, 3 kickers K1-K3, injection septum, and stored beam abort dump) in which normal beam losses occur and local shielding are needed.

Figure 6. SPEAR3 ring annual normal beam loss analysis. The injection beam is 3-GeV, 4 W at 10 Hz and the Allowed Injection Beam Power is 5 W. When averaged over 7200 h/y, the loss of both injection and stored beams is equivalent to an average power loss of 2 mW at each aperture, except stored beam abort dump (24 mW) and injection septum (8 mW). During the 6-min injection period, an instantaneous power loss of 0.05 W occurs at each aperture, except the septum (which has 0.5 W).

Figure 7. Example of shielding design and requirements for three types of beam losses (normal annual dose, mis-steered dose rate at 5-W, and dose rate during injection) around the SPEAR3 ring. Injection septum has 4' concrete outer wall, 2' inner wall, and 2' roof. These values correspond to those in Tables 2a and 2b.

Figure 8. The normalized dose equivalent source term profiles for photons (top) and neutrons (bottom) at 1 m between 0 to 100 degrees for three beam-target situations with concrete shield. Error bars are $1\sigma$ of the mean (1 Sv = 100 rem).

Figure 9. The dose equivalent attenuation profiles in concrete at various angles for photons (top) and neutrons (bottom) from 3-GeV beam hitting a thin Cu plate. The 180-cm-thick concrete shield starts at the radius of 600 cm.

Figure 10: Typical SPEAR3 in-alcove geometry featuring 2'-thick ratchet wall ray trace study [6]. The source points are SA to SL, as well as various masks (denoted by red star). The dose points outside ratchet wall are OF to OJ.

Figure 11. Dose rates outside lateral wall and ratchet wall (2'-thick wall with 1" Pb; 3'-thick wall without Pb) from normal beam losses in a low-loss aperture and mis-steered beam losses of 5 W at any point in the ring. 2" Fe local shield is assumed alongside the aperture.

Figure 12. Beam-target-shield geometry used in STAC8 to calculate the shielding needs for scattered SR in a white light hutch. Two types of targets were used: a Si disc (0.2-degree-inclined, d = 2 cm, r = 6 cm) and a perpendicular Cu disc (d = 0.5 cm, r = 0.5 cm). The ambient dose equivalent rates as a function of scattering angle outside the shielding wall for SR beams with various critical energies and power levels (W/mradH) were calculated.

Figure 13. STAC8 dose rate at 1 m outside the lead side wall for five SPEAR3 SR beams hitting the inclined Si target (top) or the perpendicular Cu target (bottom). The dose results are normalized to the SR power per mradH with a single pole.

Figure 14. STAC8 dose profile at 1 m outside lead downstream (back) wall for BL11 beam (12.2 keV, single pole, 112 W/mradH) hitting the perpendicular Cu target.

Figure 15. Diagram of the scattered SR dose calculations for either the pink or Compton light hitting a target. The white light hits the mirror at an incident angle of $0.16^{o}$ (relative to mirror surface), generating hard x-ray pink light at a reflection angle of $0.16^{o}$. Meanwhile, the Compton-scattered lights also come out of mirror at all directions and some of them (defined by masks) hit the target in the hutch (called pink hutch). The forward and lateral scattered doses from both the pink and Compton lights hitting an optimum target (a $0.16^{o}$-inclined mirror) are then calculated.

Figure 16. The STAC8-calculated dose rates at 1 m outside the lead side wall. The hard x-ray pink light (from 6 white light sources hitting the mirror) hits an inclined Si disc target and the scattered photons pass through the lead wall. Linear scaling with the fan width (mradH) of the white light hitting the mirror and the inverse square scaling with the distance from target to hutch wall are needed.

Figure 17. The STAC8-calculated dose rates at 1 m outside the lead side wall. The Compton light (from 6 white light sources hitting the mirror) hits an inclined Si disc target and the scattered photons pass through the lead wall. Linear scaling with the fan width (mradH) of the white light hitting the mirror, the inverse square scaling with the distance from target to hutch wall, and the scaling with the square of the linear half-angle (defined by apertures via ray trace) are needed.

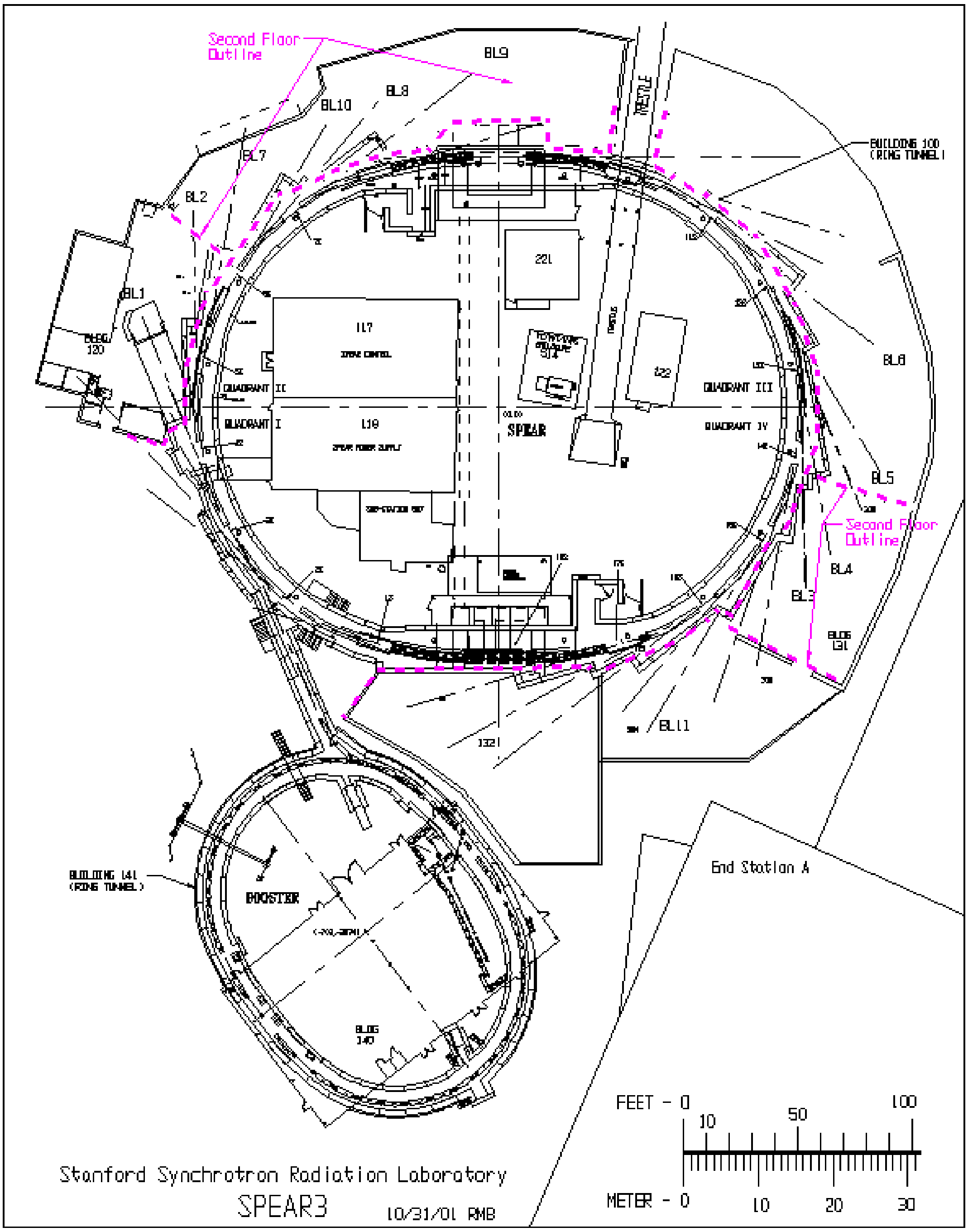
Figure 18. The FLUKA-calculated dose rates at 1 m outside the iron side wall for all lines of the unfiltered mono light series Si(220) hitting a $0.16^{o}$-inclined Si disc. The dose is normalized to the photon intensity shown in Table 2 (500-mA, 1 mradH, 1 pole, 2-T field). For filtered mono light, the mirror reflectivity can be applied.

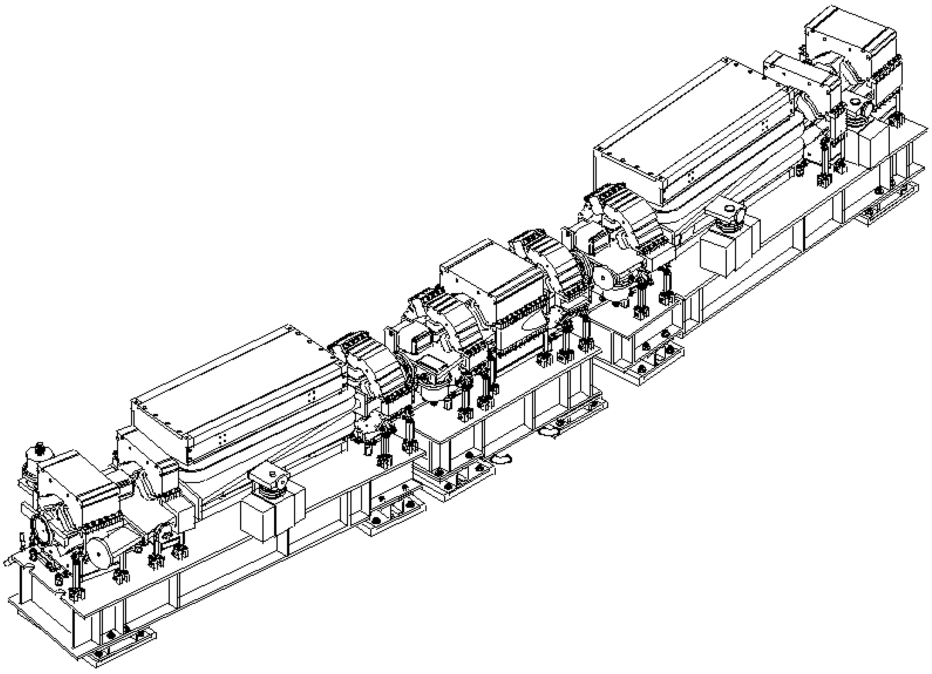
Figure 19. A diagram illustrating the Physical Envelope of the gas bremsstrahlung ray trace to determine the requirements for safety components (collimators, 2 hutch shutters, beamstops) in terms of longitudinal thickness t and lateral extension L. Physical Envelope is defined by the ring chamber aperture and the 6”-Pb collimator (or 15” Cu fixed mask). Overlap between collimators and hutch shutters is also shown. The primary GB becomes secondary GB, after passing through a minimum of 4-rl-long material, e.g., a mirror. This affects the optical component shielding.

Figure 20. Total and photon dose rates at 30-cm and 100-cm lateral from the GB beam axis for 1”-Pb lateral extension of a safety components hit by 0.038-mW of primary GB from an SPAER3 ID.

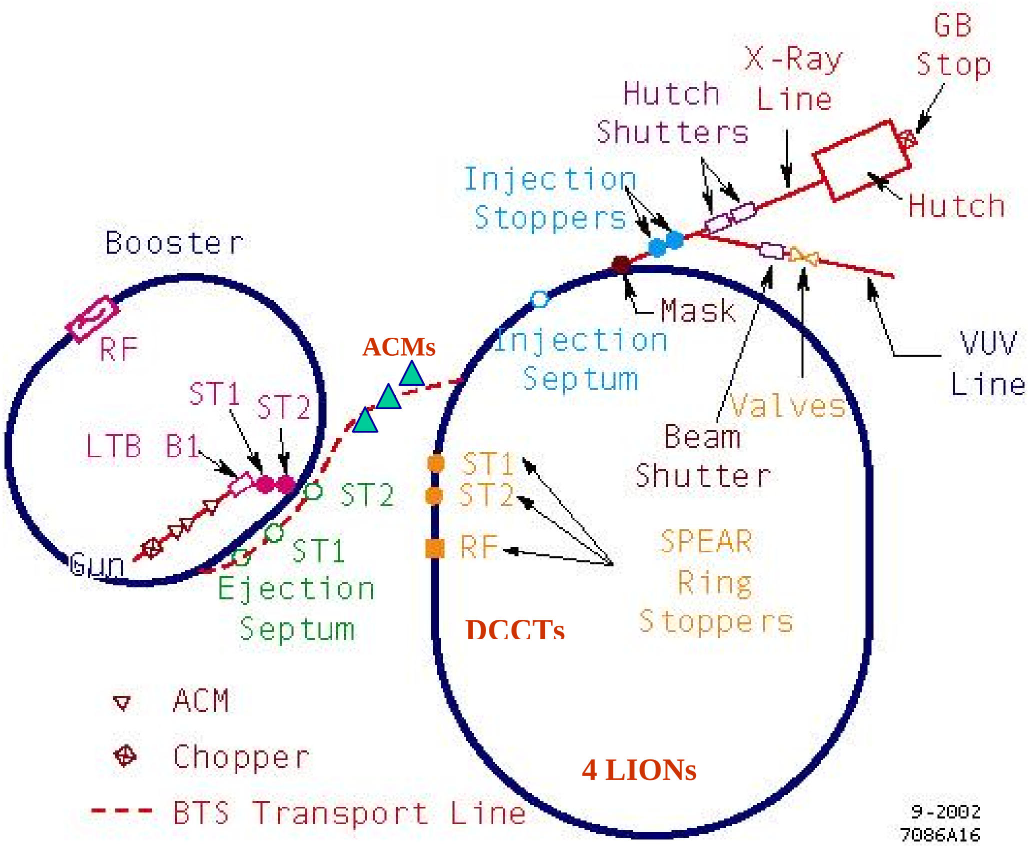
Figure 21. Comparison of photon source terms (mrem/h at 1 m) without shield as a function of angle for three types of targets hit by 0.038-mW of primary GB.

Figure 22. Photon dose equivalent rate at 1 m as a function of angle for six lead shield thicknesses (0” to 5”), from 0.038-mW of GB hitting an inclined Si target.

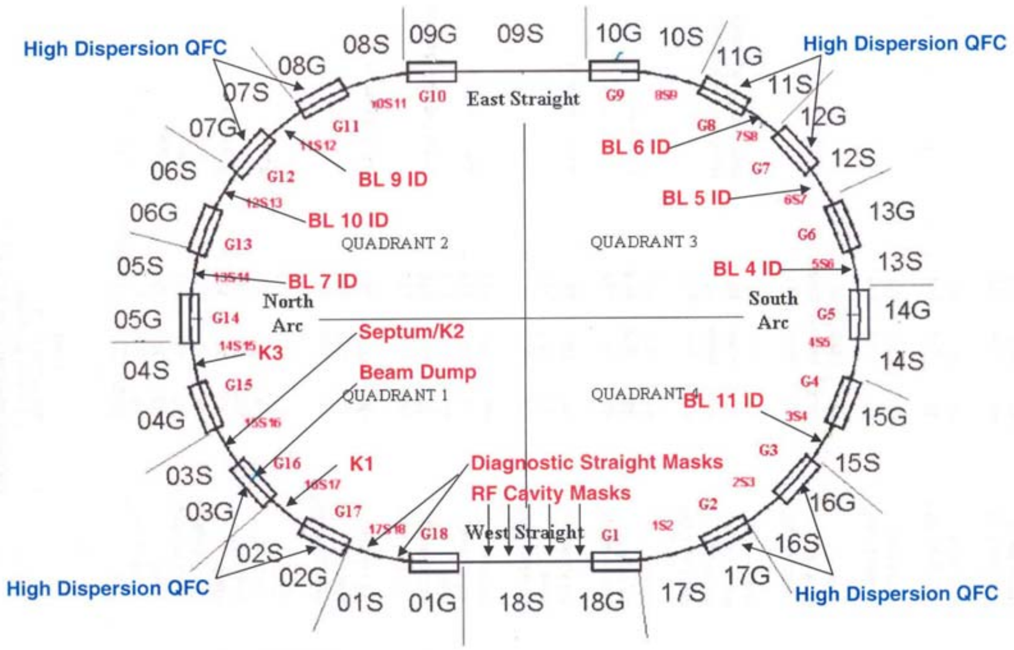

Second Floor Outline
BL9
BL8
BL10
BL7
BL2
BL1
BLDG 120
TRESTLE
BUILDING 100 (RING TUNNEL)
221
117
118
SPEAR
122
QUADRANT II
QUADRANT I
QUADRANT III
QUADRANT IV
BL6
BL5
Second Floor Outline
BL4
BL3
BLDG 131
BL11
132
BUILDING 141 (RING TUNNEL)
BOOSTER
BLDG 140
End Station A
FEET - 0
10
50
100
METER - 0
10
20
30
Stanford Synchrotron Radiation Laboratory
SPEAR3
10/31/01 RMB




DOOR CLOSE
DOOR OPENING
CABLE TRAY
PENETRATION

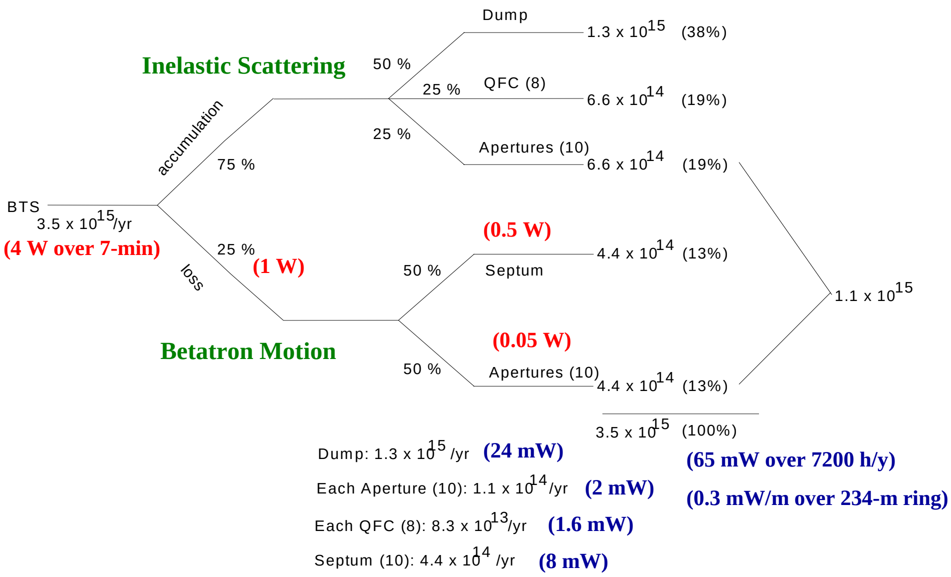


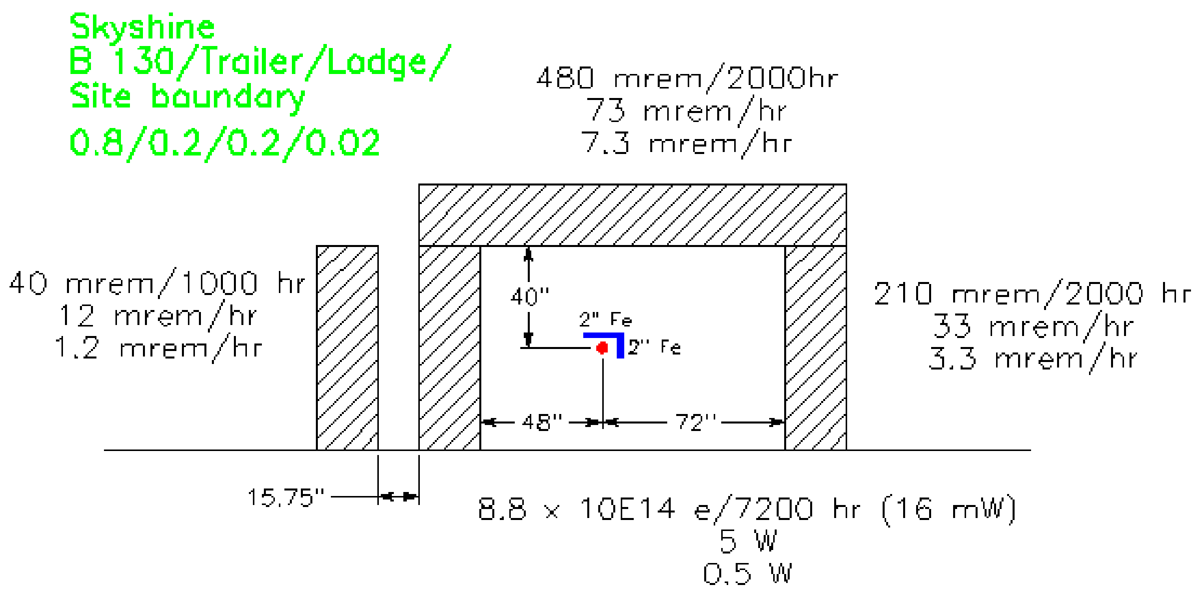
GB
Stop
X-Ray
Line
Hutch
Shutters
Injection
Stoppers
Hutch
Booster
RF
Mask
ACMs
Injection
Septum
VUV
Line
ST1
ST2
Valves
LTB B1
Beam
Shutter
ST2
ST1
ST2
RF
SPEAR
Ring
Stoppers
Gun
ST1
Ejection
Septum
DCCTs
ACM
Chopper
4 LIONs
BTS Transport Line
9-2002
7086A16




black = SPEAR 3 sector numbering
red = SPEAR 2 sector numbering
**RED BOLD: Limiting Aperture**
**BLUE BOLD: High non-linear dispersion QFC Location**

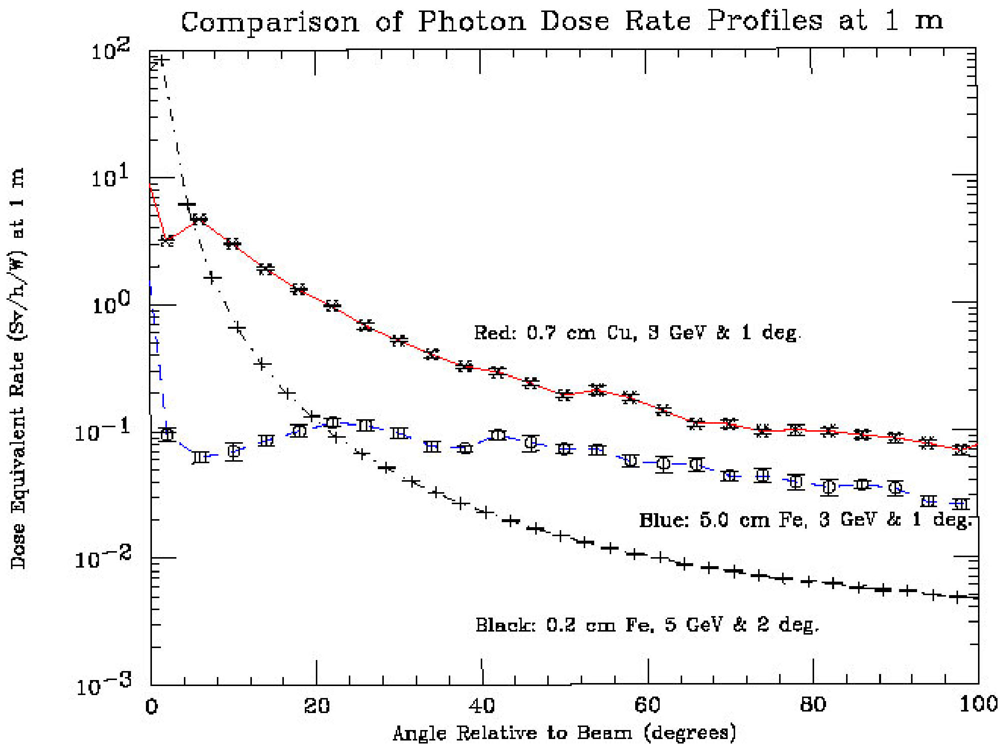
# SPEAR Annual Normal Beam Loss Channels

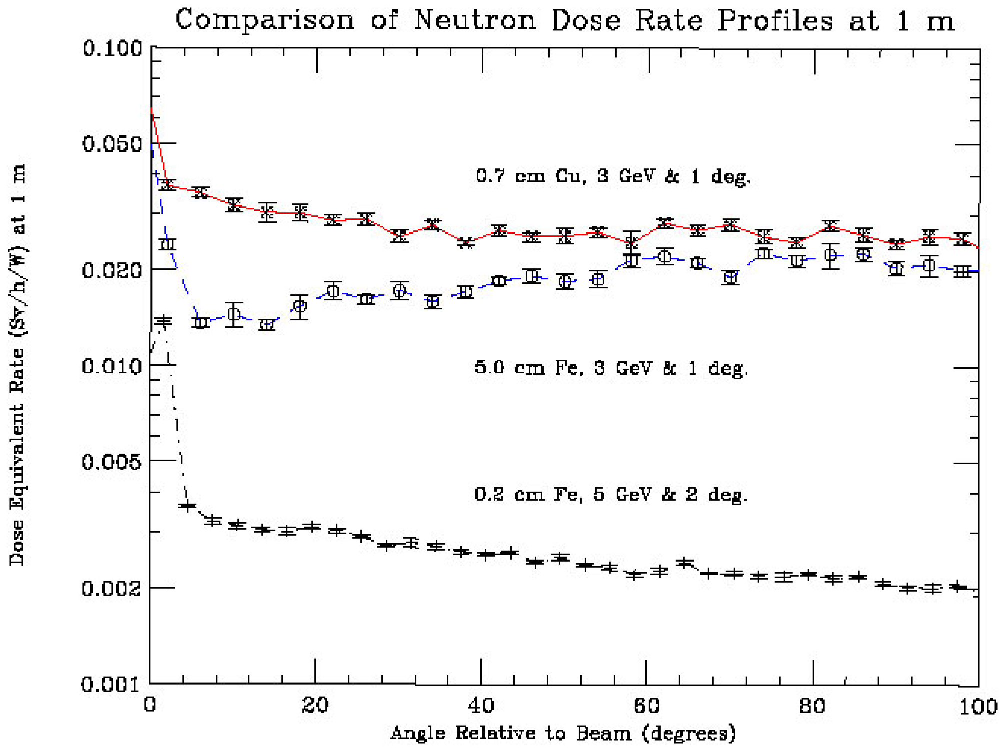


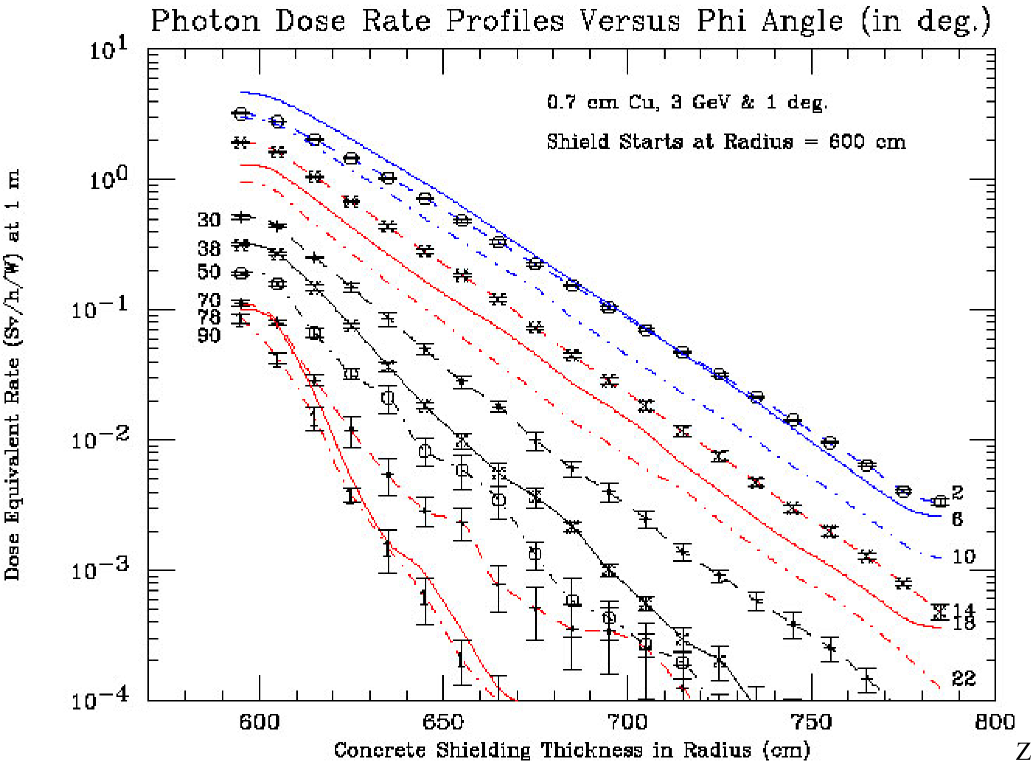



# Septum

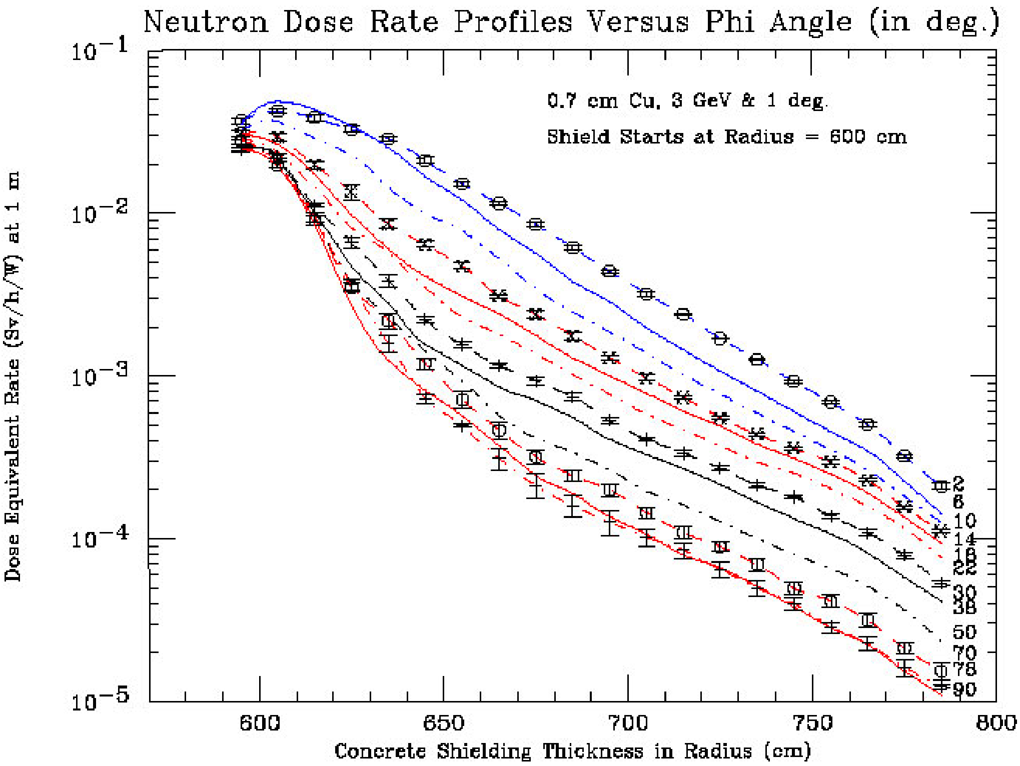
Target 2" x 12" Fe

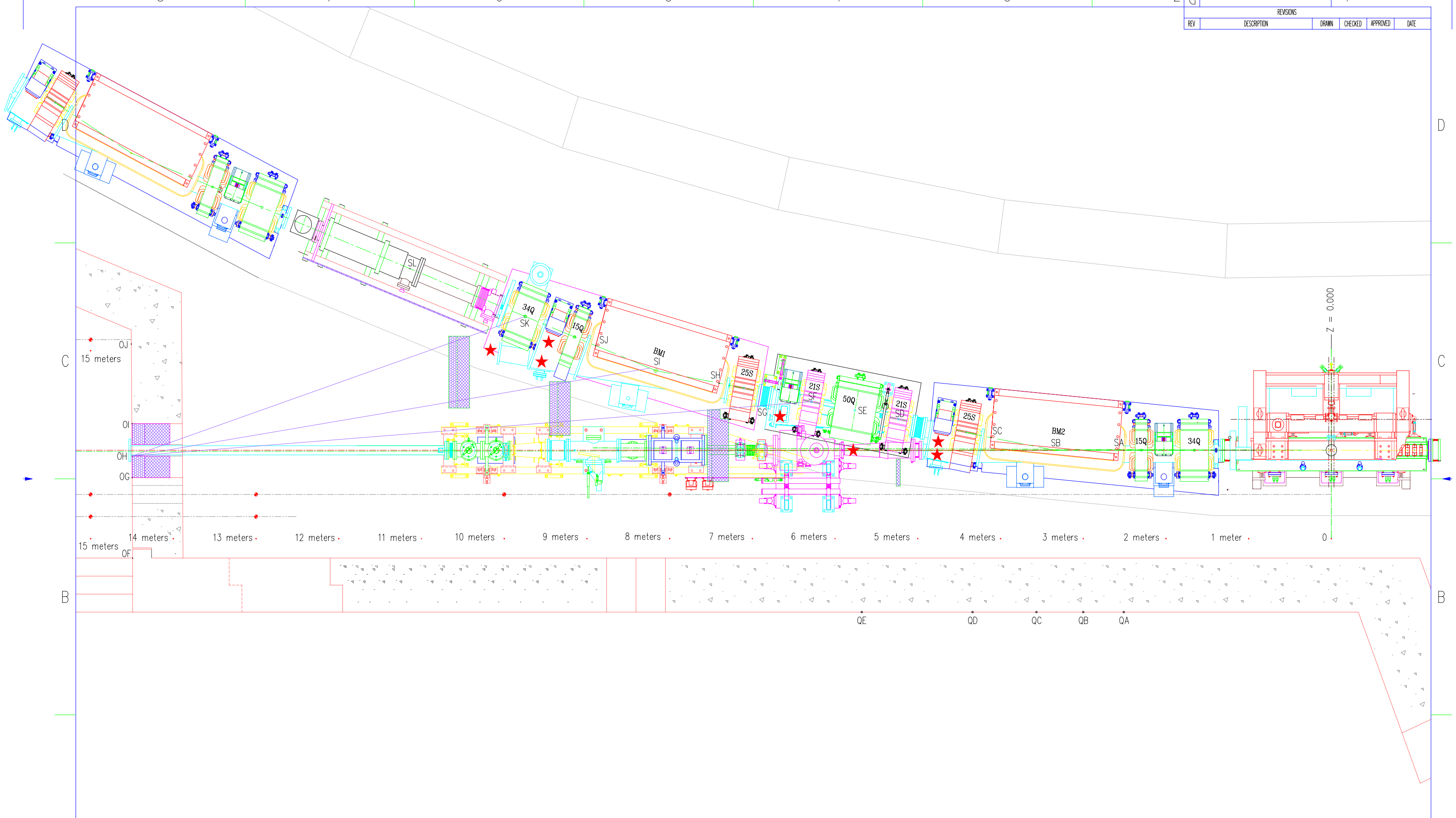

Comparison of Photon Dose Rate Profiles at 1 m
Dose Equivalent Rate (Sv/h/W) at 1 m
Angle Relative to Beam (degrees)
Red: 0.7 cm Cu, 3 GeV & 1 deg.
Blue: 5.0 cm Fe, 3 GeV & 1 deg.
Black: 0.2 cm Fe, 5 GeV & 2 deg.


Comparison of Neutron Dose Rate Profiles at 1 m
Dose Equivalent Rate (Sv/h/W) at 1 m
Angle Relative to Beam (degrees)
0.7 cm Cu, 3 GeV & 1 deg.
5.0 cm Fe, 3 GeV & 1 deg.
0.2 cm Fe, 5 GeV & 2 deg.


Photon Dose Rate Profiles Versus Phi Angle (in deg.)
0.7 cm Cu, 3 GeV & 1 deg.
Shield Starts at Radius = 600 cm
Dose Equivalent Rate (Sv/h/W) at 1 m
Concrete Shielding Thickness in Radius (cm)
30
38
50
70
78
90
2
6
10
14
18
22

Z


Neutron Dose Rate Profiles Versus Phi Angle (in deg.)
0.7 cm Cu, 3 GeV & 1 deg.
Shield Starts at Radius = 600 cm
Dose Equivalent Rate (Sv/h/W) at 1 m
Concrete Shielding Thickness in Radius (cm)
2
6
10
14
18
22
30
38
50
70
78
90




| REVISIONS | | | | | |
|---|---|---|---|---|---|
| REV | DESCRIPTION | DRAWN | CHECKED | APPROVED | DATE |

STANFORD SYNCHROTRON RADIATION LABORATORY



SLAC STANFORD UNIVERSITY STANFORD, CALIFORNIA

FILE NAME: 2 foot ratchet wall.dwg

SSRL
ALCOVE SHIELDING
2 FOOT RATCHET WALL
TYPICAL BEAM LINE LAYOUT

UNLESS OTHERWISE NOTED
DIMENSIONS IN: INCHES
TOLERANCES:
.XXX ±.005
.XX ±.01
.X ±.02
ANGLES ± 0.5
ALL SURFACES: 63

DO NOT SCALE DRAWING

DATE: 9-5-02
ENGR. T. RABEDEAU
DRFTS. WILLA LI
CHKD. T. RABEDEAU

APPROVALS:

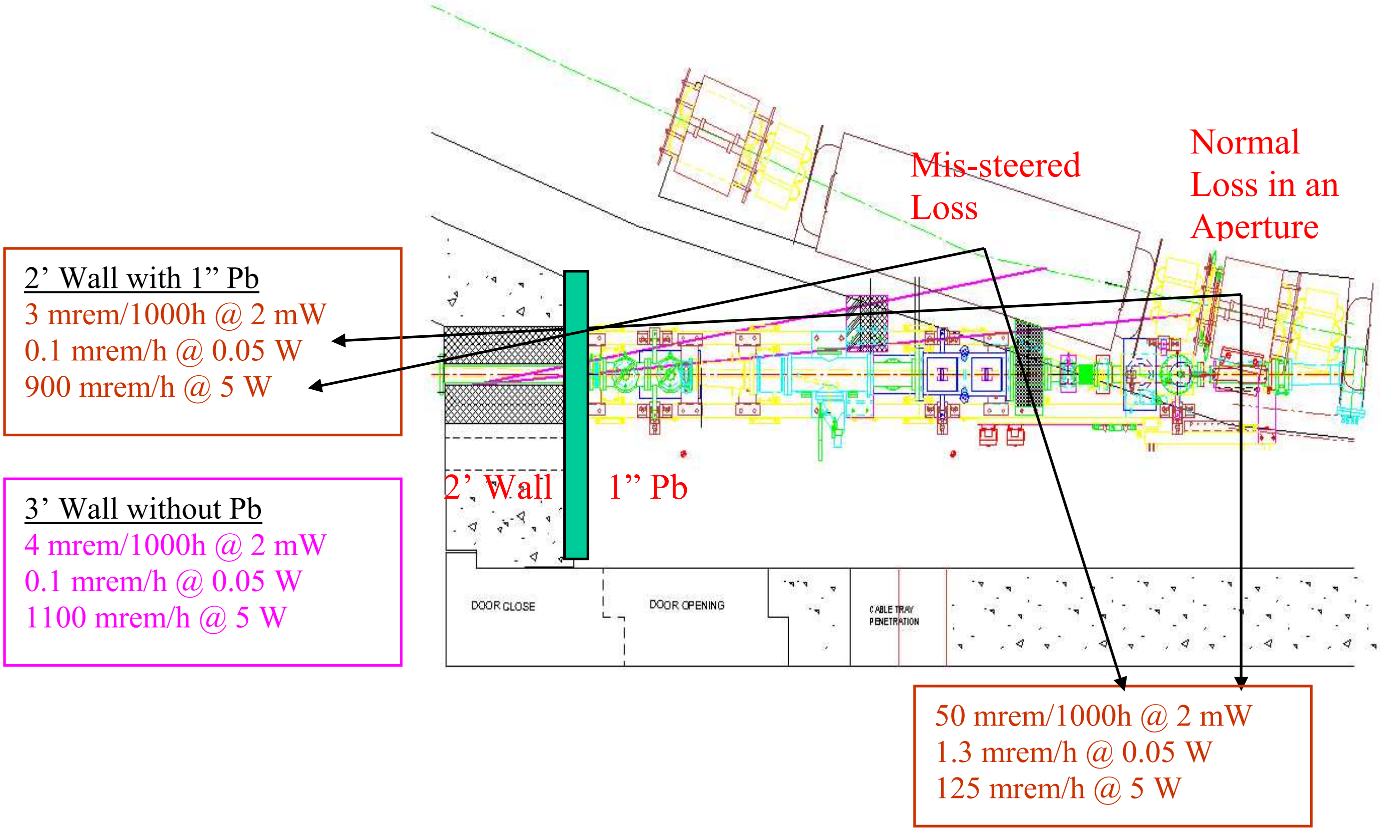
CODE: SCALE: SHEET 1 OF 1

CO D

NEXT ASSEMBLIES:

M/F SSRL 2 FOOT RATCHET WALL

## Dose Rates Around SPEAR3 Ring (2” Fe for an Aperture)



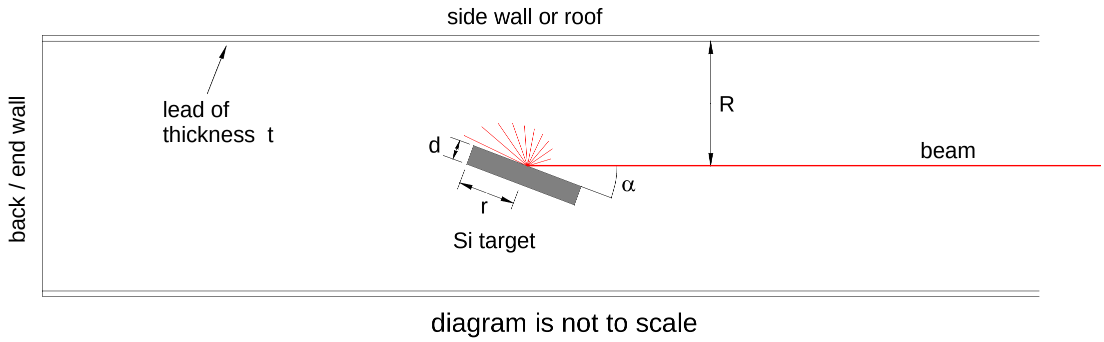
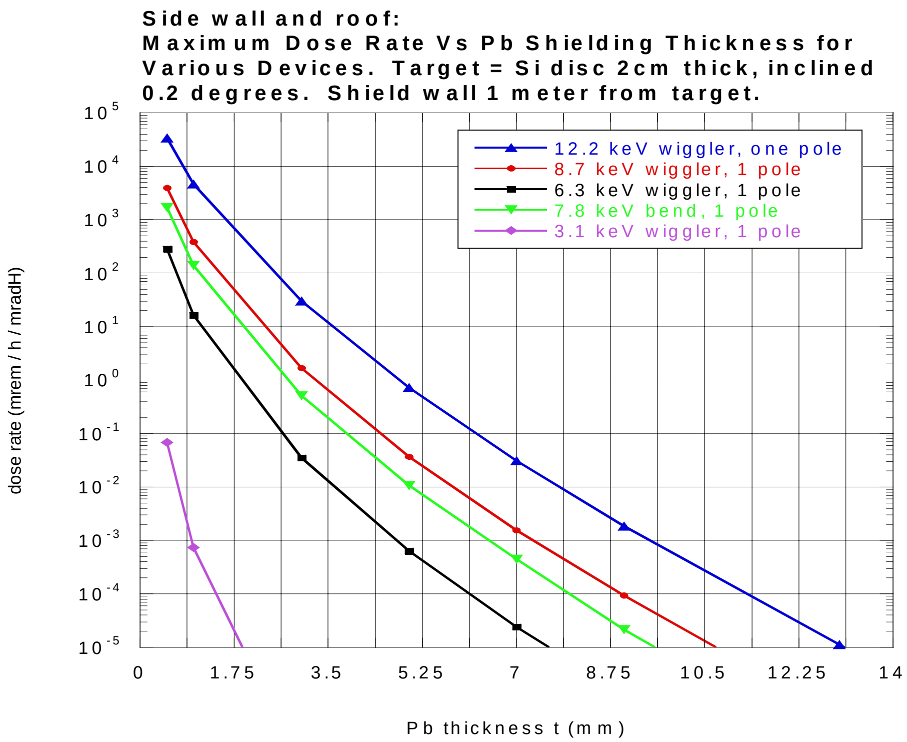
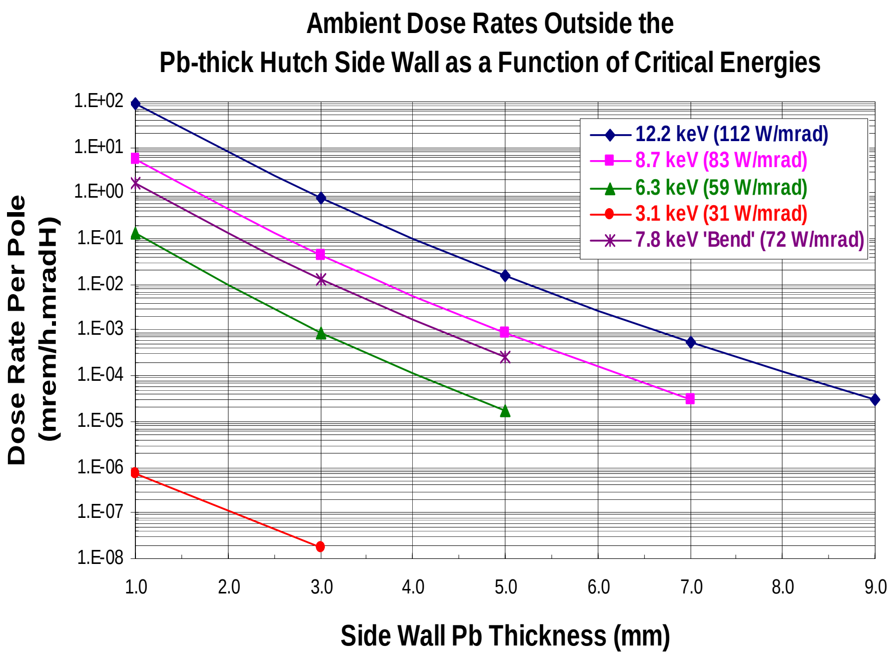



Figure 1. The beam-target-shield geometry used to calculate the shielding needs for the white light hutch. The analytic STAC8 code was used, while the FLUKA Monte Carlo code was used to benchmark STAC8 result in some cases. The effect of SR polarization was not considered and, thus, the side wall and roof can be treated the same. Two types of targets were used: an inclined Si cylinder ($\alpha$ from $0.2^o$ to $90^o$, d = 2 cm, r = 6 cm) and a perpendicular Cu cylinder ($\alpha=90^o$; d = 0.5 cm, r = 0.5 cm). The results for both targets are presented for side wall, while only the Cu target results are presented for the downstream (or back/end) wall. The distance R between target (where beam hits) and shield wall (either side or back) was 1 m. The build-up factor in lead was considered. The ambient dose rates as a function of scattering angle $\theta$ (relative to beam direction) outside the shielding wall were calculated for SR beams with various critical energies and power levels (W/mradH) and for various thickness t of lead shielding.


Side wall and roof:
Maximum Dose Rate Vs Pb Shielding Thickness for Various Devices. Target = Si disc 2cm thick, inclined 0.2 degrees. Shield wall 1 meter from target.
12.2 keV wiggler, one pole
8.7 keV wiggler, 1 pole
6.3 keV wiggler, 1 pole
7.8 keV bend, 1 pole
3.1 keV wiggler, 1 pole
dose rate (mrem / h / mradH)
Pb thickness t (mm)
0
1.75
3.5
5.25
7
8.75
10.5
12.25
14


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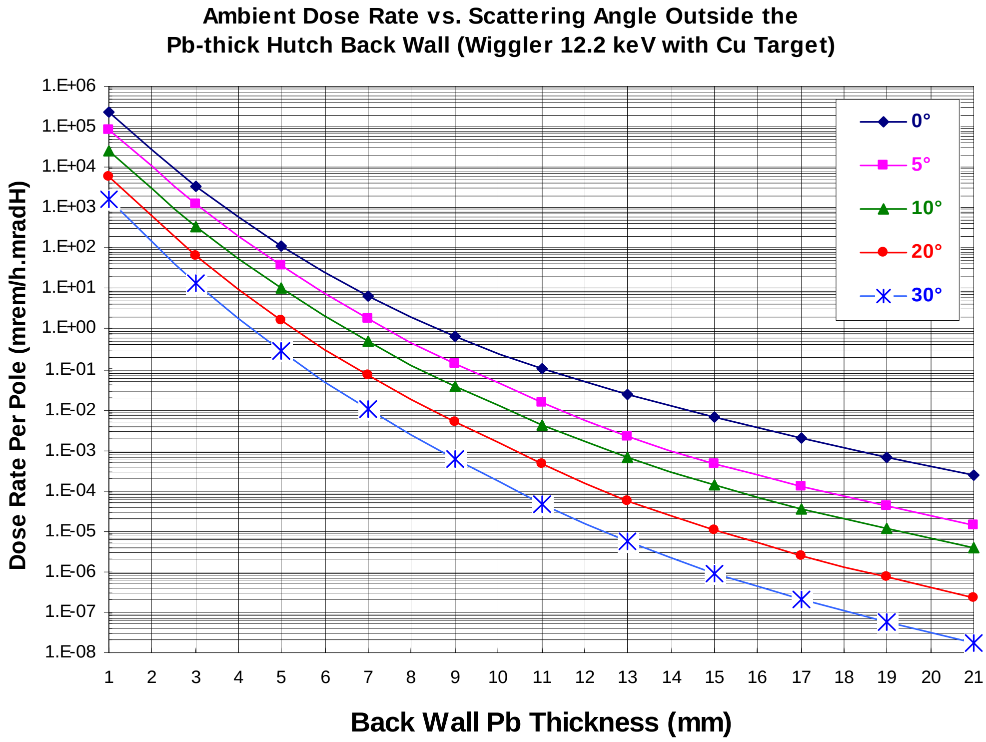
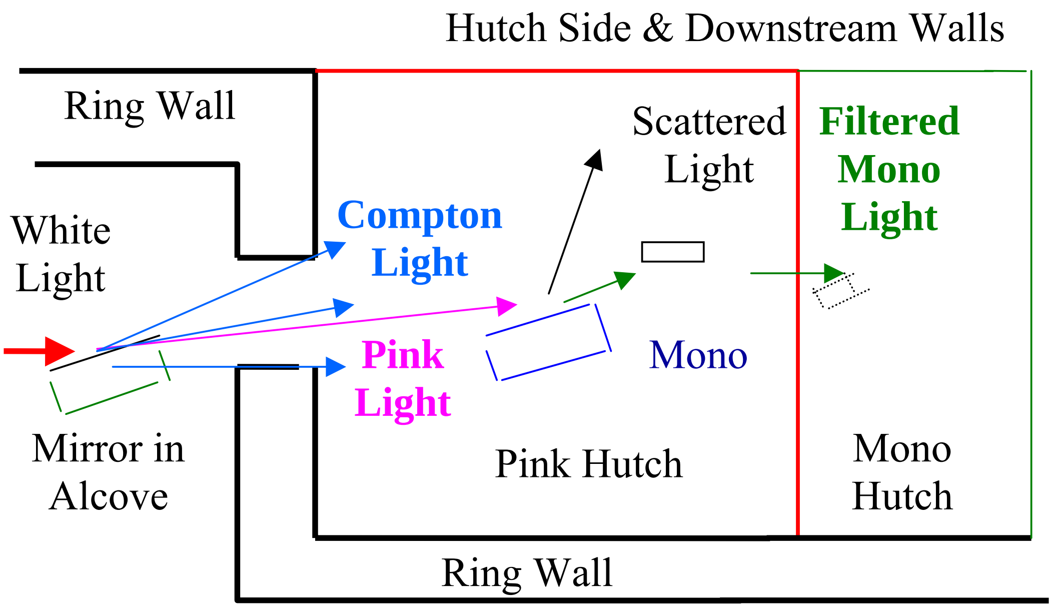
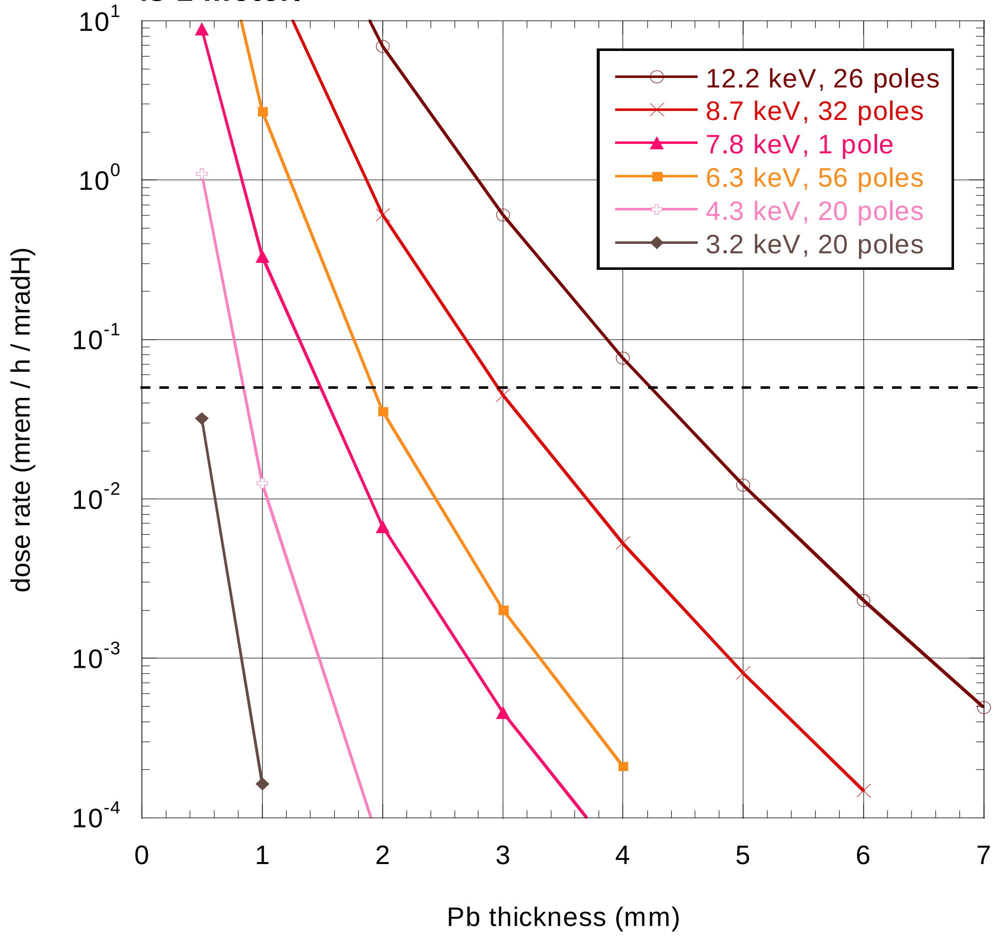
7.0
8.0
9.0

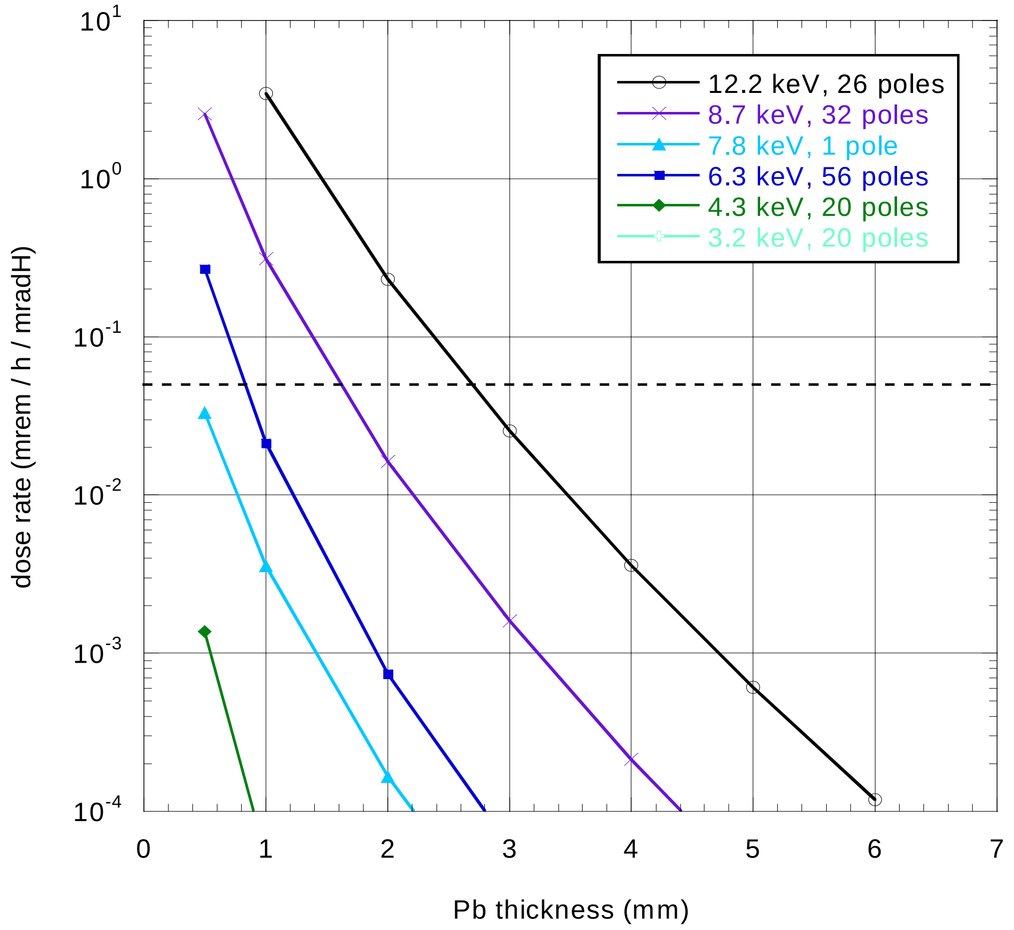

Ambient Dose Rate vs. Scattering Angle Outside the
Pb-thick Hutch Back Wall (Wiggler 12.2 keV with Cu Target)
Dose Rate Per Pole (mrem/h.mradH)
Back Wall Pb Thickness (mm)
1.E+06
1.E+05
1.E+04
1.E+03
1.E+02
1.E+01
1.E+00
1.E-01
1.E-02
1.E-03
1.E-04
1.E-05
1.E-06
1.E-07
1.E-08
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21
0°
5°
10°
20°
30°

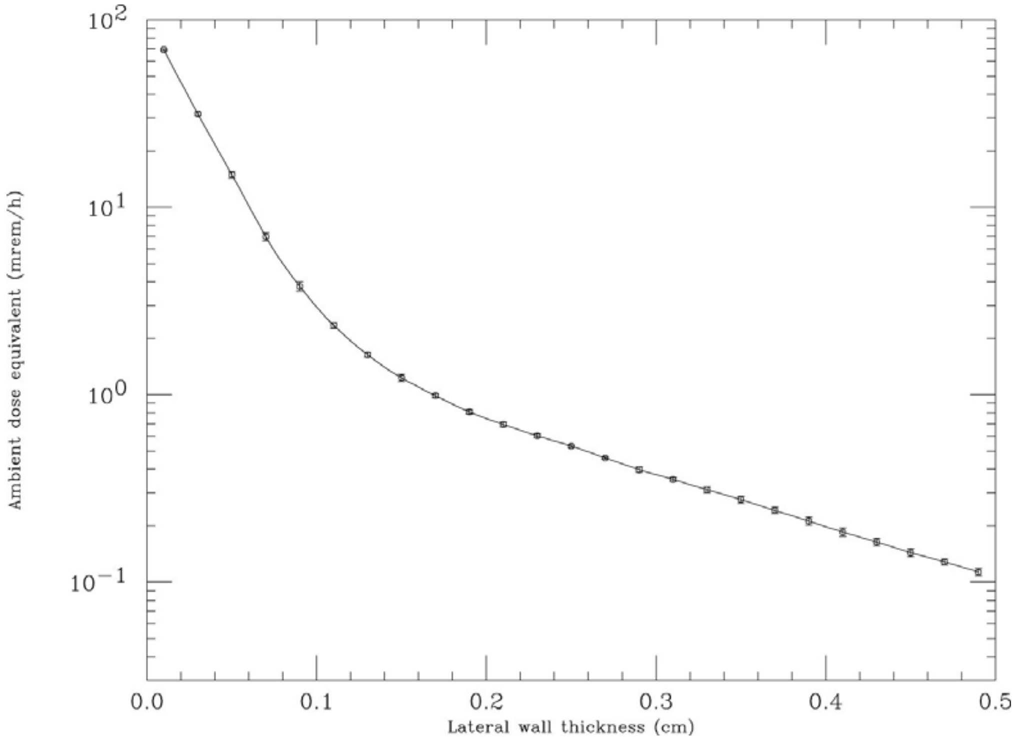

Hutch Side & Downstream Walls
Ring Wall
Scattered Light
Filtered Mono Light
White Light
Compton Light
Pink Light
Mono
Mirror in Alcove
Pink Hutch
Mono Hutch
Ring Wall

**Dose rate vs Pb thickness outside side wall, from pink light, for various values of Ec and Npoles. Targets: Pt-coated mirror followed by 2-cm thick Si disk of 40-cm radius. Incidence angles = 0.155 degrees. Distance from second target to side wall is 1 meter.**

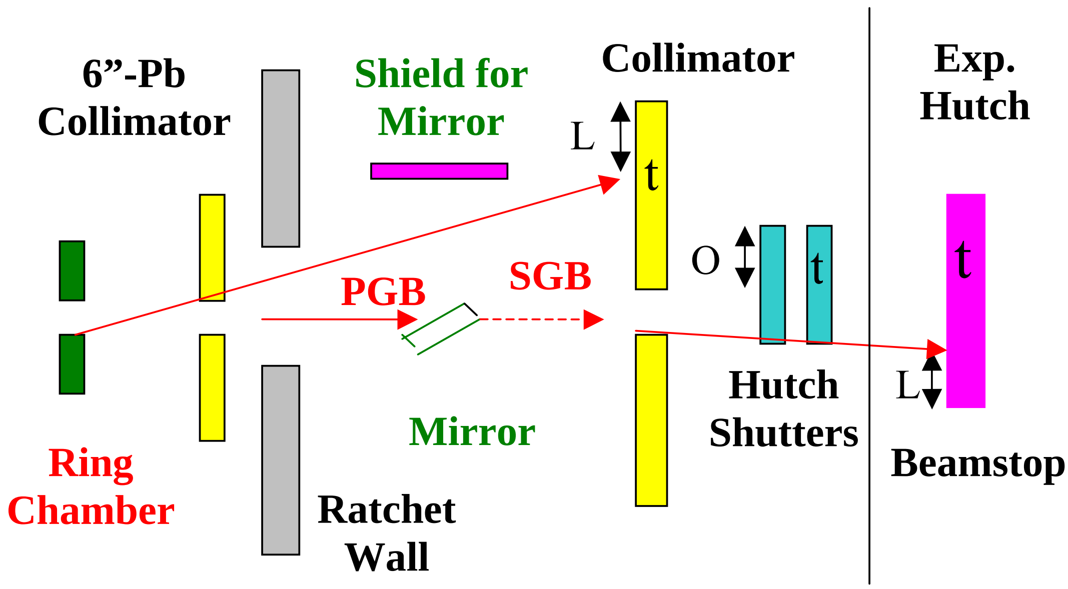


**Dose rate vs Pb thickness outside side wall, from double compton scattering, for various values of Ec and Npoles. Targets are 2-cm thick Si disks of 40-cm radius, one meter apart. Incidence angles = 0.155 degrees. Beampipe aperture is 1 mrad. Distance from second target to side wall is 1 meter.**

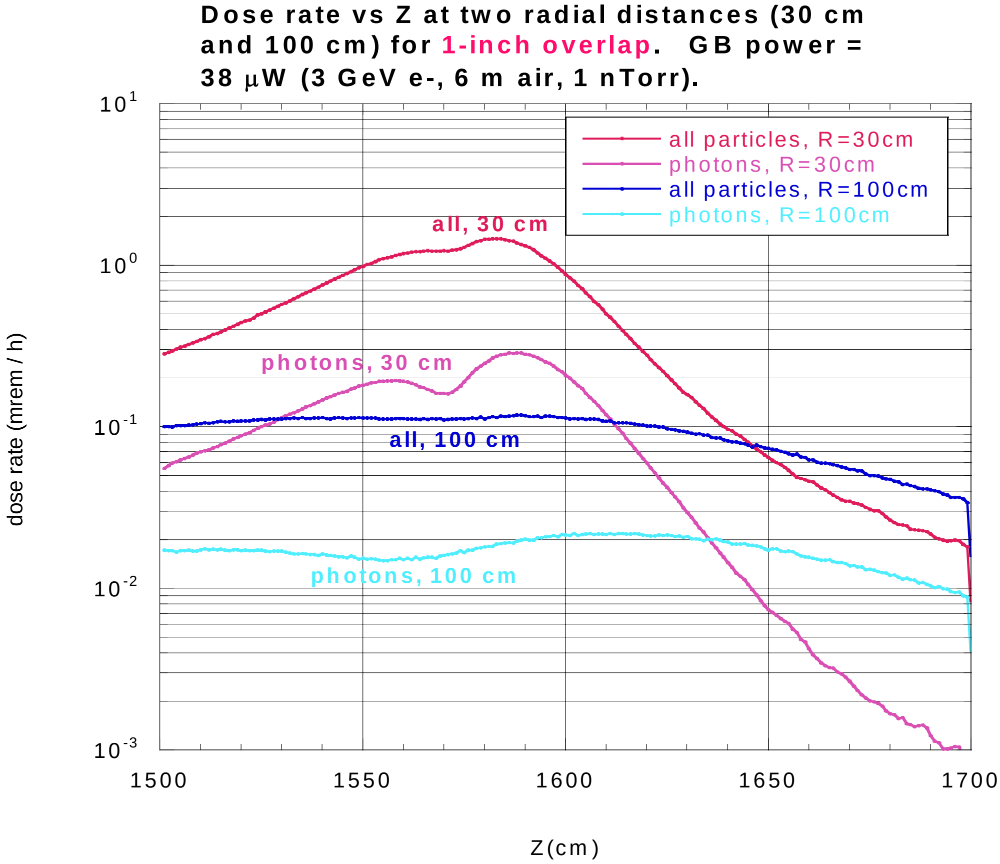




$10^2$
$10^1$
$10^0$
$10^{-1}$
Ambient dose equivalent (mrem/h)
0.0
0.1
0.2
0.3
0.4
0.5
Lateral wall thickness (cm)

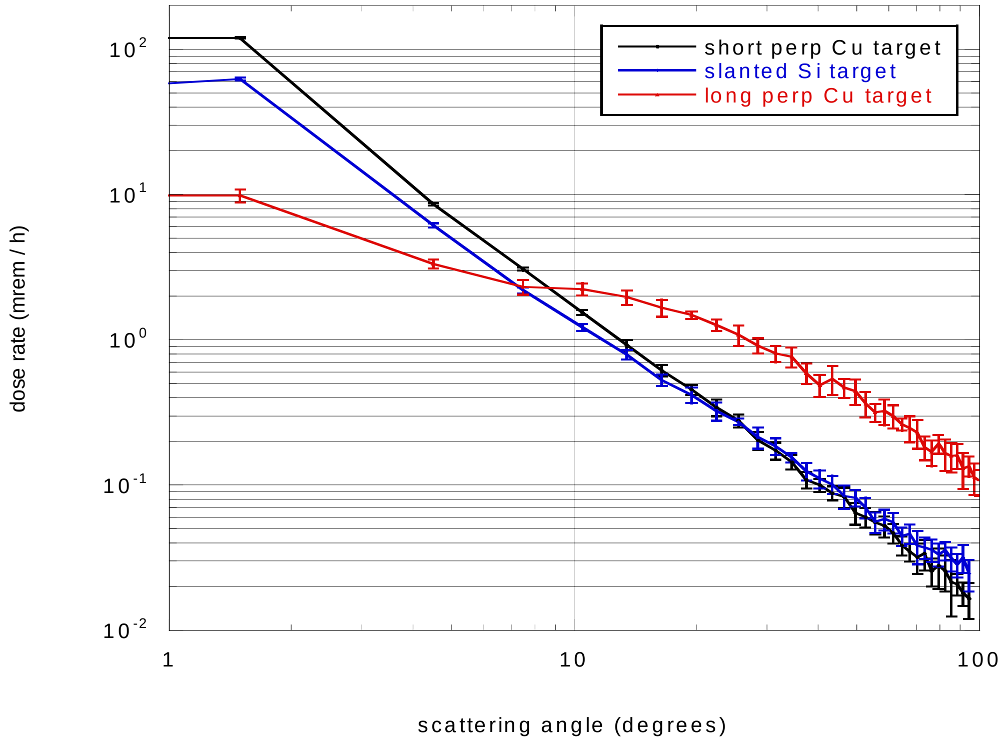


6”-Pb
Collimator
Shield for
Mirror
Collimator
Exp.
Hutch
L
t
O
t
t
PGB
SGB
Hutch
Shutters
L
Mirror
Beamstop
Ring
Chamber
Ratchet
Wall



Dose rate vs Z at two radial distances (30 cm and 100 cm) for 1-inch overlap. GB power = 38 μW (3 GeV e-, 6 m air, 1 nTorr).
all particles, R=30cm
photons, R=30cm
all particles, R=100cm
photons, R=100cm
all, 30 cm
photons, 30 cm
all, 100 cm
photons, 100 cm
dose rate (mrem / h)
Z(cm)
10^1
10^0
10^-1
10^-2
10^-3
1500
1550
1600
1650
1700

**Comparison of photon source terms: Dose rate at 1 meter vs scattering angle for all targets. (0.038-mW GB, 3-GeV e-, 500 mA, 6-m air, 1 nTorr.)**



GB dose rate from photons at 1 m vs scattering angle for optics hutch with Pb shield of various thicknesses. (Shield geometry = vertical cylinder.) Si target (8 cm thick, 3 cm wide and 1 m long) slanted at 0.2 degrees. GB from 500 mA, 3 GeV e- pencil beam through 6 m of air at 1 nTorr. End of air column is 10 m upstream of target.