Title
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Environment, Health and Safety Division

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Synchrotron Radiation Shielding Estimates for the ALS Super Bend Beamlines

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Abstract

The Advanced Light Source is proposing to replace 3 of it's bending magnets with superconducting magnets. This will substantially increase the required radiation shielding for these magnet's beamlines. In this report we outline the radiation shielding requirements for these "superbend" beamlines.

1 Introduction

The Advanced Light Source is proposing to replace 3 of it's room temperature bending magnets with superconducting magnets [1]. The magnetic field strength will increase from 1.25 T to 5 T. The synchrotron beam critical energy will increase from the present 3.25 keV to 12 keV. This will greatly increase the high-energy flux of the bend magnet synchrotron beam. In this report we catagorize the shielding requirements into three groups: white beam (unreflected), pink beam (once reflected), and monochromatic. Within each category we calculate shielding requirements for a fully scattered beam as well as the shielding

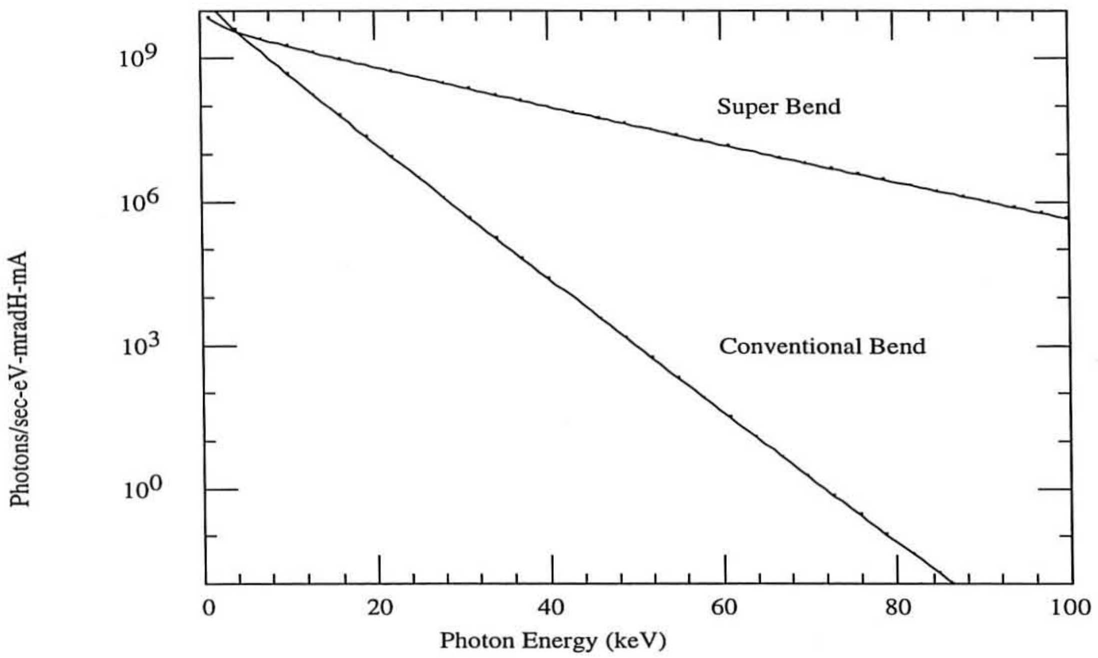


Figure 1: A comparison of the photon fluxes from both the conventional bend magnet source and the superbend source.

requirements for a direct beam stop or mask. The superbend beamlines will make an ideal source for protein crystallography which requires a useful flux to well above 20 keV. An indication of the potential impact on radiation safety can be seen in Fig. 1. This shows the photon flux from both the conventional room temperature bend magnet and the superconducting magnet. In the energy range of interest to experimenters there may by 10-40 times more flux from the superbend source. In the energy range of interest to radiation shielding (60-88 keV) there may be 6-9 orders of magnitude more flux from the superbend. Because of the desire for harder x-rays, the incident grazing angle on beam mirrors is quite small. Grazing angles are assumed to vary between 3 and 5 mradians. The resulting radiation dose rates are examined as a function of shield thickness and material. Typical superbend beamline layouts are described elsewhere [2]. Shielding calculations are performed with the PHOTON program[3].

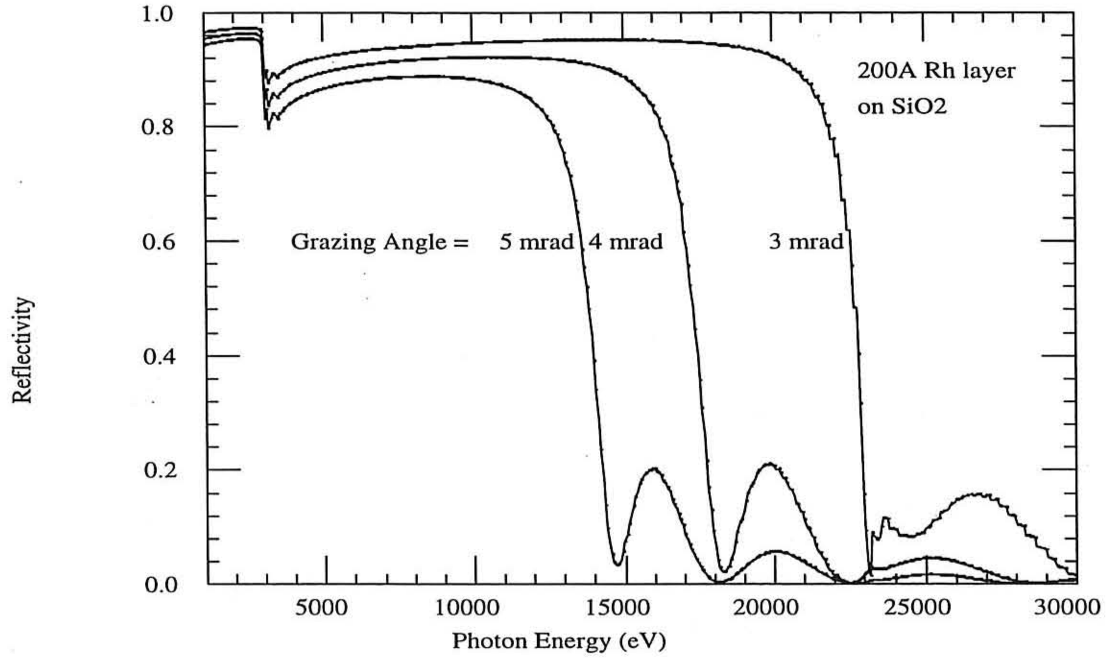


Figure 2: Calculated reflectivity for a 200Å Rh coating on SiO_2 with incident grazing angles of 3, 4 and 5 mradians.

2 Reflectivity

We assume the beamline optical layout can be characterized as containing in most cases a mirror and a pre-mirror followed by monochrometer. In some cases there may be only the two mirrors. Because of the need to reflect the harder x-rays, these mirrors will consist mostly of small grazing angle single layer mirrors such as Rh. We will use [5] the calculated reflectivities of a 200Å Rh coating on SiO_2 with incident grazing angles varying between 3 and 5 mradians to characterize the radiation shielding requirements. These are shown in Fig. 2 and are taken from Henke[6]. A $1/E^4$ scaling of the reflectivity at 30 keV is used for photon energies above 30 keV. This approximation is reasonable[4] above the K-edge of elements in the mirror coating. Rh K-edge is at 23 keV.

These reflectivities are folded into white beam dose rate energy spectra and summed over energy to determine dose rates from reflected beams.

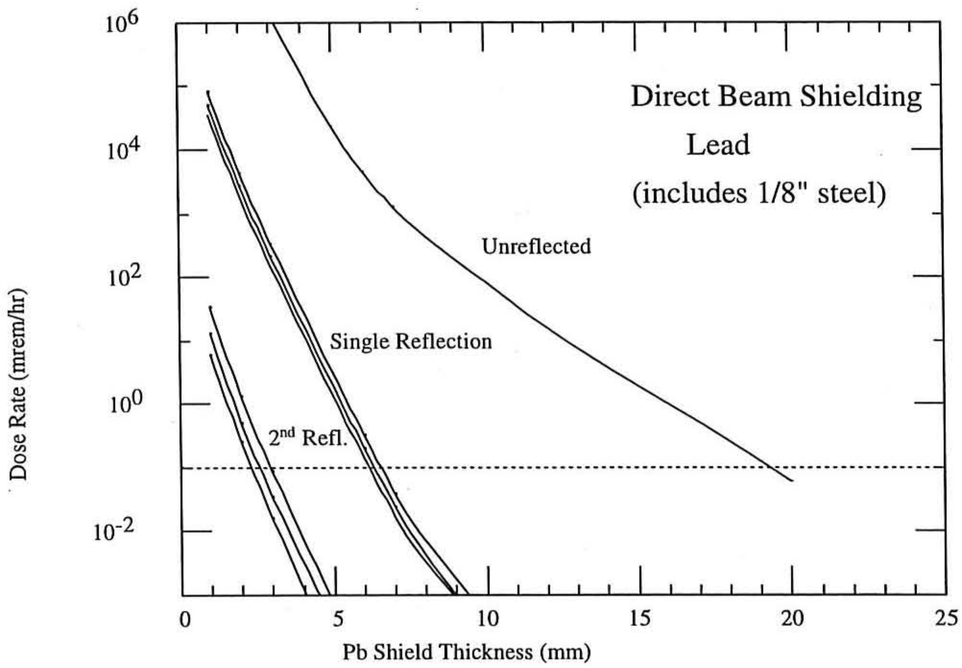


Figure 3: Direct beam Pb shielding. This includes a 1/8" steel beampipe/hutch wall.

3 Direct Beam Shielding

In this section we calculate dose rates through copper and lead shielding. Direct white beam masks must be water-cooled and constructed of copper. The same may be true for reflected beams. Lead results are presented mostly for information and comparison. All results assume 3 mradH acceptance, 1.9 GeV and 800 mA stored beam current. All shield thicknesses include 1/8" steel shielding to account for a hutch wall or beampipe.

PHOTON assumes an isotropic angular distribution for Compton scattered photons. This may be conservative for estimating dose rates at large angles but may underestimate the dose rate in the forward direction from the direct beam. For example, at 50 keV the Compton scattering cross section is two times higher for photons scattering at 0° than for photons scattering at 90°. For this reason we will use the same shielding criteria of 0.1 mrem/hr for the direct beam even though the downstream attenuated beam may still be contained in the beampipe.

The resulting required shield thicknesses are summarized in Table 1.

In contrast to these results are the shielding requirements for the present 1.3 T bend

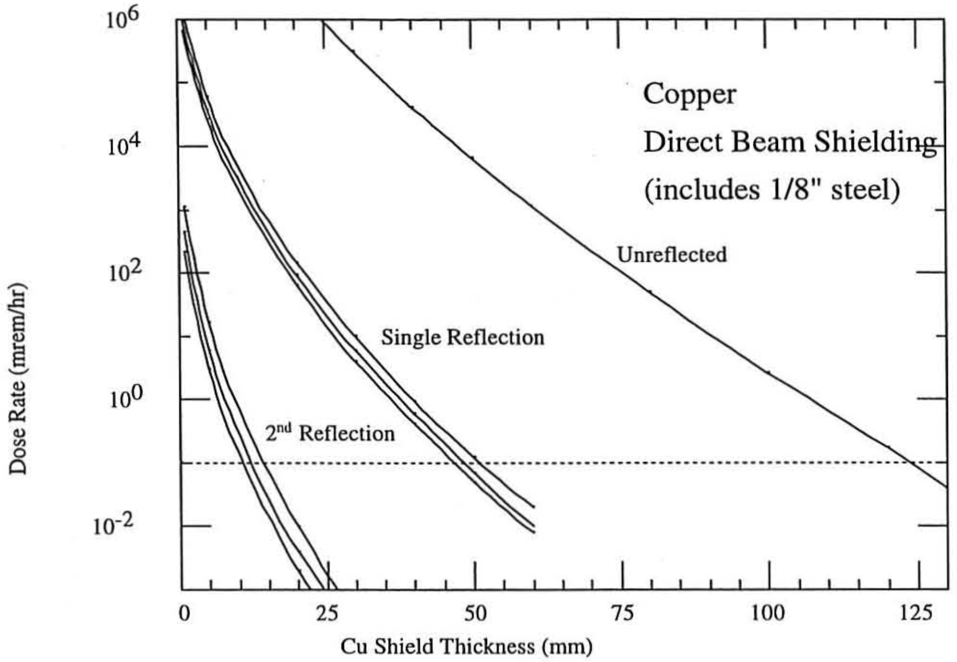


Figure 4: Direct beam Cu shielding. This includes a 1/8" steel beampipe/hutch wall.

magnets[7] which require only 3 mm of Pb to reduce the direct beam dose rates to below acceptable levels.

Table 1: Summary of Direct Beam Shielding Requirements. For reflected beams angles refer to the mirror incident grazing angle. For twice-reflected beam the first reflection is assumed to be 3 mrad in all cases.

Shield	Unreflected	Reflected			Twice-Reflected		
		3 mrad	4 mrad	5 mrad	3 mrad	4 mrad	5 mrad
Cu	125mm	50mm	50mm	50mm	15mm	14mm	13mm
Pb	20mm	7mm	7mm	6mm	3mm	3mm	3mm

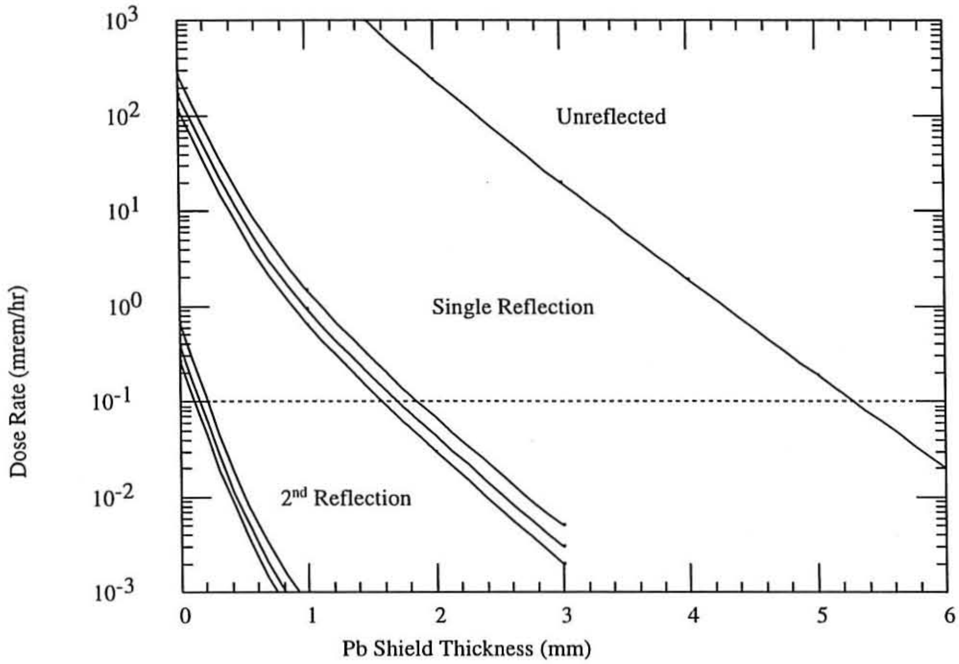


Figure 5: Scattered beam Pb shielding. This includes a 1/16" steel beampipe/hutch wall.

4 Scattered Beam Shielding

In this section we calculate the minimum shielding requirements for a fully scattered beam. For conservatism no self-absorption is assumed in the target material. Results are presented in Table 2 for white and reflected beams using Pb shielding. These values have been plotted in Fig. 5. The horizontal dotted line at 0.1 mrem/hr represents the shielding criteria.

No shielding is required for a twice-reflected beam if each reflection is $\geq$3 mrad incident grazing angle. In Fig. 5 it can be seen that without Pb shielding (only 1/16" steel) the dose rate from a doubly scattered beam is $\leq$0.6 mrem/hr. Because of the relatively low possible dose rate and the conservatism built into the scatter calculations no shielding is required. Radiation surveys may indicate areas of chronic low level scatter which can be locally shielded.

The photon dose rate spectra for various beamline configurations are shown in Figs. 6, 7, and 8. Results are shown for white beam in Fig. 6, pink beam in Fig. 7, and twice/reflected beam (two 3 mrad mirrors) in Fig. 8. For each plot the 4 curves represent the dose rate spectra unshielded (1/16" beampipe/wall only) as well as for 1, 2 and 3 mm of Pb. The Pb K-edge is evident at approximately 88 keV.

Table 2: Summary of Scattered Beam Shielding Requirements. For reflected beams angles refer to the mirror incident grazing angle. For twice-reflected beam the first reflection is assumed to be 3 mrad in all cases.

Shield	Unreflected	Reflected			Twice-Reflected		
		3 mrad	4 mrad	5 mrad	3 mrad	4 mrad	5 mrad
Pb	5mm	2mm	2mm	2mm	0	0	0

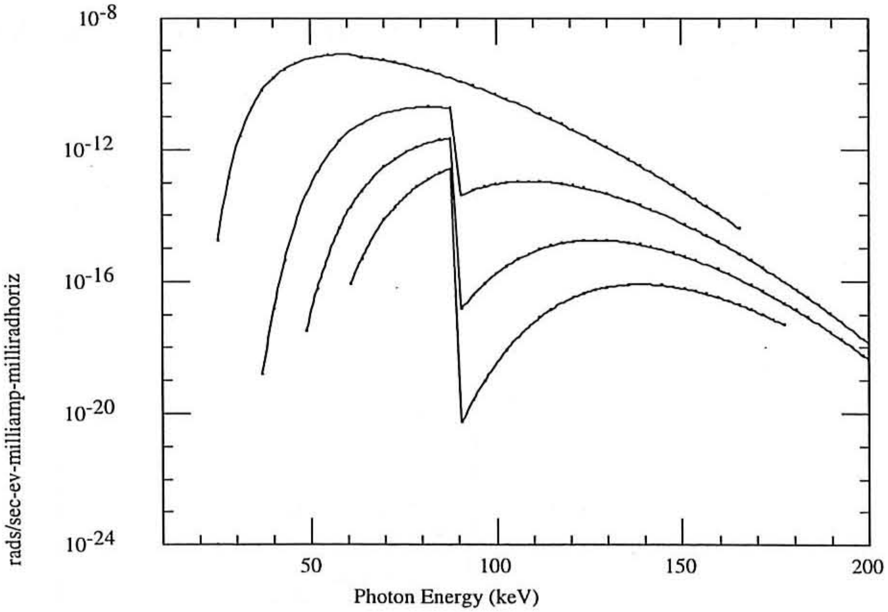


Figure 6: Photon dose rate spectra from scattered white (unreflected) Superbend beamline. Curves represent the spectra through 0, 1, 2 and 3 mm of Pb.

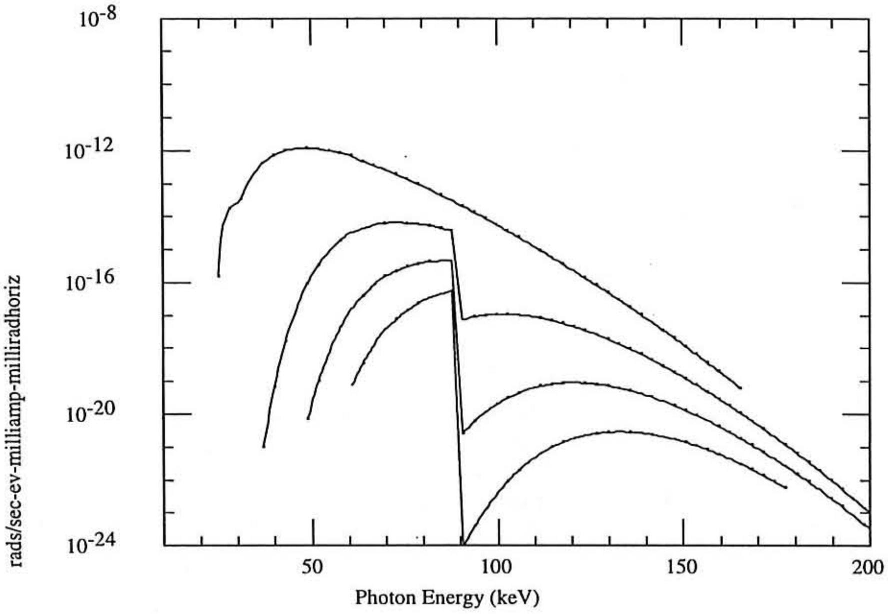


Figure 7: Photon dose rate spectra from scattered pink beam (3 mrad incident grazing angle on 200Å Rh mirror). Curves represent the spectra through 0, 1, 2 and 3 mm of Pb.

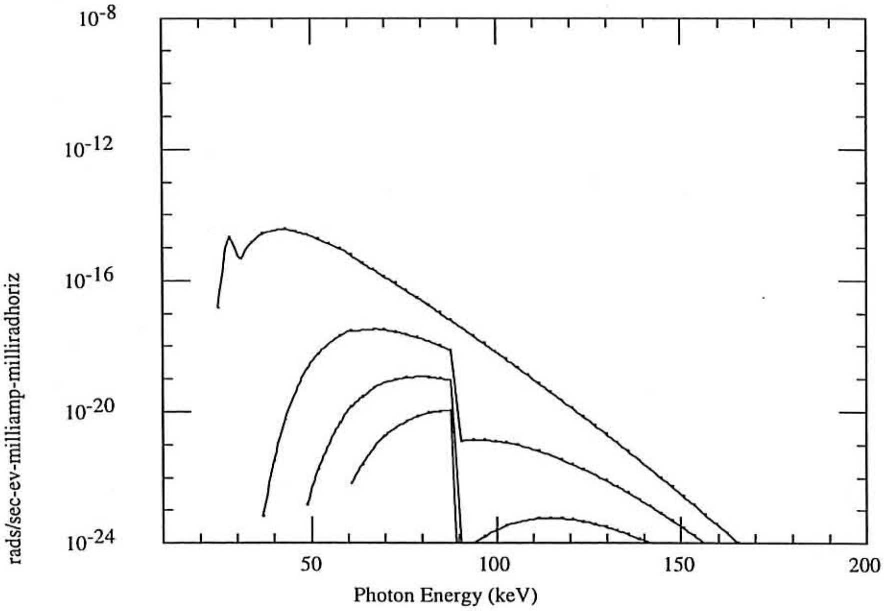


Figure 8: Photon dose rate spectra from scattered twice-reflected (two 3 mrad incident grazing angle on 200Å Rh mirror). Curves represent the spectra through 0, 1, 2 and 3 mm of Pb.

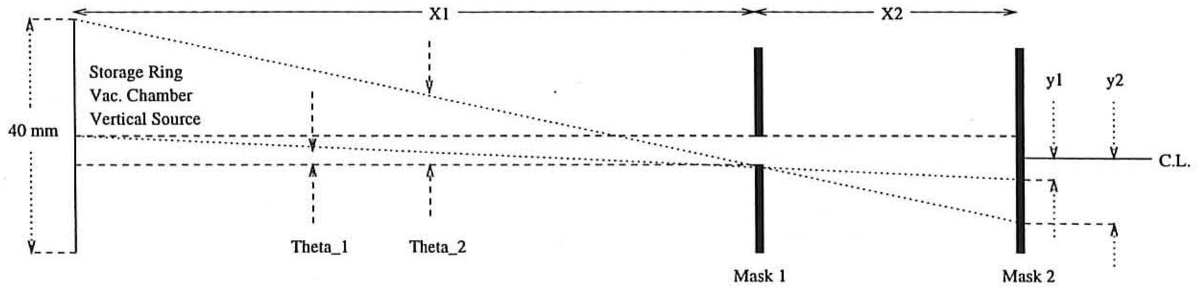


Figure 9: A raytracing...

As can be seen in these dose rate spectra, the dose rate outside Pb shields is dominated by x-rays in the range 60-88 keV. This range can be characterized as being from about 5X the critical energy ($E_{crit} = 12$ keV) and extending up to the Pb K-edge.

5 Masking Requirements

To ensure safe containment of x-rays, ray traces of the superbend synchrotron beam will be required. Fixed masks will be required at various locations to limit and/or stop the beam. In the horizontal plane the source size will be the entire horizontal acceptance of the beamline/frontend as limited by fixed masks. In the vertical plane, there are at least two possible methods of specifying the source size for the synchrotron ray traces. The first method would be to assume an isotropic point source at the center of the bend magnet and then require a 10 mm overlap between white beam edge and physical mask edge. This will be referred to as the 'point source approach'. The second method would be to assume an isotropic source vertically the size of the vacuum chamber (± 20 mm) as is used in the bremsstrahlung ray tracing at the center of the magnet, but then require no overlap between white beam edge and mask edge. This will be referred to as the 'large source approach'. These two ray tracings are shown in Fig. 9. The ray tracing from a point at the center of the e- beam vacuum chamber to the bottom edge of Mask 1 (creating the angle θ_1) represents the point source approach. The ray tracing from a point at the top of the e- beam vacuum chamber to the bottom edge of Mask 1 (creating the angle θ_2) represents the large source approach. X_1 and X_2 represent the distances from source to Mask 1, and from Mask 1 to Mask 2, respectively. Let h be the vertical half-height opening at Mask 1.

Table 3: Comparison of ray tracing techniques.

X_1	h	θ_1	X_2	θ_2	$y_1 + 10$ mm	y_2	θ_{mirror}	x_{clear}
7m	2 mm	0.286 mrad	1 m	3.14 mrad	12.3 mm	5.1 mm	6 mrad	2050 mm
			1.5 m		12.4 mm	6.7 mm		2072 mm
			3.0 m		12.9 mm	11.4 mm		2143 mm
8m	2 mm	0.25 mrad	1 m	2.75 mrad	12.3 mm	4.8 mm	6 mrad	2042 mm
			3.0 m		12.8 mm	10.25mm		2125 mm
	4 mm		1.0 m		14.3 mm	6.7 mm		2375 mm
			3.0 m		14.7 mm	12.3 mm		2485 mm

To compare the two possible approaches we compare the quantities y_1 $(= \theta_1 \cdot X_2 + h)$ and y_2 $(= \theta_2 \cdot X_2 + h)$ at the second mask. If we use the point source approach then Mask 2 must overlap the beam by the distance $y_1 + 10$ mm. If we use the large source approach then Mask 2 must overlap the beam by the distance y_2. These have been calculated for various values of X_1, X_2, h, and mirror incident grazing angle in Table 3. In addition to these values we also calculate the distance from a mirror to Mask 2 at which the reflected beam of angle θ_{mirror} (total reflection angle, not the incident grazing angle) clears Mask 2 which has a height of $y_1 + 10$ mm. This distance is equal to $(y_1 + 10 \text{ mm})/\theta_{mirror}$.

One can see from these results that when the masks are placed close to the source and the distance between masks is small then the large source approach (y_2) may only require an overlap of ~5 mm, whereas the point source approach provides a greater overlap and more consistency.

To provide a larger safety factor and margin of design error we recommend that synchrotron ray traces in the vertical plane use a point isotropic source in the center of the e- beam vacuum chamber. A combination of two masks must be used downstream of a reflected beam if a reduction in radiation shielding requirements is desired. The first mask serves to limit the trajectory of the unreflected beam, and the second mask stops the unreflected beam. An overlap of 10 mm is required from the edge of the unreflected beam, as defined by using a point isotropic source at the center of the e- vacuum chamber, and the physical edge of the second mask. For reflected beams the ray tracing reflected source should be isotropic in angular distribution from the surface of the mirror through the first downstream aperature.

6 Summary

Shielding requirements for the direct synchrotron beam have been summarized in Table 1 for both Pb and Cu. These include results for white beam, pink beam and twice-reflected beam.

Shielding requirements for scattered synchrotron radiation have been summarized in Table 2 for Pb. These include results for white beam, pink beam and twice-reflected beam.

Synchrotron beam ray traces must be drawn for superbend beamlines. Any reduction in white beam shielding requirements must be done with the use of two masks. White beam shielding requirements extend to the end of the 2nd mask. Ray traces of this idealized synchrotron beam must be drawn using the above described source sizes for vertical and horizontal planes. Masks must be placed such that ray traces show that all extreme unreflected ray traces are defined by the first mask downstream of the mirror and blocked by the 2nd mask. The slit opening in the two masks which allows the beam(s) (white+reflected for 1st mask, reflected only for 2nd mask) should be minimized. The masks should cover the entire beamline cross sectional area except for the slit. All masks used for safety purposes must be fixed in place. It is acceptable to use the frontend beamline aperature, AP001, as the first white light shielding mask.

Any reduction in pink beam shielding is performed in the same manner with 2 masks and ray tracings. The major difference is that the source size for the pink beam should be the extreme edges of the reflecting mirror and the ray traces are defined by the 1st and 2nd white masks. The 2 masks are put downstream of the second reflecting mirror. Everything from the shield wall to the 2nd white mask is assumed to be white beam transport and shielded as such. Everything from the downstream edge of the 2nd white beam mask to the 2nd pink beam mask is shielded using the pink beam (once reflected) shielding requirements. Everything downstream of the 2nd pink mask requires only 1/8" steel construction.

Ray trace drawings must be submitted for approval to the ALS Beamline Review Committee as part of the standard beamline design review package. Both vertical and horizontal plane ray tracings should be included. A copy of the first approved super bend synchrotron ray trace (Beamline 8.3.1, Dwg #25F5686) is attached.

References

[1] H. A. Padmore, *A Superconducting Bending Magnet Source for Protein Crystallography*, ALS Light Source Note LSBL-486, September 22, 1998.

[2] H. A. Padmore, *Optical Layout of Superbend Beamlines 4.2 and 4.3*, ALS Light Source Note LSBL-487, September 23, 1998.

[3] D. Chapman, N. Gmür, N. Lazarz and W. Thomlinson, *PHOTON: A Program For Synchrotron Radiation Dose Calculations*, NIM **A266**, 191-194 (1988).

[4] E. Gullikson, Center For X-ray Optics, LBNL, personal communication.

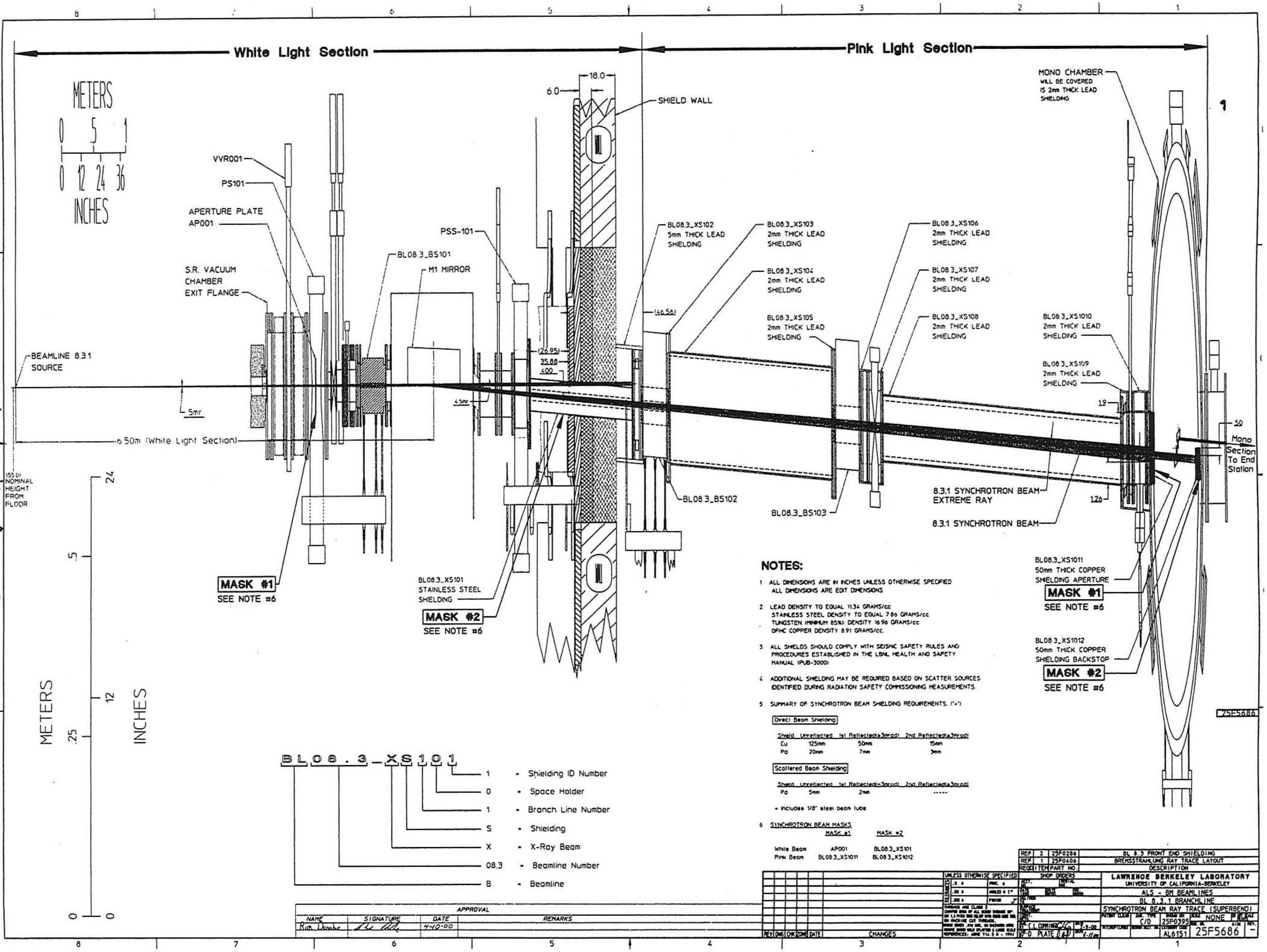
[5] H. A. Padmore, ALS Experimental Systems Group, LBNL, personal communication.

[6] B. L. Henke, E. M. Gullikson, and J. C. Davis, *X-ray interactions: photoabsorption, scattering, transmission, and reflection at E=50-30000 eV, Z=1-92*, Atomic Data and Nuclear Data Tables, July 1993, vol.54, (no.2):181-342 (see http://www-cxro.lbl.gov/optical_constants/).

[7] R. J. Donahue *ALS Synchrotron Radiation Shielding*, LBL-37801, October 1995.

Attachment 1

1



NOTES:

1 ALL DIMENSIONS ARE IN INCHES UNLESS OTHERWISE SPECIFIED
ALL DIMENSIONS ARE EDIT DIMENSIONS

2 LEAD DENSITY TO EQUAL 11.34 GRAMS/cc
STAINLESS STEEL DENSITY TO EQUAL 7.86 GRAMS/cc
TUNGSTEN (MINIMUM 85%) DENSITY 16.96 GRAMS/cc
OFHC COPPER DENSITY 8.91 GRAMS/cc.

3 ALL SHIELDS SHOULD COMPLY WITH SEISMIC SAFETY RULES AND PROCEDURES ESTABLISHED IN THE LBNL HEALTH AND SAFETY MANUAL (PUB-3000)

4 ADDITIONAL SHIELDING MAY BE REQUIRED BASED ON SCATTER SOURCES IDENTIFIED DURING RADIATION SAFETY COMMISSIONING MEASUREMENTS.

5 SUMMARY OF SYNCHROTRON BEAM SHIELDING REQUIREMENTS. ('*')

Direct Beam Shielding

Shield	Unreflected	1st Reflected(≥3mrad)	2nd Reflected(≥3mrad)
Cu	125mm	50mm	15mm
Pd	20mm	7mm	3mm

Scattered Beam Shielding

Shield	Unreflected	1st Reflected(>3mrad)	2nd Reflected(≥3mrad)
Pd	5mm	2mm	-----

* Includes 1/8" steel beam tube

6 SYNCHROTRON BEAM MASKS

	MASK #1	MASK #2
White Beam	AP001	BL08.3_XS101
Pink Beam	BL08.3_XS1011	BL08.3_XS1012

BL08.3_XS101

1 - Shielding ID Number
0 - Space Holder
1 - Branch Line Number
S - Shielding
X - X-Ray Beam
08.3 - Beamline Number
B - Beamline

APPROVAL			
NAME	SIGNATURE	DATE	REMARKS
Rick Donahue		4-10-00	

REQ'D	ITEM	PART NO.	DESCRIPTION
REF	2	25F0286	BL 8.3 FRONT END SHIELDING
REF	1	25F0406	BREMSSTRAHLUNG RAY TRACE LAYOUT

REV | DWG | CHK | ZONE | DATE | CHANGES

UNLESS OTHERWISE SPECIFIED
TOLERANCES .X ± / .XX ± / .XXX ± / FRAC. ± / ANGLES ± 1° / FINISH

SHOP ORDERS

C.L. CUMMINGS 4-9-00
D. PLATE 4-11-00

LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA-BERKELEY
ALS - BM BEAMLINES
BL 8.3.1 BRANCHLINE
SYNCHROTRON BEAM RAY TRACE (SUPERBEND)

DWG. TYPE C/D
DRAWN ON 25F0395
SCALE NONE
CATEGORY CODE AL6151
DWG. NO. 25F5686
REV. -

25F5686