SINGLE PASS COLLIDER MEMO CN-357

TITLE: RADIATION MEASUREMENTS IN THE NORTH ARC
- NOV 1986 THROUGH APRIL 1987
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DATE: 12 May 1987

Introduction. This note is an effort to share preliminary data on radiation measurements. We report measurements made using passive lithium-fluoride thermoluminescent dosimeters (TLD) placed in the North arc during the start-up period of the Stanford Linear Collider (SLC). Li-7 dosimeters were used for ionizing radiation measurements, and Li-6 dosimeters moderated by polyethylene were used for measuring neutrons. In addition, some measurements were made near alcove N-6 using a Cs-137 gamma-ray source in order to determine the effectiveness of the 2 inch lead wall placed at the entrance to the alcove.

The initial beam energy, about 34 GeV, was quickly raised to 47 GeV. None of the measurements should be strongly dependent on beam energy. For the first few months, the beam was taken to the reverse bend. Thereafter, it was allowed to go as far as the North final focus, and beyond the interaction point. For the period when the beam was stopping at the reverse bend, there was no Pb in the magnet gaps and no Pb wall at the alcoves (except N-3). When it became apparent that significant doses were being recorded at some alcoves, Pb walls were put in front of those electronic racks and Pb was put in the magnets. The Pb (approximately 1/2 inch square) in the magnet gaps was placed only on those magnets where the gap faces the aisle, and typically was put on four such magnets upstream of each alcove and three such magnets downstream of the alcoves.

Vertical profiles were made of the photon dose at the entrance to alcove N-3 before and after the Pb was added to the magnets. Measurements were also made in front of and behind the 2 inch thick Pb wall. In addition, measurements were made of the transmission of photons in Pb using spheres of different wall thicknesses.

Finally, neutron fluences were measured at a few selected alcoves (N-1, N-3 and N-15T). Only one of these was made in the shadow of a Pb wall.

MEASUREMENTS OF CS-137. Since the spectrum of photons escaping from an e-m cascade is rich in low energies which are readily scattered from tunnel walls, the simulation of this component with a CS-137 source (662 keV) seemed appropriate. The CS-137 source was placed in three different locations; 1) on top of a magnet directly opposite the alcove, 2) behind a magnet directly opposite the alcove, and 3) on top of a magnet about 30 feet upstream of the alcove. Measurements, using a plastic scintillator survey meter, were made in front of the shield wall (center, upper and lower edges, right and left edges), behind the wall, in front of the electronics rack, to the rear of the rack, and in the space beside the rack not shadowed by the Pb wall (See Fig 1 for a better view).

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Fig 1. Typical alcove (N-6) with Pb wall.
X = Measurement points for CS-137.

The absolute decrease in dose at the entrance to the alcove for a source on top of the magnet versus one shadowed by the magnet (*i.e.*, behind it) is a factor of about 20. This is consistent with the expected scattering of X-rays of this energy from concrete.

Table 1 gives the relative dose rate ratios measured at the center of the shield. The 'shadow' is fairly uniform right-to-left and up and down; that is, the front-to-back or front-to-rack ratios are fairly constant across the shield until one reaches the shield edge. Dose rates beside the rack (not in the shadow of the wall) fall off approximately as $1/r^2$ as expected for the source on top of the magnet, and somewhat faster for the source located on the far side of the magnet.

Table 1
Photon Dose ratios - Front of shield-to-location

Source	Back of shield	Front of rack	Back of rack
On magnet	30	31	32
Behind magnet	29	21	17.3
30 ft upbeam	9.4	6.2	48.5

From this, we note that the front-to-back or to-rack ratios are little affected by having the source 'visible' or 'shadowed' by the magnet when the source is located directly opposite an alcove. Also, the ratios (and the doses) don't change from front of the rack to rear of the rack.

When the source is upbeam of the alcove, however, there is a decrease in the front-to-rear ratio (*i.e.*, the Pb shield is less effective), which probably is due to radiation leaking past the upbeam gap between Pb wall and alcove wall; *i.e.*, radiation arrives without being transmitted through the Pb. However, there is a large decrease in the ratio at the rear of the alcove where the shadowing of the alcove wall becomes the dominant shield.

These measurements suggest that the location of the source, upbeam or opposite the alcove, is very important for the shield. Also, the shield wall shouldn't have any large gaps if it is to be effective (this is not the case for the present alcove shield walls).

BEAM MEASUREMENTS - PHOTONS. Measurements were made at alcove N-3 which had a source location (determined from residual radiation) in the 3rd open gap magnet (with open face toward the aisle) upbeam of the alcove. Vertical profiles were determined before and after Pb was added to the aisle-facing open-gap magnets (4 such magnets upbeam and 3 downbeam of the alcove). These are shown in Fig. 2, normalized at the end points. The peak-to-edge dose is reduced by a factor of about 4 with the addition of the Pb; *i.e.*, without Pb, the peak-to-edge ratio is about 5.8 and with Pb, it is about 1.5. Nothing can be said about the absolute reduction in dose per incident electron since we had no reliable beam intensity information for this period.

Figure 2. Vertical radiation profile at Alcove N-3.

Transmission measurements of ionizing radiation were made using Pb spheres with different wall thicknesses. These spheres were located in the aisle in front of alcove N-3. Each sphere had a TLD on the outside as well as one inside in case there were differences in the incident radiation field. In addition to the spheres, thin Pb disk absorbers were placed inside a 1-1/4 inch diameter hole in a Pb brick, with the hole (and absorbers) facing the accelerator. All absorbers were placed at beam height.

Fig. 3 shows a 2-component transmission curve. The initial steeper slope is due either to low energy photons or to electrons. The second component is due to photons with an average energy of either 1 or 10 MeV (there are two possible values because the slope corresponds to points on either side of the Compton minimum). We would anticipate a slope corresponding to the minimum at about 3 or 4 MeV in Pb.

Figure 3. Dose as measured with Li-7 TLD's through various thicknesses of Pb.

Measurements were also made using the Pb disks inside the Pb brick with the unit about 6 inches from the open gap of the first open-gap magnet downbeam of N-3. This magnet showed no sign of induced activity, and thus the measurements should be of a small beam loss perhaps located upstream somewhere. The results are shown in Fig. 4, where an initial rise is seen (photons generating electrons) followed by attenuation.

Figure 4. Dose through Pb adjacent to a 'quiet' magnet.

The front-to-back (front of Pb wall-to-back of Pb wall) or front-to-rack (front of Pb wall-to-front of electronic rack) ratios tend to vary somewhat with time and location, but average about 6.4 for front-to-rack over most of the alcoves. Table 2 gives what little data is available to date.

Table 2
Photon Dose ratios - Front of shield-to-location

Alcove	Back of shield	Front of rack
N-3 (Dec 86)	5.2	
N-3 (Jan 87)	17	
N-3 (Mar 87)		9.6
N-15T (Apr 87)		7.5 ^a
N-6 (Apr 87)		12.1
N-15T (Apr 87)		4.1 ^b
N-14 (Apr 87)		7.1

Note a) The 'front' TLD was actually located on the front of the electronics rack, but above the shadow of the Pb shield.

Note b) The front TLD was located on the front of the Pb shield. The shield was moved closer to the rack, and an additional shield was placed at the side of the rack before this measurement.

The apparent worsening of the front-to-rack ratio in alcove 15T between early April and late April is confusing, and points out some of the difficulties in projecting these measurements to normal running conditions. The higher ratio in early April may be due to a non-uniform radiation field in the vertical plane; i.e., the dose seen by the TLD above the shadow of the Pb wall may be higher than a dose at the plane of the beam (due to shadowing effect of components in the beam line, for example). We have no vertical profile measurements in the Final Focus, nor would we have any confidence in such a measurement since it would be a strong function of where the beam was striking.

The lower ratio seen in late April may be due to radiation coming from PC-24 upbeam at a shallow angle, and which might contain high energy photons. Future readings hopefully will clarify this picture.

The cumulative doses in all the north arcs are shown in Fig 5 as a function of time since beam turn-on (in Oct 1986). These show the effects of initial high beam currents, transmission difficulties and other problems associated with new beam lines.

The week of 14 - 22 April was used as a basis for extrapolating to full beam intensity (5×10^{10} particles per pulse), 180 pps and 4000 hrs per year operation. Shift summaries made by the shift operators were used to get beam-delivered times, currents and rep rates. For this period, a total of 1.23×10^6 bunches of 2×10^9 electrons per bunch were delivered to the arc, for a total number of electrons delivered of 2.46×10^{15} . The total number of electrons that would be delivered in a 4000 hr year at 180 pps and $5 \times 10^{10} e^-$ per bunch would be 1.3×10^{20} . Thus, the April 14 - 22 run represents 1.7×10^{-5} of a year's operation, or conversely, there will be 5.28×10^4 times more electrons in a nominal year's run.

Fig. 5a-b. Cumulative photon doses in the North alcoves.

Fig. 5c-d. Cumulative photon doses in the North alcoves.

There are many reasons for not extrapolating a week's run at low currents to a year's run at full current, among which are: 1) the wake fields increase with bunch intensity with a concomittant increase in tail size, 2) some of these losses are due to poor steering and will get better (less) with time, 3) Many of the beam line components aren't in position, or aren't set to nominal settings. This is especially true of the Final Focus where some protection collimators still are to be installed, and those which are in place are set to maximum aperature, 4) A few of the alcoves already have a Pb wall, leaky as it may be, and thus represent some shielding, and 5) as can be seen from Fig 4, loss points (and subsequent dose rates) vary dramatically from week to week, and projecting doses from any one week is fraught with hazards. Also, during some of this period, there was intentional beam missteering for phase shift studies.

However, in spite of the above worries, and knowing full well that the numbers generated will come back to haunt us (since many readers will remember the numbers but none of the admonitions that accompany them), we present Table 3, an extrapolation to full beam running based on the April 14 - 22 run.

Table 3
Annual photon doses extrapolated to full running.

Alcove	Rads/year
N-1	8.6×10^6
N-2	7.9×10^5
N-3	2.0×10^7
N-4	7.3×10^5
N-5	2.1×10^6
N-6	4.6×10^5
N-7	5.2×10^5
N-8	4.7×10^4
N-9	1.7×10^5
N-10	1.0×10^5
N-11	1.9×10^5
N-12	6.9×10^4
N-13	3.0×10^6
N-14	1.2×10^5
N-15	1.5×10^5
N-15T	7.4×10^5
N-16	4.1×10^5

BEAM MEASUREMENTS - NEUTRONS. Neutron fluences were measured with moderated Li-6 TLD's which measure neutrons in the energy range of about 10 keV to about 10 MeV. Only a few select alcoves were monitored (N-1, N-3 and N-15T), and of these, only N-1 has any measurements behind a shielding wall. The hope was to find a uniform neutron fluence-to-photon rad dose ratio that could be applied to all alcoves. This should be adequate since neutrons are expected to be some orders of magnitude less of a problem than photons. (The annual criteria are 10^3 rads/yr and 10^{13} n - cm⁻²/yr.) The ratios given in Table 4 are those using the photon rad dose measured at the outside surface of the moderator; i.e., it is the ratio at the spot the moderator happens to be. In alcove N-1, the first measurements were made with the moderator on the ledge between the alcove and the BSY. Subsequent measurements were made with the moderator on top of one of the modules inside the electronics rack, and with a Pb/concrete shadow shield between the rack and the BSY. Measurements at N-3 were made with the moderator on the very top of the electronics rack well above the Pb shadow shield. The moderator at N-15T was placed on the floor not shielded at all.

Table 4
Neutron fluence-to-photon rad dose ratios..

Dates	Alcove N-1	Alcove N-3	Alcove N-15T
1/15 - 1/20		6.1×10^5 a	
1/22 - 1/26	8.7×10^5		
1/22 - 2/8			3.3×10^6
2/8 - 2/24	1.2×10^6		
2/23 - 4/22	1.0×10^6	5.4×10^6	
3/17 - 3/31			4.1×10^6
3/31 - 4/15			4.8×10^6
4/22 - 4/28		8.4×10^6	
4/15 - 4/28			4.4×10^6

Note a) The moderator was in the aisle for this first measurement.

An average ratio might be about 5×10^6 n - cm⁻² per photon rad. If this were included in Table 3, the annual projected neutron fluences would range from a high of 1×10^{14} n - cm⁻² - yr⁻¹ (Alcove N-3) to a low of 2.4×10^{11} n - cm⁻² - yr⁻¹ (Alcove N-8); i.e., the highest alcove is only a factor of 10 above the annual neutron fluence criterion.

SHIELDING TO TOLERANCE. From Fig 2, we see an initial drop from absorption of low energy ionizing radiation. As soon as some shielding material is added, this component of the measured dose will disappear. Thus, we take the values given

in Table 3 and divide by 4 to get the zero thickness values due only to the higher energy component. To these values, we apply the absorption length of $32g/cm^2$.

The worst alcove is N-3, where the annual dose due to the higher energy photon component would be 6.7×10^6 rad/yr ($2 \times 10^7 / 4 = 6.7 \times 10^6$). To reach 10^3 rad/yr, we need a reduction of 1.5×10^{-4} . This would be achieved by the addition of 24.8 cm of Pb (about 10 inches).

The best alcove (N-8) is $4.7 \times 10^7 / 4 = 1.2 \times 10^4$ rad/yr. A reduction of 8.3×10^{-2} is needed to reach 10^3 rad/yr, which is achieved by the addition of about 7 cm (about 3 inches).

SUMMARY. Radiation measurements in the tunnel have been increasing since beam turn-on in late October. The ionizing doses are such that a few alcoves have already exceeded the annual criterion of 10^3 rad per year, with some of those doses acquired with a 2 inch Pb wall in place. Measurements before and after the Pb wall indicate ratios on the order of 20 to 30 for a CS-137 source located opposite the alcove, and about 6.5 for beam operation. Gaps in the shield wall are important from the standpoint of radiation leakage.

Vertical profiles made before and after Pb was placed in the open gaps of the magnets facing the aisle show a relative reduction in the peak of a factor of about 4.

The annual doses, projected to full beam operation from one week's run, are some 10^2 to 10^4 above the tolerance criterion. To shield these would require Pb thicknesses of 25 cm or so in the worst case, and 7 cm in the best.

We note that with shielding factors of 10^3 or more needed, holes in the shield become very important. The present shields, which are no more than leaky shadows, would be inadequate even if they were made thicker.

As the photons are attenuated by adding Pb, the neutron fluences become increasingly important since they are almost unattenuated, even by large thicknesses (the fluence of giant resonance neutrons is reduced only to 80% through 6 inches of Pb). The energy is reduced, however, such that subsequent moderation (by polyethylene, for example) is quite effective. To achieve a factor of 10 reduction, about 5 cm (2 inches) of polyethylene would be required on the inside of the Pb shield.

Finally, measurements to date suffer from insufficient beam intensity information. To be able to make any absolute sense of the data, torroids at the beginning of the arcs and the end of the final focus should be working.

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