SHIELDING DESIGN FOR THE PROPOSED ADVANCED PHOTON SOURCE AT ARGONNE*

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Introduction

Bulk shielding was designed for the proposed Argonne Advanced Photon Source. The shielding is for two linacs, the positron converter, booster synchrotron, and the storage ring. Shielding design limits exposure to 20 mrem/wk for occupational and 25 mrem/y for an individual member of the public[1,2] from the radiation products, which include high energy neutrons(HEN), giant resonance neutrons (GRN), and Bremsstrahlung radiation(BR). The beam loss parameters at various components were estimated from Fasso, et al.[3] Dose rates were computed for continuous loss during beam decay using an empirical method from Swanson[4]. Normal operational losses and certain accidental beam losses were also considered.

Types of Radiations and Attenuation Lengths

Bremsstrahlung, giant resonance neutrons and high energy neutrons were considered in the bulk shielding design. The muon dose contribution was found to be negligible.

A review of literature[5-9] for attenuation of the relevant radiations by various shielding materials indicated a spread of values. Conservative values were used in this study and they are shown in Table 1.

Table 1
Attenuation Lengths

Radiation Component	Material	Attenuation Length in g/cm^2
Bremsstrahlung	Lead	25
	Concrete	49
	Iron	37
	Sand	70
GRN	Concrete	40
	Sand	33
	Dense Polyethylene	6.3
HEN	Concrete	65 ($E \leq 100$ MeV)
		115 ($E > 100$ MeV)
	Dense Polyethylene	18.1 ($E > 100$ MeV)

Radiation Dose Equivalent Factors

The unshielded radiation dose equivalent factors available in the literature were reviewed and the following values were adapted from Fasso, et al.,[3] with their suggested modifications. The factors refer to unshielded dose rates at 1 m in the transverse direction to the positron beam. In the forward direction, (0 degrees), the Bremsstrahlung dose equivalent factor is given by 8.3 E mrem m^2/J[3,9] where E is in MeV. In general, the same factors given above were used for the neutrons in the forward direction.

Radiation Component	Radiation Dose Equivalent Factor F_H (mrem $\cdot$ m^2/J)
Bremsstrahlung	2.80
Giant resonance neutrons	0.63
High energy component	0.075

Bulk Shielding Formulae

The following formulae were used to compute the bulk shielding for the various components of the system:

$$\dot{H} = \sum_i \frac{F_{Hi}}{r^2} W e^{-d/\lambda_i}$$

where $\dot{H}$ is the dose equivalent rate, F_{Hi} is the appropriate dose equivalent factor for the i^{th} radiation component (see above), r is the source to dose point distance in meters, d is the shield thickness in g/cm^2, $\lambda_i (g/cm^2)$ is the attenuation length for the i^{th} component, and W is the energy loss rate, in J/h.

Shielding Estimates

The shielding computations were primarily based on point losses in different components of the system. For the linacs, since the beam characteristics are similar to the CERN-LEP linac system, estimates of the fractional beam losses were obtained from Fasso, et al.[3]

First Linac, Positron Converter and Second Linac

For the first linac, the highest value of the power lost is between the buncher output and the first linac output (4.5W). The computed total dose rate for a concrete shielding of 2 m, and a distance of 4 m is 0.25 mrem/h.

The power loss at the positron converter is higher; with 0.3 m of iron and 1.7 m of concrete shielding, the total dose rate is 1.07 mrem/h. The total dose rate exceeds the design goal. But the operational time for injection is conservatively estimated to be only 20%. The average dose rate will then become 0.21 mrem/h.

In the second linac, the power losses are down significantly due to lower positron current and the suggested 2-m concrete shielding is adequate.

Booster Synchrotron

We assume an injection energy of 450 MeV with a loss rate of 50% at the injection point, and 5×10^9 positrons are accelerated per second to an energy of 7 GeV. With an 0.8-m concrete shield at the point of injection and the distance of closest approach to be 3 m, the estimated dose rates are:

$\dot{H}_{BR}$=4.35 mrem/h, $\dot{H}_{GR}$=0.41 mrem/h and $\dot{H}_{HE}$=0.30 mrem/h.

The total dose rate is 5.06 mrem/h. Assuming a 20% operational time for injection and localized lead shielding (5 cm) at high loss points, the average radiation level is reduced to below the design goal.

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For the injection into the main ring, a point loss of 50% was assumed. The energy is taken as 7 GeV. With these assumptions, the computed dose rates at 4 m with 0.8 m of concrete shielding are:

$$\dot{H}_{BR}=38.0 \text{ mrem/h}, \ \dot{H}_{GR}=3.6 \text{ mrem/h and } \dot{H}_{HE}=9.2 \text{ mrem/h}.$$

The total dose rate is 50.8 mrem/h. Addition of 10 cm of lead at high loss points would reduce the photon dose rate to 0.38 mrem/h. A 20% operational time, and an addition of 25 cm of dense polyethylene at high loss points of the injection system, will reduce the average total dose rate to the design goal.

Main Storage Ring Shielding

The shielding calculations were based upon the assumption that the maximum beam of 6.62×10^{12} positrons at 7.0 GeV must be shielded. A concrete thickness of 0.8 m on both sides and 1 m on top of the tunnel were assumed. A circumference of 1060 m for the ring was used. In addition, the distance of closest approach was taken as 2 m.

Collisions of positrons with gas molecules, interaction of beam particles, and orbital excursions, lead to positrons being lost from the beam and striking the vacuum chamber. Swanson[4] suggests the following empirical formula to calculate the Bremsstrahlung doses due to uniform interactions around the ring circumference.

$$\frac{H}{W} = 1.67 \times 10^{-2} E_0 2^{-(\theta_B/\theta_{1/2})} + (0.833)10^{-\theta_B/21} + (0.025)10^{-\theta_B/110}$$

where H is in rems at 1 m, W is in joules, E_0 is in MeV, θ_B is the Bremsstrahlung angle in degrees and $\theta_{1/2} E_0 =$ 100 MeV•deg. The distributions for Bremsstrahlung and HE are shown in Figures 1 and 2, respectively. Isotropic emission was assumed for neutron components. The curve for the GRN distribution is similar in shape to that shown for the HE neutrons. The cumulative contribution at the point due to the loss of the entire beam is obtained by integration over all angles. For a beam decay rate of 10 h, the power loss is 1.3 J/degree.hour, and the resultant total dose rate is $\sim 5.17 \times 10^{-2}$ mrem/h. Experience at Aladdin and NSLS[4,10] indicates localized loss patterns at open ends of bending magnets, around the straight sections, at maximum dispersion points in quadrupole magnets, and Bremsstrahlung jets at the end of straight sections. Therefore, additional localized shielding may have to be provided at high loss points.

Loss of Beam at a Single Point

For this case, the transverse and radial components are to be evaluated. For the transverse component, with a distance of closest approach of 3 m and 0.8 m of concrete shielding in place, for a loss of 7414 joules at a single point, the estimated doses are:

$$H_{BR}=50 \text{ mrem}, \ H_{GR}=4.4 \text{ mrem, and } H_{HE}=12.4 \text{ mrem}.$$

For the radial dose component, the closest distance would be 26 m, of which 6 m would be concrete due to slant penetration. This increased shielding thickness would offset increased Bremsstrahlung in the forward direction and results in negligible doses.

Loss of Beam into an Optical Beam Line

In the unlikely event of a dipole failure, part of the positron beam could be lost down an optical beam line. All beam lines are shielded with at least 25-cm lead shutters in the beam direction and 10-cm lead in the transverse direction, inside the shield tunnel to adequately protect from neutrons. For a very rare event of 10% beam lost down an optical beam line, the unshielded Bremsstrahlung dose would be 4.3×10^4 rem at 1 m. If this occurs just inside the shield wall, the total dose outside the wall at 1 m would drop to 5 mrem due to the 25 cm lead and 80 cm of concrete, and a total distance of 2.1 m.

Dose to Public

Assuming a distance of 220 m to the site boundary and a total operation time of 8000 h per year, the site boundary annual dose is found from Fig. 3 to be 1.6 mrem due to direct radiation.

The skyshine contribution due to the high energy component was computed assuming the expression for a well shielded accelerator:

$$\phi(r) = \frac{a\, Q\, e^{-r/\lambda}}{4 \pi r^2}$$

in which a and λ are constants, $\phi(r)$ is the flux density (n/cm^{2}s), Q is the source strength in n/s and r is the distance to the dose point in cm. Experimental values for a and λ are obtained from Rindi[11]. Values of Q were computed based upon the yield of 0.12 n/e, given by Bathow[5] for 6.3 GeV electrons. A ten-hour mean lifetime is assumed. Using a conversion factor of 1 mrem/h = 3.3 n/cm^{2}s, the dose rate is computed to be 1.04 μrem/h and for an 8000 h annual time of operation, the annual dose would be about 8.3 mrem. The total annual dose from both direct and skyshine radiation will be about 10 mrem/y which is within the guidelines.

References

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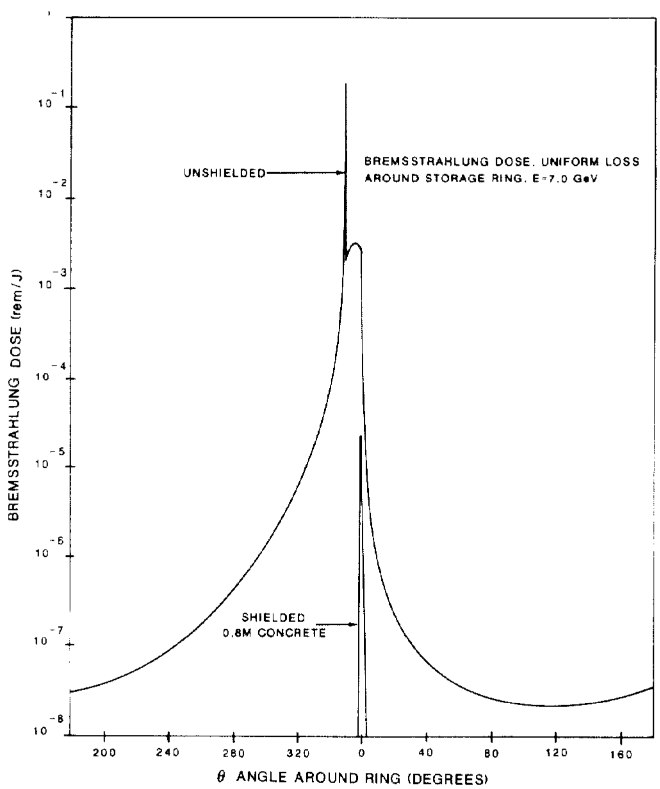

Fig. 1. Bremsstrahlung Dose - Uniform Loss Around Storage Ring.

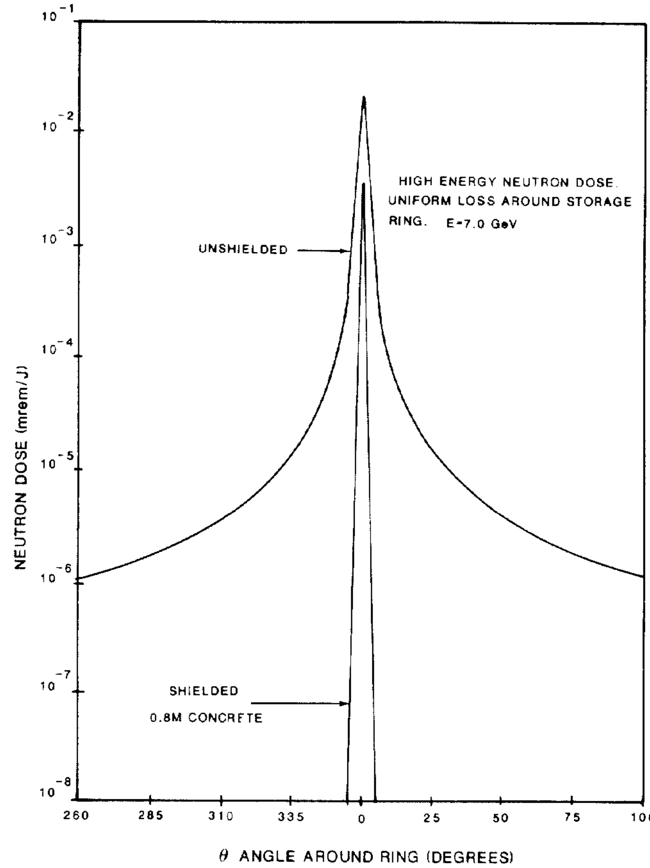

Fig. 2. High Energy Neutron Dose - Uniform Loss Around Storage Ring.

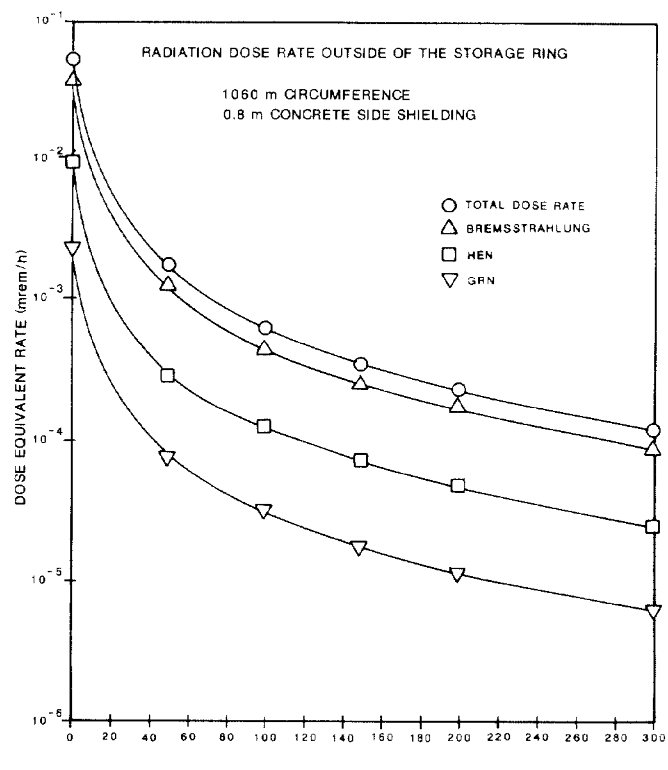

Fig. 3. Variation of the Integrated Radiation Dose Rate Outside the Storage Ring with Distance.