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RADIATION SAFETY CONSIDERATIONS FOR DESIGN OF THE SPEAR3 STORAGE RING*

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Abstract

The SPEAR3 storage ring at the Stanford Synchrotron Radiation Laboratory (SSRL) is an upgrade of the existing SPEAR2 ring to a 3rd-generation storage ring with beam parameters of 3 GeV of electron beam energy, 18 nm-radian emittance and up to 500 mA of circulating current. While the existing injector will not be changed, the 234-m-circumference SPEAR2 ring components will be completely replaced with new components including C-shaped dipoles. The concrete shielding walls are to remain unchanged. This restriction, when considered in conjunction with the significant increase in the current and loss of self-shielding in the dipole magnets, requires careful study of the SPEAR3 shielding. This paper describes the methodology used for calculating the required shielding in a generic method. The criteria used for the design of shielding and beam loss estimates for various modes of beam operation are also presented. FLUKA Monte Carlo code was used extensively in generating source term data (dose rate as a function of angle for photons and neutrons) for both thin and thick targets. Attenuation profiles of neutrons and photons in concrete and lead shield materials are also presented. These data are being used to evaluate the shielding requirements for the lateral and ratchet walls. The current status of this approach will be discussed. Other issues presented include the use of active devices that are part of the radiation safety systems for the SPEAR3.

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1. Introduction

Stanford Synchrotron Radiation Laboratory (SSRL) is upgrading its existing SPEAR2 (Fig. 1.) to a 3rd-generation storage ring, SPEAR3 [1]. In the upgrade, the ring tunnel floor as well as the entire ring components of the 234-m-circumference SPEAR2 (including vacuum chamber, magnets, power supplies, RF system) will be replaced. The 18-cell SPEAR2 FODO lattice will be replaced with a completely new Double Bend Achromat 18-cell lattice, increasing the circulating electron current from 100 mA to 500 mA. With the new optics, the horizontal beam emittance will be reduced from160 nm-rad to18 nm-rad. The betatron function will also be reduced throughout the storage ring resulting in a beam size that is approximately 4 times smaller than that in SPEAR2. The dipole critical energy will increase from 4.8 keV to 7.6 keV. The stored beam lifetime at maximum current will exceed 15 hours [1].

The existing SSRL injector system of 150 MeV Linac and the 3 GeV Booster ring will remain unchanged [2]. For the SPEAR2, the injector is operated at 2.3 GeV; the stored beam energy is then ramped up to 3 GeV. For the SPEAR3, the injection will occur on energy at 3 GeV. The beam will be injected from the Booster into the ring at 4 W compared to 1 W of average beam power for the SPEAR2.

In SPEAR3, the C-shaped dipole magnets with the opening toward the outside of storage ring remove the self-shielding (~ 5 cm of iron) provided for the user side of the SSRL that has been present in the H-shaped dipole magnets for the SPEAR2. Another restriction in design of the SPEAR3 shielding is that the bulk shielding structure (lateral and ratchet walls, roof) may not be changed. The existing shielding for the SPEAR ring is comprised of: 61-cm thick concrete lateral walls, 30-cm thick concrete roof, and 61-cm or 91-cm thick concrete ratchet walls. Therefore, the radiation safety considerations are focused on detailed review of beam loss patterns and study of how local shielding can be used to augment the existing bulk shielding of the SPEAR ring.

In this document some of the issues faced in the design of the shielding for SPEAR3 are discussed and methods used in the calculations described. Beam parameters that are relevant to the radiation safety analysis including beam loss estimates during injection and stored beam operations for normal and abnormal scenarios are presented in section 2. The active components of the radiation safety systems are presented in section 3. Criteria used in design of shielding are presented in section 4. The Monte Carlo simulations used for calculating the photon and neutron source terms and the attenuation profile of radiation in the concrete shield are described in sections 5 and 6.

2. Beam Parameters

The SPEAR3 parameters that are important for the design of shielding are listed in Table 1.

Table 1. SPEAR3 beam parameters

Beam Energy (GeV)	3.0
Injection Frequency (Hz)	10
Dipole Critical Energy (keV)	7.6
Particle per Pulse at Linac	3.1×10^9
Injected Beam Power (W)	4
Allowed Injected Beam Power (W)	5
Injection Efficiency (%)	75
Injection Mode (per day)	1 Full / 3 Top up
Stored Current (mA)	500
Number of Stored Particles	2.43×10^{12}
Stored Beam Energy (J)	1200
Stored Beam Power (GW)	1.5
Stored Beam Lifetime at 500 mA (h)	> 15

A comprehensive study of SPEAR3 normal beam operation has been performed by Corbett et al. [3]. This study has established beam losses for the injected beam into the ring and the stored electron beam. It gives the total number of electrons injected into the ring as 3.5×10^{15} electrons per year, the injection efficiency into the ring as 75%, and identifies possible locations for loss of electrons. The largest angle of incidence of electrons on the vacuum pipe for both stored and the injected beam is also set at 1-degree. Of the total number of electrons injected into the ring per year, the estimated fractional losses for each of these programs are: up to 37% during the 1 month of start-up, 51% during the10 months of scientific program, and 12% for the machine development that is scheduled for one day per week during the scientific program [3,4].

The SPEAR3 annual, and fractional beam losses at various locations are summarized in Figure 2 [3,4]. The 3 GeV electron beam is injected into the ring at 1.33 nA, 10 Hz (4 W). As the injection efficiency is estimated to be 75%, one out of every four electrons injected into the ring will be lost in the 6 minute injection period that would take to fill the ring from 0 to 500 mA. Half of the electrons that are lost during the injection strike the injection septum. The remaining half is lost with equal probability in 10 limiting apertures in the ring.

The other 75% of the injected beam that will be added to the stored beam bunches in the ring will be lost through the decay processes dominated by inelastic scattering with gas particles and within the electron bunches, and through elastic Coulomb scattering with residual gas. Corbett et al have estimated 50% of the stored beam losses to occur in the Beam Abort Dump, 25% at eight quadrupole magnets, and 25% at the same 10 limiting apertures that a fraction of injected beam is lost.

The average beam power that is lost in any of these locations can be estimated over 7200 hours operation per year. These estimates are: 24 mW at the Beam Abort Dump, 8 mW at the injection septum, 2 mW at each of the other nine apertures (excluding the septum), and 1.6 mW at each of the eight quadruploe magnets. While these average values are very useful in design of shielding for the ring, for the short injection period the instantaneous beam loss values at these apertures and the resulting dose rates outside the shield are much higher than the stored beam operation. As an example, during the injection, the beam power lost in the septum and each of the nine other apertures are equivalent to 550 mW, and 50 mW, respectively [3,4].

However, it is important to note that, over the course of a year, 3 times more particles are lost in the stored beam operation than the injection of beam into the ring. Thus, the integrated dose would be dominated by losses of the stored beam.

In additional to the normal operations, scenarios considering the case of a mis-steered loss of the allowed injection beam power of 5 W and the case of failures of safety systems to be evaluated. The Maximum Credible Beam power that the can be injected into the ring, assuming that all the safety systems have failed, has also been estimated to be 45 W [3].

3. Radiation Safety Systems

In addition to shielding (bulk and local) the SPEAR3 radiation safety system will have Beam Containment System (BCS) that is designed to ensure parameters such as the average beam power and beam losses along the ring do not exceed preset limits [5, 6]. As part of the BCS, Average Current Monitors (ACM) will be used to limit the injection beam power to a preset level of 5 W. Long Ion Chambers (LIONs) will be used to limit normal beam losses to the design values.

Similar to SPEAR2, access to the storage ring and to synchrotron radiation hutches will be controlled with the Personnel Protection System (PPS) and the Hutch Protection System (HPS), respectively [6].

Additionally, a number of tissue equivalent gas ion chambers (BSOIC) are placed at various locations outside the ring wall shield that will shut off the beam if they detect radiation levels exceeding 0.1 mSv/h (10 mrem/h). These BSOICs serve as active area monitors of the radiation fields outside the shield. Figure 3 shows a layout of the active elements of the radiation safety system for SPEAR3.

4. Shielding Design Criteria

Criteria used in design of the SPEAR3 shielding and other radiation safety systems are [7]:

- The integrated dose equivalent to the users working in the experimental floor area outside the SPEAR3 shielding barriers must not exceed 1 mSv (0.1 rem) in a year for normal beam operation.
- The dose equivalent-rate in the event of the Maximum Credible Incident is limited to less than 0.25 Sv/h (25 rem/h), and integrated dose equivalent per event of less than 30 mSv (3 rem).
- The maximum dose equivalent rates in accessible areas outside shielding should not exceed 4 mSv/h (400 mrem/h) for mis-steering conditions defined as conditions that are comprised of infrequent or short-duration situations in which the allowed beam power is lost locally or in a limited area [2].
- The dose equivalent for the maximally exposed member of the public exposed to ionizing radiation from SLAC produced pathways must be less than or equal to 100 μSv (10 mrem) in a year. The dose equivalent at the site boundary from the operation of the SPEAR3 must be a small fraction of that total for normal beam operation.

Considering various modes of operation of the SPEAR3 and different occupancy in the region inside the inner ring (SSRL side), on the roof, and outside the ring in the experimental floor (users side), different dose limits for the SPEAR3 shielding are considered. The design goal for the user side of the ring is set at an average dose arte of 1 μSv/h (0.1 mrem/h), or (2 mSv) 200 mrem for 2000 h of exposure. The integrated dose to a SSRL "Power User", estimated to be present less than 1000 hours per year, would be less than 1 mSv/h (100 mrem/y). Since the SSRL side is not normally occupied by the users, a higher limit of 5 μSv/h (0.5 mrem/h), or 10 mSv (1000 mrem) per 2000 hours, can be allowed. The roof will be fenced off, thus a higher limit 15 μSv/h (1.5 mrem/h), or 30 mSv (3000 mrem) per 2000 hours, is considered.

The instantaneous beam power losses are higher during injection, resulting in higher dose rates that last for a short time. The injection dose rate limits have been selected such that, with the addition of local shielding at locations where higher beam loss is expected, they would not exceed the dose rate values measured during injection for SPEAR2 (i.e., less than 50 μSv/h). Theselimit are on average 10 times higher than dose limits for the stored beam, however, the integrated injection time is a small fraction of the operation of SPEAR3, thus the additional dose that any user may get from the injectionsource is rather low.

The normal beam loss limit for SPEAR3 is 0.1 mrem/h for 2-mW loss at a ring aperture [10], equivalent to 50 mrem/h/W or $5x10^{-4}$ Sv/h/W. The mis-steered beam loss limit is 4 mSv/h (400 mrem/h) for the Allowed Injection Beam Power of 5-W (limited by 3 BCS Average Current Monitors) loss at a point, equivalent to $8x10^{-4}$ Sv/h/W (80 mrem/h/W). The BCS system-failure limit is 0.25 Sv/h (25 rem/h) for the Maximum Credible Beam Power of 45-W [3] loss at a point, equivalent to 5.5 mSv/h/W (555 mrem/h/W). Thus, in general the normal beam loss dictates the shielding design for beam losses in the ring.

5. Shielding Calculations

Loss of electrons in the stored or injected beam in the ring components such as vacuum chamber and Synchrotron Radiation (SR) masks generate electromagnetic shower producing bremsstrahlung photons and neutrons that dominate the requirement for design of the SPEAR3 ring shield.

To estimate the shielding needs two typical beam-target-shielding geometries in the ring were simulated using the FLUKA Monte Carlo particle generation and transport code [8, 9]. As the geometry of the source term and the shielding walls is repeated around the ring, it is expected that the results can be applied generically throughout the ring [10, 11].

For the thin target, a 1^{o}-tilted, 0.7-cm-thick Cu plate (10 cm high in Z, 200 cm long) was used as the target (see Figure 4). For the thick target, a 1^{o}-tilted, 5-cm-thick Fe plate (10 cm high in Z, 200 cm long) was used in the simulation [10]. These geometries represent the 3-GeV electron beam striking the thin ring antechamber wall in the C-shaped dipole, and thick targets like masks, dipoles, quadrupole or sextupole in the ring, respectively

In order to obtain results that could be applied generically, beam hits the target at the center and six layers of cylinder (each 30-cm-thick concrete or 5-cm-thick lead) starting at a radial distance of 600 cm were used. A roof and a floor (30-cm-thick concrete) are at a distance of 100 cm from target (Fig. 4.). Concrete has a density of 2.35 g/cm^3 while lead has a density of 11.35 g/cm^3. The doses from photon, neutron and electron were scored as a function of polar angle and shield depth at the median plane. The dose is obtained by folding the calculated particle fluence in various regions with the corresponding fluence-to-dose equivalent conversion factors. The fluence was calculated using the track length option (USRBIN with SDUM of EWTMP) at various depth regions of the shield (including the source term prior to the shield) The USRBIN binning information is: 10 cm radial bin for concrete and 0.5 cm radial bin for lead, 4-degree polar angular bin between 0 and 360 degrees, Z from –5 to +5 cm for concrete and –2 to +2 cm for lead.

Figures 5a and 5b show the photon and neutron dose profiles from the 3-GeV electrons hitting a 1^{o}-tilted, 0.7-cm-thick Cu plate. The photon dose profile is peaked at forward angles while the neutron profile is more isotropic. Note that the dip at forward direction in the photon dose profile is due to self-shielding offered by the target at forward angles.

The photon and neutron source terms, dose equivalent normalized to1 m, at positive angles between 0 to 100 degrees for SPEAR3 beam on thin and thick targets are shown on Figure 6. The photon dose rates from the thin target (0.7 cm copper) are much higher than the corresponding dose rates for the thick target (5 cm iron), particularly at forward angles, due to the self-shielding offered of the thick target. However, the neutron dose rates from the targets are rather comparable, especially at large angles.

The contribution of the electrons exiting from thin targets to the dose equivalent is rather large, however, this contribution can be reduced readily in a thin shield layer (as the electrons are very low energies) and will not play a role in determining the required shield thickness.

6. Depth Dose Profiles in the Shield for Various Angles

The photon and neutron depth dose profiles in the 180 cm thick concrete shield were also calculated with FLUKA. A useful way of presenting the results is to show the dose as a function of depth in the shield for various angles relative to beam direction. After correction for the inverse-square distance, the attenuation profiles at various angles can be obtained. The source terms and the attenuation profile information can then be used to determine the required shielding.

Figure 7a shows the photon dose equivalent attenuation profiles in concrete normalized at 1 m at 12 different angles (2^o, 6^o, 10^o, 14^o, 18^o, 22^o, 30^o, 38^o, 50^o, 70^o, 78^o and 90^o) from 3-GeV electron beam hitting the 0.7-cm Cu target at 1 degree. Note that the 180-cm-thick concrete shield is at the radii of 600 to 780 cm. The first point of each curve (at radius = 595 cm) is the source-term dose at various angles presented in Figure 6. Since there are no shields beyond the radius of 780 cm and the inverse-square correction has already been made, the attenuation profiles become flat. Note that the curves for angles > 50 degrees have large errors at thick depths that is due to paucity of statistics. The attenuation length, λ (the shield thickness required to reduce the dose equivalent by 1/e) can be derived from the slopes of the curves. Note that the slope at shallow depth is larger than that at thick shield. This is due to that fact that the secondary radiation exiting from the thin 0.7-cm Cu target, particularly at forward angles, is still of high energy and can induce a shower at surface layer of shield. Thus, radiation is not attenuated as fast as expected at shallow region. The slope is also dependent on the angle. The slope becomes constant at thicker depths (equilibrium slope). The photon λ in concrete derived from an equilibrium slope (e.g., 10-degree curve) is 52 g/cm^2. Note the commonly used analytic SHIELD11 code [12] has a photon λ of 42 g/cm^2 in concrete.

Figures 7b shows the corresponding dose equivalent attenuation profiles in concrete for neutron. The equilibrium λ of neutron in concrete is 72 g/cm^2. This is close to the "mean" value of the three attenuation lengths used for high-energy (120 g/cm^2), mid-energy (55 g/cm^2), and low-energy (30 g/cm^2) neutrons in SHIELD11.

Similarly the attenuation profiles of photons and neutrons in lead from thin and thick targets are also generated. The lead shielding results are needed for the analysis of radiation going from the ring chamber to the beamline hole in the ratchet wall. A detailed description of the calculations and results for different shield materials is given in Liu et al. [10].

Table 2 summarizes the dose equivalent rate source terms (from Figures 7a and 7b) and the equilibrium attenuation lengths for thin Cu and thick Fe targets [10]. The attenuation length of photon is 52 g/cm^2 in concrete and 27 g/cm^2 in lead, which are in good agreement with those in SHIELD11.

Table 2. Summary of source term dose rates (from Figures 7c and 7d) and the "equilibrium" attenuation lengths for photon and neutron [10].

Target	**0.7-cm Cu**		**5-cm Fe**	
Source Terms Under Concrete Shield, H (Sv/h/W at 1 m)				
Photon (Fig. 7a)	5 at 4^o to 0.1 at 90^o		0.1 at 4^o to 0.03 at 90^o	
Neutron (Fig. 7b)	0.04 at 4^o to 0.03 at 90^o		0.02 between 4^o and 90^o	
"Equilibrium" Attenuation Length, λ (g/cm^2)				
Shield	**Concrete**	**Lead**	**Concrete**	**Lead**
Photon	52	27	52	27
Neutron	72	NA	110	NA

The slopes of the dose attenuation profiles (in Figures 7a,b) at an arbitrary thickness, for example 0-30 cm and 30-120 cm of shield depths, can be fitted to obtain the "1st" and "2nd" attenuation lengths (called λ1 and λ2, respectively) as function of angle [10].Note that at angles less than 35 degrees, both λ1 and λ2 would be larger than the λ given in SHIELD11 due to the above-mentioned effect of showering in surface layer. On the other hand, at large angles, λ1 is smaller than, while λ2 would remain close to, the SHIELD11 λ value. The implication of this effect is that the use of attenuation length derived from thick targets could result in underestimation of the radiation levels at forward angles from a thin target, especially for thin shielding walls. Therefore, for thin shield walls (~30 cm of concrete or less) it is imperative for the forward-directed shower to be fully contained in the target or in local shielding.

The results of these calculations are currently being used to design the local shielding [10,13] that is required for the SPEAR3 to meet the design goals.

7. Summary

SPEAR3 beam parameters and operation mode are described. The radiation safety systems for the SPEAR3 project at the SSRL, that are comprised of active systems (BCS, PPS) and shielding, are presented Shielding design criteria are also given. Evaluation of the adequacy of the existing concrete walls, ratchet walls and the roof for the SPEAR ring parameters is performed with the FLUKA Monte Carlo particle generation and transport code. Two typical beam target geometries are simulated, a thin 0.7-cm copper target and a thick 5-cm iron target hit by 3-GeV electron beam at a shallow angle of 1 degree. Results of FLUKA calculations are used to develop the photon and neutron dose rate source terms for these targets. Attenuation profiles for photons and neutrons in concrete and lead shields have also been simulated and presented. This information allows for determination of the shielding needs of SPEAR3 in a generic method.

Acknowledgment

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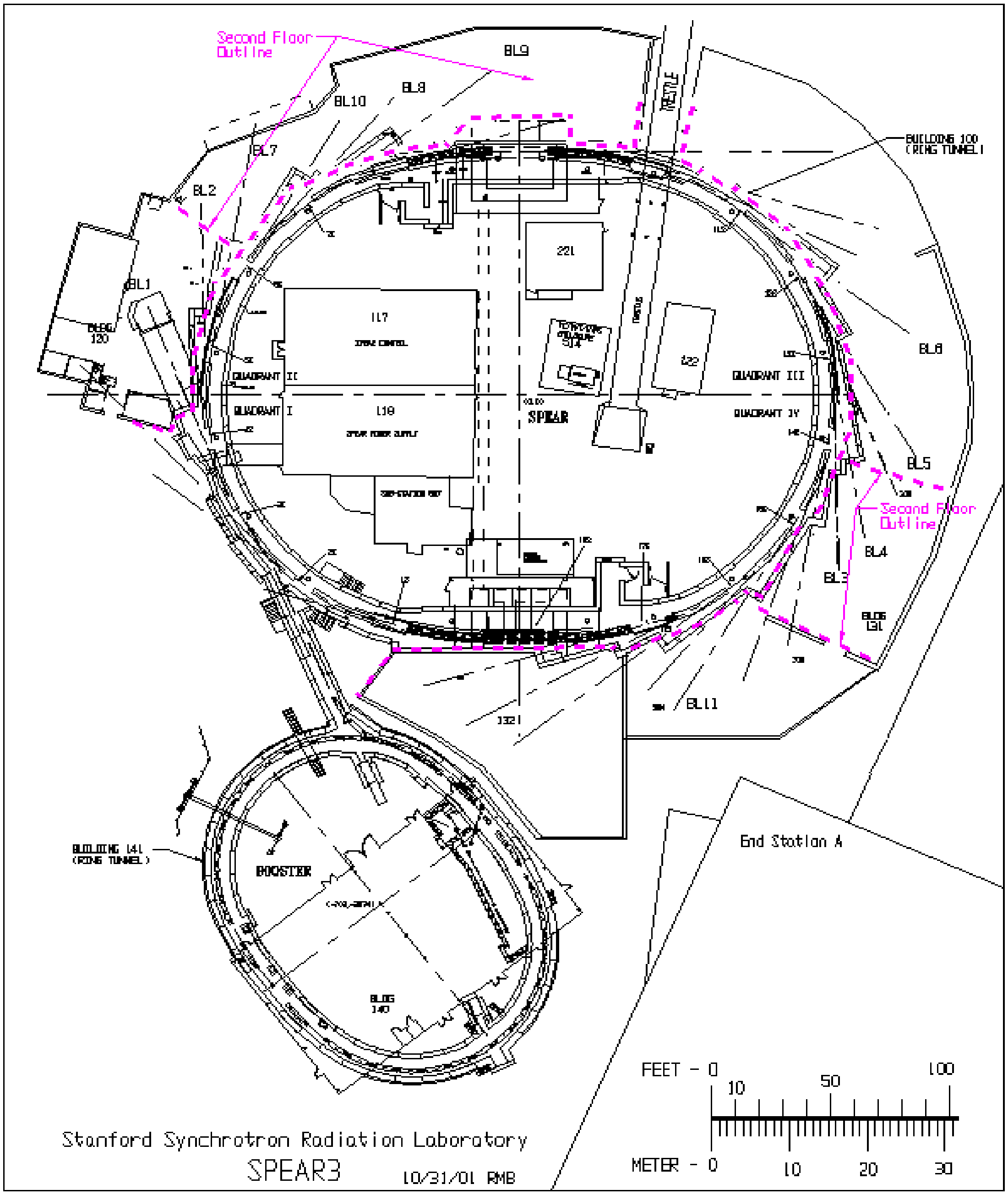


Fig. 1. The SSRL layout, showing the injector (10-Hz, 150-MeV Linac and 3-GeV Booster ring), 234-m-circumference, 3-GeV SPEAR3 ring, and synchrotron radiation beamlines, as well as the building contour around the outer rim of the ring and the 2nd floor offices (red dashed line).

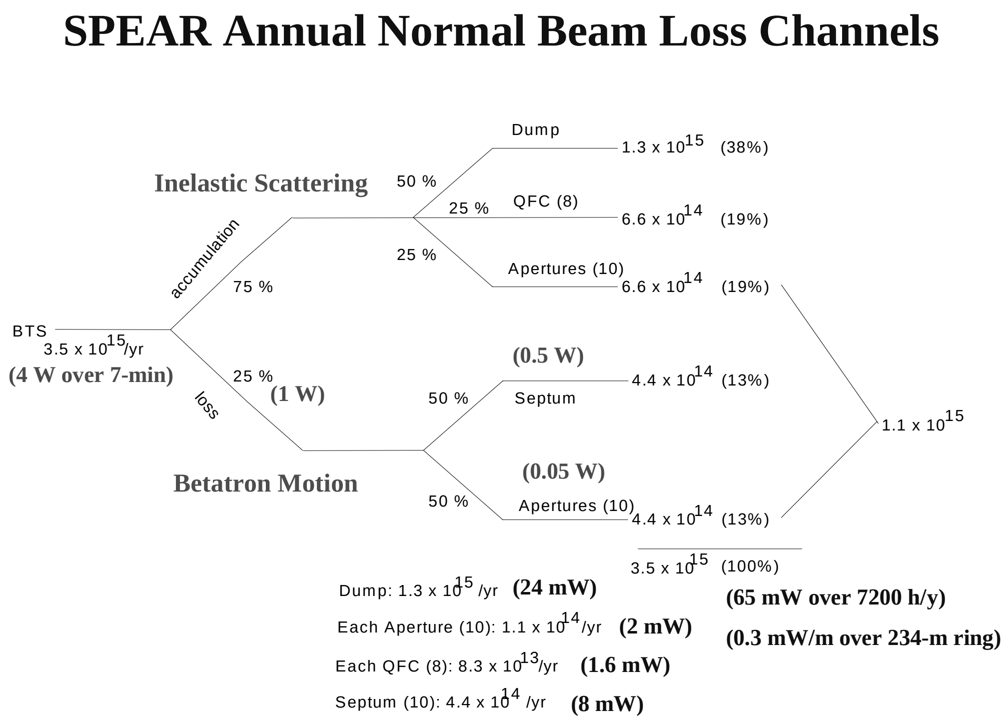


Fig. 2. Annual normal beam loss estimates for SPEAR3 storage ring operation [3,4]

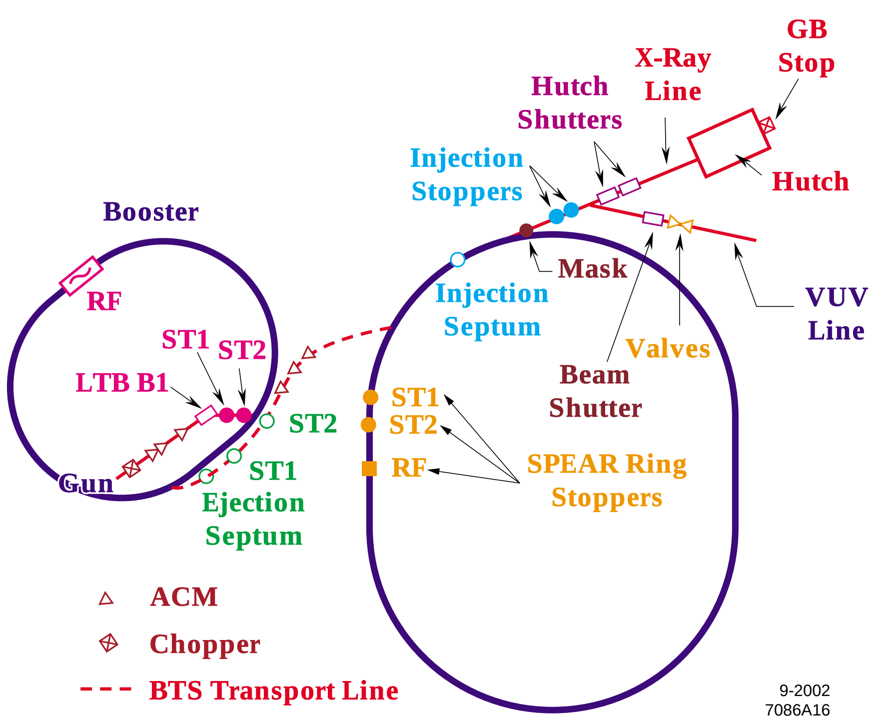
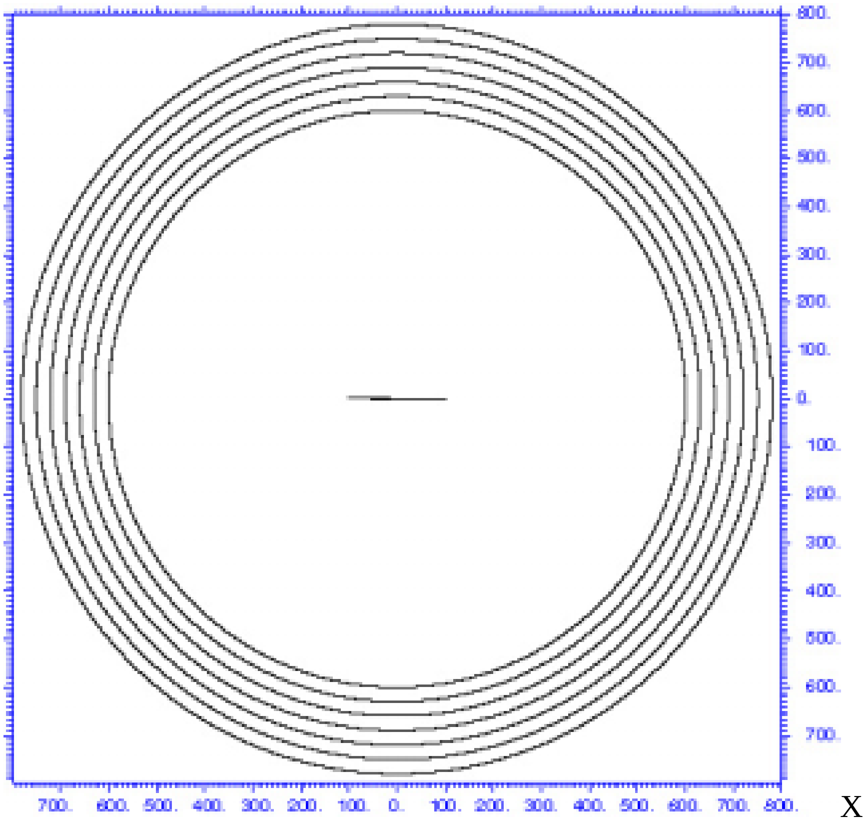


Fig. 3. Main components of the radiation safety system for the SPEAR injector and the ring and a typical synchrotron radiation beam line.



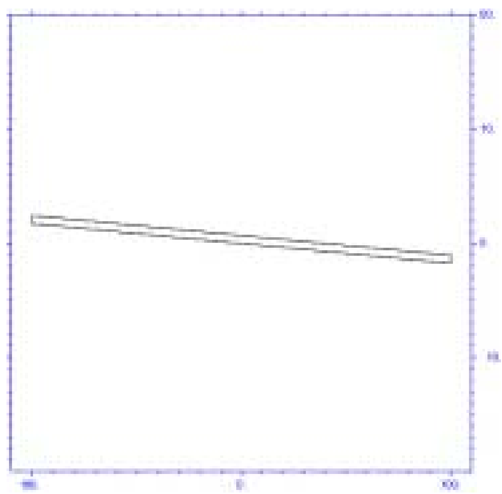


Fig. 4. FLUKA cylindrical shield geometry (top figure) for the generic calculation of SPEAR3 ring shielding design. The 180-cm-thick concrete shield starts at the radius of 600 cm. Electron beam (3 or 5 GeV) direction is +X axis and it hits the target plate at (0,0,0) with the target plate tilted at 1°. The bottom figure shows the 0.7-cm thick copper target plate. The dose is scored as a function of angle and shield depth at the median plane (Z = 0 cm) [10].

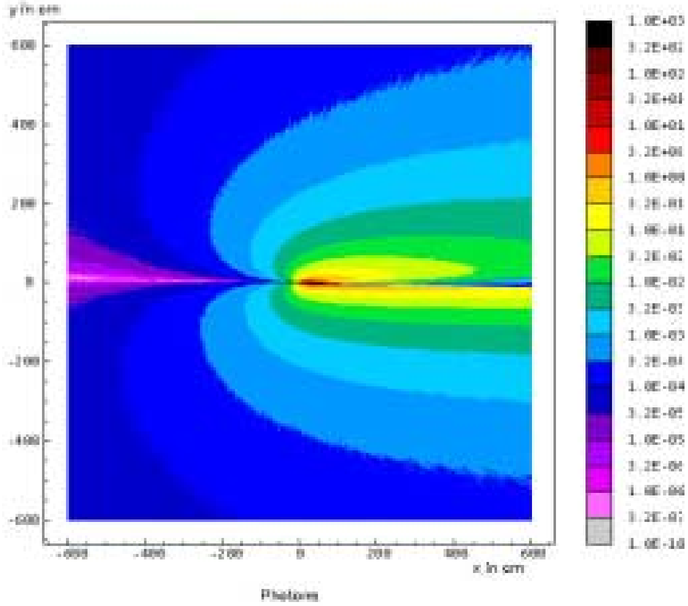


Fig. 5a. Forward-peaked photon dose profile from 3-GeV electrons hitting 1^{o}-tilted, 0.7-cm-thick Cu plate without shield. Note that the dip at forward direction occurs at positive angles.

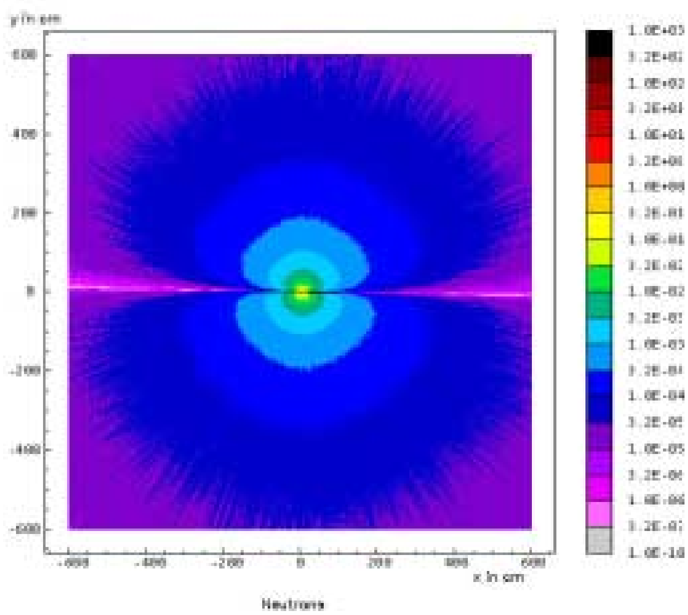


Fig. 5b. Isotropic neutron dose profile from 3-GeV electrons hitting 1^{o}-tilted, 0.7-cm-thick Cu plate without shield.

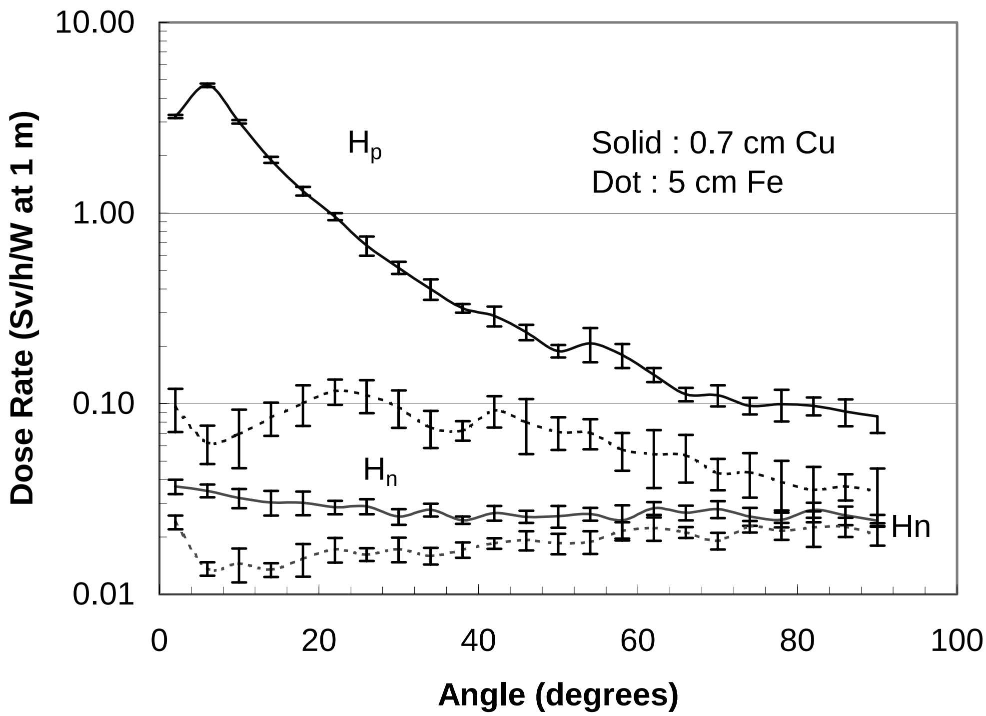


Fig. 6. Photon and neutron source term at 1 m at positive angles between 0 to 100 degrees for SPEAR3 beam on thin and thick targets.

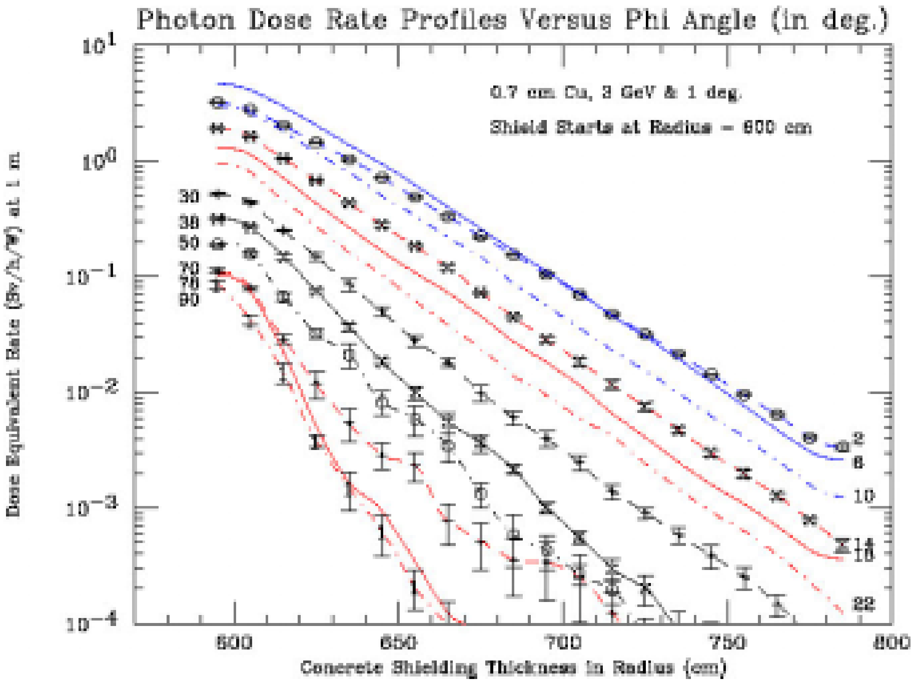


Fig. 7a. Photon depth dose profiles in concrete at 1 m for various angles from 3-GeV electron beam hitting the 0.7-cm Cu at 1°. 180-cm-thick concrete shield starts at the radius of 600 cm [10].

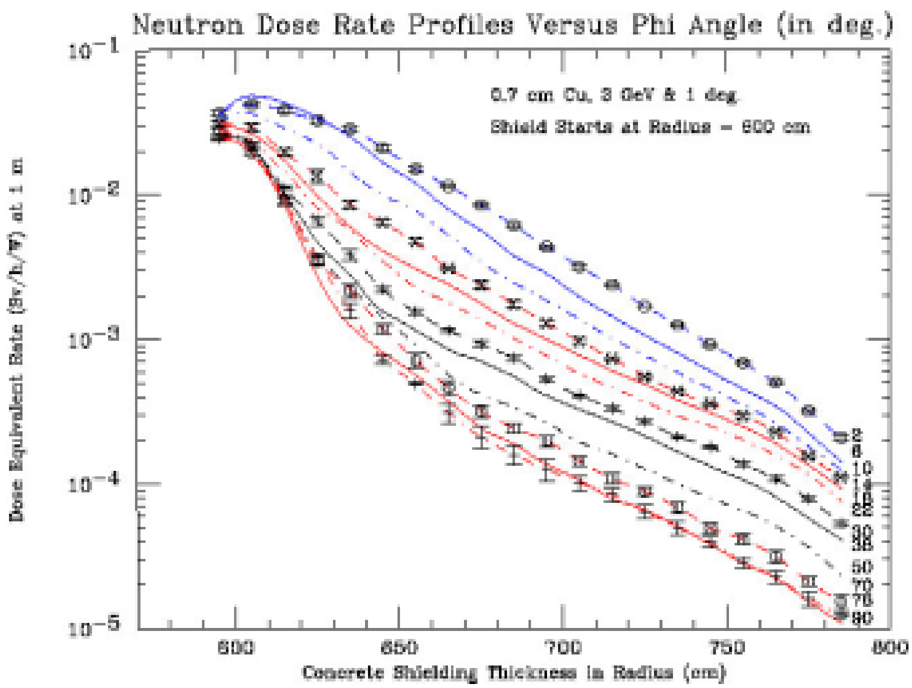


Fig. 7b. Neutron depth dose profiles in concrete shield at 1 m for various angles from 3-GeV electron beam hitting the 0.7-cm Cu at 1° [10].