Appendix 9

Calculation of Scattered Radiation [1] From Insertion Device Beam Lines

Introduction

Insertion devices are used at the X-1, X-9, X-13, X-17, X-21, X-25, and X-29 beam lines. Insertion device beam lines have the potential to create higher radiation fields at scatter points than those discussed in section 4.12.4.3.1 for bending magnet beam lines. The most extensive shielding is required for X-17 because of the much higher critical energy produced by the super-conducting wiggler. Shielding requirements for the X-17 beam line are discussed in appendix 10. In this appendix, shielding evaluations[2] conducted for the hybrid wigglers used in the X21 and X25 beam lines are described. These radiation sources produce spectra which are similar to those produced by a standard bend magnet, but have increased flux by a factor of ~ 30 due to the number of poles in the wiggler, each pole acting as one effective bend magnet. When operated at a closed gap, these wiggler magnets will produce an on-axis field of 1.1 Tesla, resulting in a peak critical energy of 4.57 keV when the storage ring is operated at 2.5 GeV, and 5.74 keV when the storage ring runs at 2.8 GeV.

The horizontal opening angle of the wiggler radiation is 5.0 mrad at 2.5 GeV and 4.5 mrad at 2.8 GeV. The critical energy of the radiation, however, is not constant across the fan. Only at the center of the fan does it reach its peak value; at 80% of the distance to the edges of the fan from the center (i.e., at ±2.0 mrad relative to the center line at 2.5 GeV, and ±1.8 mrad at 2.8 GeV), the critical energy falls to 60% of its peak value. For larger angular excursions, the critical energy falls precipitously, to a value of zero at the edges of the horizontal fan. The radiation shielding calculations discussed in this appendix were based on a model spectrum which used the appropriate peak critical energy (4.57 keV at 2.5 GeV, 5.74 keV at 2.8 GeV) over a horizontal fan covering 80% of the full angular opening (4.0 mrad at 2.5 GeV, 3.6 mrad at 2.8 GeV), and zero critical energy (i.e., no x-ray intensity) over the extremal 20% of the fan.

With 250 mA of machine current (assumed in the calculations), the total power radiated from this wiggler source is 2.15 kW at 2.5 GeV and 2.70 kW at 2.8 GeV. 90% of the total power emanates within the central 80% of the horizontal angular opening used in the calculations. The 10% of the power radiated into the extremal 20% of the fan is associated with a relatively soft x-ray spectrum and poses no significant hazard.

Three sections of the beam line were treated separately in the calculations: (1) the front end (i.e. the portion of the line on the machine side of the concrete shield wall) (2) the

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[1] This appendix is based on analysis performed by NSLS staff member, L. Berman.

[2] Shielding requirements were evaluated using the program "Photon" to determine the necessary shielding at scatter points along the beam line

transport section (i.e. the portion of the line with components between the shield wall and the hutch, e.g., mirror and monochromator tanks, windows and filters), and (3) the hutch. All radiation doses were calculated at unit density ICRU4 artificial tissue surface located perpendicular to the scatter source. It was also assumed that the full, unattenuated x-ray spectrum was incident on a particular scatter source.

Front End

The front end components are all located within the shielded tunnel containing the x-ray ring. The calculations (not presented in the tables) show that a cement wall of 12 inches thickness is more than adequate radiation shielding, with the worst dose rates outside the shield being < 1×10^{-8} mrads/hr at 2.5 GeV and < 1×10^{-6} mrads/hr at 2.8 GeV, assuming complete scatter of the white beam off a copper aperture. The calculations predict the corresponding doses to be < 0.1 mrads/hr at 2.5 GeV and < 1 mrads/hr at 2.8 GeV assuming replacement of the concrete wall with 12 inches of 5% borated polyethylene,. These calculations include the stainless steel vacuum chamber of 1/8-inch thickness as part of the shield wall.

Transport Section

Compared with a standard bend magnet beam line, the requisite radiation shielding of transport section components in a hybrid wiggler beam line is unusual only at locations where the white beam encounters matter. Calculations were made with typical beam line components servings as scatter points for the white beam; including carbon filters of 0.0066 inch total thickness, 0.010 inch thick beryllium windows, silicon crystals, copper masks, lead masks, and helium gas at 1 atmosphere pressure. Tables I – IV summarize the calculated dose rates at 90^{o} to the scattering point through various shield walls at a distance of 4 inches from the scatter source. The calculations were performed for electron energies of 2.5 and 2.8 GeV. These represent the worst-case estimates, since 4 inches is the closest distance of any shield wall to a possible scatter source, and most scatter sources are not point-like but extended. The dose falls inversely with the square of the distance from the source point. The doses due to scatter from helium gas assume scatter from a 1 meter length of 1 atmosphere gas condensed down to a point, and should be considered as overestimated and simply indicative of the expected order of magnitude.

For all cases, stainless steel of up to 1/8 inch thickness (e.g., the walls of beam transport tubes, bellows, and vacuum chambers), at 4 inches from the scatter point, should be considered to be inadequate shielding, and therefore appropriate only when the relevant section is evacuated. An additional 1/16-inch thickness of lead will provide enough shielding at 2.5 GeV (except perhaps for scatter off silicon) and 2.8 GeV (except for scatter off silicon and copper, and perhaps lead). For the exceptions, the required lead thickness may be 1/8 inch, pending survey. Stainless steel of thickness 3/8 inch should be appropriate except perhaps for scatter off silicon, copper, and lead, in which cases an additional 1/16 inch of lead may be required, pending survey. Stainless steel of thickness 3/4 inches should be appropriate in all cases. The shielding in areas where the calculated doses are borderline should be finalized following a survey.

Hutch

Hutch shielding in excess of that for hutches used on standard bend magnet beam lines (1/8 inch thick steel) is necessary only if the white beam will enter the hutch. In the hutch, the white beam could be incident on beryllium, 1 atmosphere air, silicon, copper, lead, or any object a user places in the beam. Of the objects likely to be placed in the beam, calculations show that the worst-case scatter would probably occur off a thick silicon crystal. At 0.6 meters from the silicon scatter source, 1/8 inch of steel shielding is insufficient, but 1/8 inch of steel backed by 1/16 inch of lead will suffice and will be used (Table V - VI). Additionally, 2 inches of cement, a possible component of a hutch wall, may be inadequate at 2.5 GeV (and certainly so at 2.8 GeV), but will suffice when backed by 1/16 inch of lead. 1/16 inch of lead alone is sufficient shielding at 2.5 GeV, but may not be at 2.8 GeV. Where lead glass is used for windows, 1/16 inch lead equivalent is suggested at 2.5 GeV, and 1/8 inch lead equivalent is suggested at 2.8 GeV. If the windows are a least 1-meter away from the scatterer, then 1/16 inch lead equivalent will suffice at both machine energies.

Conclusion

The results of these calculations show that typical undulator beam lines can create significant radiation levels at scatter points that will need evaluation at the design and commissioning stages for all such beam lines. However, the calculations and operating experience clearly show that radiation levels can be reduced to very low levels with small amounts of lead shielding.

Table I

Transport Section Shielding

2.5 GeV, 250 mA, 4 horizontal mrad, E_c = 4.57 keV

mRad/hr - 4” from scatterer

	Shielding from Scatterer					
Scatterer	1/8” Stainless Steel	3/8” Stainless Steel	3/4” Stainless Steel	1/8” Steel + 1/16” Pb	1/8” Steel + 1/8” Pb	3/8” Steel + 1/16” Pb
0.0066” carbon	64	0.07	0.0002	0.007	0.00004	0.0002
0.010” beryllium	77	0.09	0.0003	0.008	0.00004	0.0002
Thick Silicon	4800	8.6	0.03	0.9	0.005	0.03
Thick Copper	810	2.1	0.009	0.2	0.002	0.008
Thick Lead	190	0.5	0.001	0.04	0.0002	0.001
1 atm. Helium Gas (1 meter length)	33	0.04	0.0001	0.004	0.00002	0.00009

Table II

Transport Section Shielding

2.5 GeV, 250 mA, 4 horizontal mrad, E_C = 4.57 keV,

mRad/hr – 4” from scatterer

	Shield wall				
Scatterer	1/16” Stainless Steel	1/16” Pb	1/8” Pb	1/16” Steel + 1/16” Pb	1/16” Steel + 1/8” Pb
0.0066” carbon	1700	0.065	0.0002	0.02	0.00008
0.010” beryllium	2000	0.08	0.0002	0.02	0.0001
Thick Silicon	86000	7.5	0.03	2.5	0.01
Thick Copper	12000	1.8	0.008	0.6	0.004
Thick Lead	2900	0.4	0.001	0.1	0.0004
1 atm. Helium Gas (1 meter length)	870	0.03	0.0001	0.01	0.00004

Table III
Transport Section Shielding
2.8 GeV, 250 mA, 3.6 horizontal mrad, E_C= 5.74 keV
mRad/hr – 4” from scatterer

	Shielding from Scatterer					
Scatterer	1/8” Stainless Steel	3/8” Stainless Steel	3/4” Stainless Steel	1/8” Steel + 1/16” Pb	1/8” Steel + 1/8” Pb	3/8” Steel + 1/16” Pb
0.0066” carbon	760	2.2	0.01	0.3	0.002	0.01
0.010” beryllium	910	2.6	0.02	0.3	0.003	0.01
Thick Silicon	64000	270	1.8	36	0.3	1.4
Thick Copper	12000	73	0.62	10	0.1	0.4
Thick Lead	2800	13	0.06	1.6	0.01	0.05
1 atm. Helium Gas (1 meter length)	390	1.1	0.006	0.1	0.001	0.005

Table IV
Transport Section Shielding
2.8 GeV, 250 mA, 3.6 horizontal mrad, E_C= 5.74 keV,
mRad/hr – 4” from scatterer

	Shield wall				
Scatterer	1/16” Stainless Steel	1/16” Pb	1/8” Pb	1/16” Steel + 1/16” Pb	1/16” Steel + 1/8” Pb
0.0066” carbon	13000	1.9	0.01	0.69	0.005
0.010” beryllium	15000	2.3	0.01	0.8	0.006
Thick Silicon	750,000	240	1.4	90	0.7
Thick Copper	110,000	64	0.5	25	0.2
Thick Lead	27,000	12	0.05	4.2	0.02
1 atm. Helium Gas (1 meter length)	6500	1	0.005	0.4	0.002

Table V

Hutch Shielding

2.5 GeV, 250 mA, 4 horizontal mrad, E_C= 4.57 keV

mRad/hr – 0.6m from Silicon scatterer

	1/16” Pb	1/8” Pb	1/8” Stainless Steel	1/8” Steel + 1/16” Pb	2” cement	2” cement + 1/16” Pb
Si Scatterer	0.2	0.0008	140	0.03	7.7	0.004

Table VI

Hutch Shielding

2.8 GeV, 250 mA, 3.6 horizontal mrad, E_C=5.74 keV

mRad/hr – 0.6m from Silicon scatterer

	1/16” Pb	1/8” Pb	1/8” Stainless Steel	1/8” Steel + 1/16” Pb	2” cement	2” cement + 1/16” Pb
Si Scatterer	7.5	0.04	1800	1.1	130	0.2