Radiation Protection Scheme for the LCLS Injector

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The Linac Coherent Light Source (LCLS) at SLAC will be the world's first hard x-ray free electron laser when it becomes operational in 2009. Commissioning of the injector for LCLS started in March of 2007. This injector includes an RF-gun and two accelerator sections (installed within a vault off the main SLAC – Sector-20 vault), followed by a spectrometer, a Bunch Compressor and a tune up dump (installed in the existing LINAC tunnel – Sector-21). Areas of concern include four penetrations in the Sector-20 Alcove and five penetrations in Sector 21 tunnel. The shielding requirements for injector operation are described in this paper. The total dose rates above the penetrations are shielded to be less than 5 µSv/hr, 0.1 mSv/hr and 10 mSv/hr for normal, mis-steering, and maximum credible beam losses, respectively. Beam Shut-Off Ionization Chambers (BSIOCs) and the Beam Containment System (BCS) devices are employed to detect abnormal beam losses in mis-steering conditions and maximum credible beam losses.

I. RADITION LEVELS in SECTOR-20 ALCOVE

An alcove above sector-20 vault was rebuilt and used as the LCLS injector laser room and injector control center. There are four penetrations through 25' earth from the Injector Vault to the ground surface of the alcove (Figure 1): the stairway, one laser penetration, one unused penetration, and one ventilation penetration.

I.A. Design Criteria

In the shielding calculations which follow, the following three criteria must be satisfied:

1) Normal loss scenario: < 5 µSv/hr
2) Mis-steering scenario: < 4 mSv/hr
3) Accident scenario: < 250 mSv/hr

I.B. Radiation Sources and shielding requirements

The radiation entering the Sector-20 Alcove has two sources:

a. Radiation streaming through the penetrations from the Injector Vault below,
b. Radiation from SLED cavities and klystrons in the adjacent Klystron Gallery.

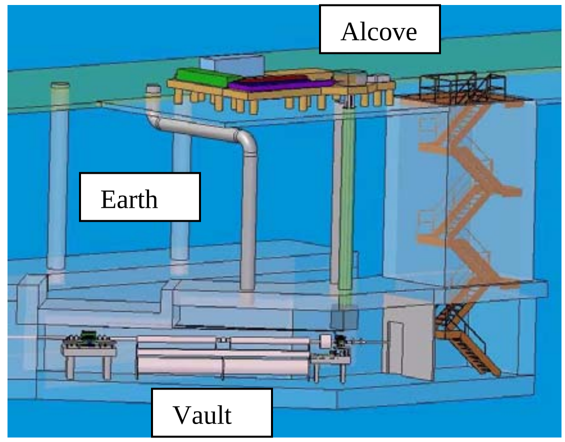

Fig. 1. Sector-20 vault and alcove

Emma et al. described the radiation sources and nominal beam powers during operation of the injector in LCLS Physics Requirements Document, "Electron Beam Loss in the LCLS" [1]. Figure 2 shows the beam loss points A to E, where Faraday Cups and insertable view screens are located. Screens also exist beyond point E but are far enough from the injector penetrations to have little contribution.

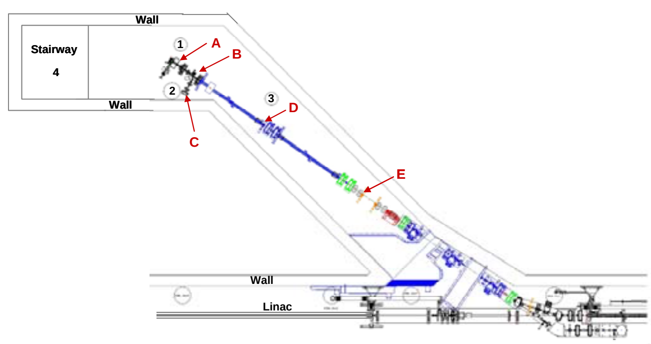

Fig. 2 LCLS injector beam loss points

Table 1 lists the radiation sources from inserted Faraday cups and profile screens, and nominal beam powers during 120 Hz operation of the LCLS injector. Note that dark current from the gun may be lost at Point A *or* Point

B, but not both simultaneously since FC01 stops the beam. Beam may be lost at any point from A to E.

Table 1. The radiation sources from inserted Faraday cups and profile screens, and nominal beam powers

Beam loss point	Dark current parameters	Beam parameters
A Faraday cup FC01	6.2 MeV, 2.2 W (source = gun)	6.2 MeV, 0.7 W
B YAG02, thick screen	6.2 MeV, 2.2 W (source = gun)	6.2 MeV, 0.7 W
C Faraday cup FCG1	6.2 MeV, 0.45W (source=gun)	6.2 MeV, 0.7 W
D YAG03, thin screen	56 MeV, 1.1 W (source = accelerator section L0A)	62 MeV, 7.4 W
E OTRH1, thin screen	130 MeV, 2.5 W (source = sections L0A&L0B)	135 MeV, 16 W

N. Nakao, *et al.*, [2] used the MARS14 Monte Carlo code to calculate dose rates from radiation streaming through the injector penetrations (assuming no shielding), based on the beam losses provided by Emma. (It is assumed that the entire nominal beam power can be lost at a single point.) The dose rate above the ventilation penetration is very low (1.5×10^{-4} µSv/hr) since this penetration has two bends. Iron shielding is used to attenuate the radiation levels in the alcove to design criteria. In the iron shielding calculations, the gamma attenuation was estimated using $\mu_{en}/\rho = 1.997\times10^{-2}$ cm^2/g and the neutron attenuation was estimated using $\mu/\rho = 7.6\times10^{-3}$ cm^2/g for Giant Dipole Resonance neutrons.

Radiation in the alcove also comes from the Sector-20 klystrons and SLED cavities. Lead shielding was installed around SLED cavities. Radiation levels were about 0.5 to 1 µSv/hr in the general area of the Alcove with the klystrons operating at 120 Hz as measured by the RPFO group.

Table 2 summarizes the shielding requirements and dose rates for the Sector 20 Alcove penetrations, with the effect of the klystrons and SLED cavities included.

Table 2. Sector-20 Alcove Summary

	Above Laser Penetration	Above Unused Penetration	1 ft to the side of Stairway Penetration
Beam losses in normal running condition	Mainly from point A Beam and dark current	Mainly from point C Beam and dark current	Mainly from point C Beam and dark current
Shielding requirement	7" iron	18" iron	PPS barrier 1 ft away from the edge of the penetration
Dose rate in normal running condition	5.2 µSv/hr Gamma	4.0 µSv/hr Gamma	3.2 µSv/hr Gamma
Dose rate from SLED	< 1 µSv/hr Gamma	< 1 µSv/hr Gamma	< 1 µSv/hr Gamma
Total dose rate	6.2 µSv/hr Gamma	5.0 µSv/hr Gamma	4.2 µSv/hr Gamma
Dose rate limit	10 mSv/year	10 mSv/year	10 mSv/year

* A person working above laser penetration should be less than 2000 hr/year.

I.C. Dose Rates and Shielding Requirements for Maximum Credible Beam

The source of the maximum credible beam is explosive electron emission from the photocathode should the drive laser intensity exceed the threshold for plasma production. In this event, the gun's RF field can extract a large number of electrons from the plasma which are accelerated out of the gun and into the beamline. This electron emission persists until it has depleted the gun of all its energy. The time to deplete the gun of all its energy is approximately 300ns [3]. P. Emma et al. described the maximum credible beam powers in different locations in LCLS Physics Requirements Document, "Electron Beam Loss in the LCLS" [1].

The maximum credible beam power in the gun region is 1000 W. It is conservatively assumed that the entire 1000-W beam can be lost at point A (FC01). Table 3 lists the dose rates above the penetrations and the required Beam Shut-off Ion Chamber (BSOIC) for this case.

Table 3. Dose rates above the penetrations and required BSOIC for maximum credible beam loss in gun region

	Laser Penetration	Unused Penetration	Stairway Penetration (1ft outside)
Dose rate	1.75 mSv/hr	0.054 mSv/hr	0.21 mSv/hr
Radiation type	Gamma	Gamma	Gamma
BSOIC	Yes, Gamma sensor	N/A	Yes, Gamma sensor
Trip level	0.1 mSv/hr	N/A	0.1 mSv/hr

The maximum credible beam power that can be lost at point C is 200 W. Table 4 lists the dose rates above the penetrations and the required BSOIC for this case.

Table 4. Dose rates above the penetrations and required BSOICs for maximum credible beam loss at point C

	Laser Penetration	Unused Penetration	Stairway Penetration (1ft outside)
Dose rate	0.001 mSv/hr	0.67 mSv/hr	0.55 mSv/hr
Radiation type	Gamma	Gamma	Gamma
BSOIC	N/A	N/A	Yes, Gamma sensor
Trip level	N/A	N/A	0.1 mSv/hr

The maximum credible beam power loss in L0B (between points D and E in Figure 2) is 2200 W. It is conservatively assumed that the entire 2200-W beam can be lost at the beginning of L0B. Table 5 lists the dose rates above the penetrations and the required BSOICs for this case.

Table 5. Dose rates above the penetrations and required BSOICs for maximum credible beam loss at L0B

	Laser Penetration	Unused Penetration	Stairway Penetration (1 foot outside)
Dose rate	0.27 mSv/hr	0.071 mSv/hr	0.34 mSv/hr
Radiation type	Neutron	Neutron	Neutron
BSOIC			Yes, Neutron sensor

It is required to install two BSOICs in the Sector 20 alcove: one on the top of the laser penetration (with gamma sensor only), and one with both gamma and neutron sensors on the PPS barrier wall around the stairway. These BSOICs are required to be set to trip at 0.1 mSv/hr.

II.A. RADITION LEVELS IN IN THE EXISTING LINAC TUNNEL – SECTOR-21

The LCLS injector beam is bent to the existing Linac – sector-21 using magnet BX01/02 after the beam leaves the vault (Figure 2). The beam will park on tune up dump SDMP when magnet BX01/02 is off. The beam will go through accelerator section 21-1, X-iris, Beam Compressor 1 (BC1) and hit tune up dump TD11 when magnet BX01/02 is on. Five penetrations are located above the 2-Mile Linac tunnel in the region between the injector vault and Dump TD11: penetrations 21-1, 21-2, 21-3, 21-4 and 21-5.

Emma et al. described the normal beam losses and the maximum credible beam power in different locations in LCLS Physics Requirements Document, "Electron Beam Loss in the LCLS" [1]. Table 6 lists the normal beam losses at five locations and related geometries to adjacent penetrations.

Table 6. Radiation sources and penetrations in the region between the LCLS Injector Vault and Dump TD11

Penetration	Nearest main source	Energy (GeV)	Beam loss (W)
21-1	Magnet BX01/02	0.135	2
21-2	Dump SDMP	0.135	16
21-3	X-iris (Aperture radius = 3.73 mm)	0.250	0.5 Dark current
21-4	Collimator CE11 in BC1 chicane	0.250	0.1 – 30 Nominal = 0.1 W
21-5	Dump TD11	0.250	30

The neutron and photon source terms (dose rates at the entrance of the penetration) were obtained with the SHIELD11 code [4]. The SHIELD11 results were scaled to the beam loss power, and the attenuation in the penetrations was estimated using the universal transmission curves [5] (see Figure 3).

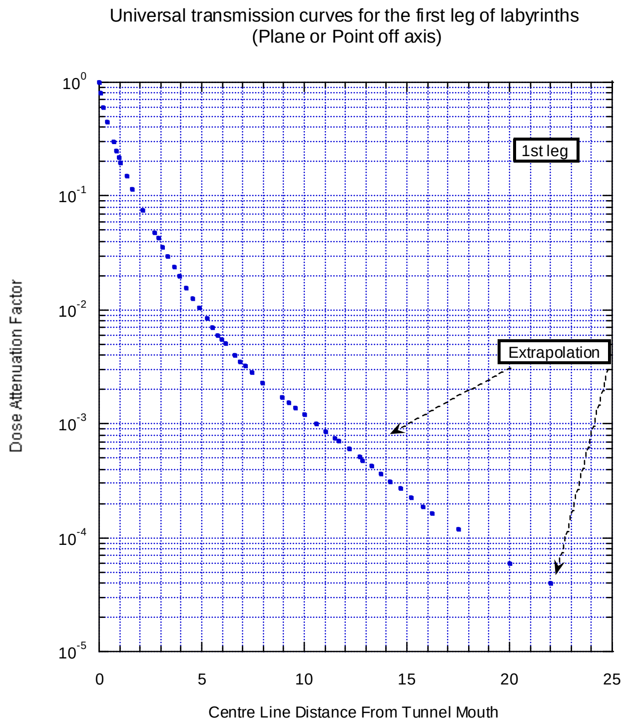

Fig. 3 Universal transmission curves

Iron shielding and borax is used to attenuate the radiation levels above the penetration to design criteria. In the iron shielding calculations, the gamma attenuation was estimated using $\mu_{en}/\rho = 1.997\times10^{-2}$ cm^2/g and the neutron attenuation was estimated using $\mu/\rho = 7.6\times10^{-3}$ cm^2/g for Giant Dipole Resonance neutrons. The Borax attenuation data were from W. R. Nelson's measurements [7]. Table 7 lists the radiation dose rates above/outside the penetrations when the required shielding is in place.

Table 7. Shielding requirements for penetrations

Main Source	Penetration	Shielding requirements	Total dose rate above (mSv/hr)	Total dose rate outside (mSv/hr)
Magnet BX01/02	21-1	24" Borax	4.1	0.9
Dump SDMP	21-2	24" Borax	11	2.4
X-iris	21-3	16" Borax	1.6	0.3
Collimator CE11	21-4	24" Borax	33/30 W	7.3/30 W
Dump TD11	21-5	16" Borax + 3" steel	23	4.4

Residual radiation dose rates from activated beam components are normally shielded to about 0.1 mSv/hr at 1 foot in the main LINAC, except for a few hot spots, based on ALARA. Table 8 lists the shielding requirements and dose rates (with shielding) for residual radiation from dumps SDMP and TD11. The dose rates are for a 1-foot distance and assume a 1-hour cooldown period.

Table 8. Minimum shielding requirements and dose rates for residual radiation from SDMP and TD11

Source	5" steel (mSv/hr)
Dump SDMP	0.11
Dump TD11	0.21

The dose rates around Dump TD11 are designed to be 0.21 mSv/hr, which are higher than those around Dump SDMP. The shielding near Dump TD11 needs to be removable for alignment purposes. Thinner shielding would be easier to be moved in and out. The shielding height and length should cover ± 45^o from the centers of the dumps on the aisle side.

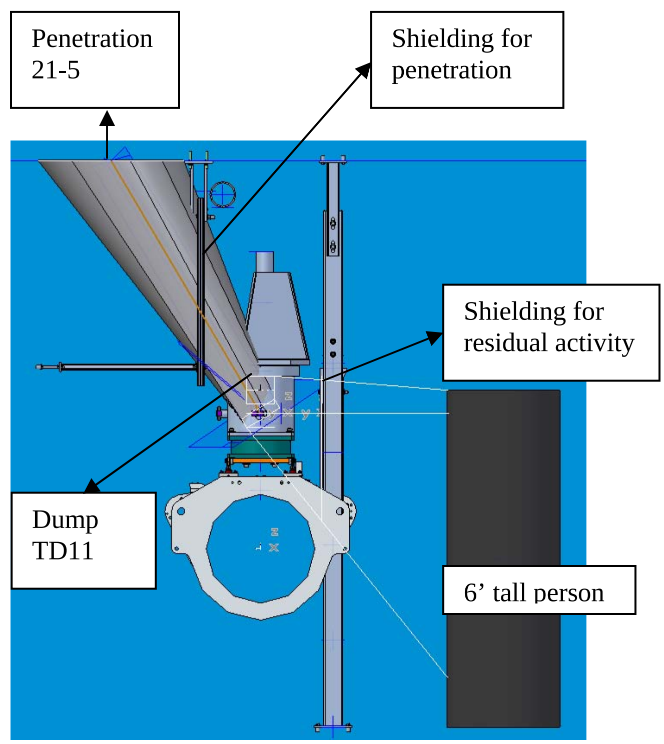

Fig 4. Shielding engineering design for dump TD11

The design of the shielding on the aisle side for Dumps SDMP and TD11 was completed [7] and is shown in figure 4. Figure 4 shows the aisle shield (foreground) mounted floor to ceiling. The black cylinder represents a 6 foot tall person standing approximately in the center of the aisle. The steel shielding with thickness of 5 inches covers the person when the dumps are in the “in” and “out” positions.

II.B. BCS Requirements, Mis-steering Conditions, and Maximum Credible Beam Loss – from LCLS Injector gun only

Two BCS flow switches will be required on the dump SDMP. The power capability of the dump is 20 kW with water cooling [8]. This dump is capable of absorbing LCLS maximum credible beam indefinitely, so ion chamber protection and a burn-through monitor are not required. These devices will fault both LCLS gun and LINAC gun.

A pair of LIONs (LION 1A and 1B) will limit beam losses to 100 W or less in the BX01/BX02, BXS/SDMP region; these are the magnets that deflect LCLS beam into the LINAC, or deflect beam into the SDMP tune-up dump (see Figure 5). These LIONs will fault both LCLS gun and LINAC gun. A pair of LIONs (LION 2A and 2B) will limit beam losses to 100 W or less in the LINAC X-iris, BC1/CE11, and dump TD11 areas. LINAC X-iris has a small limiting aperture, BC1 is a moveable chicane, CE11 is a set of energy collimator jaws in BC1, and TD11 in an insertable tune-up dump. (see Figure 5). These LIONs will fault both LCLS gun and LINAC gun.

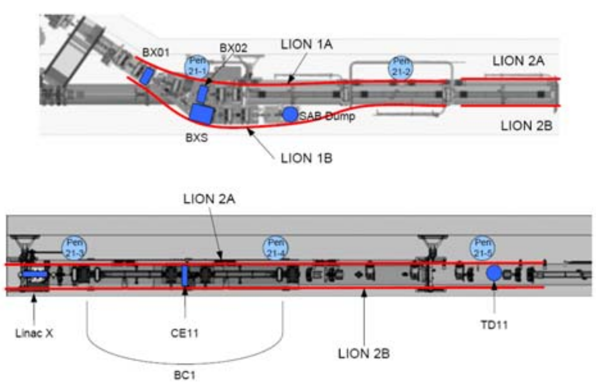

Fig. 5 BCS - LIONs locations

P. Emma et al. described the LCLS maximum credible beam power in different locations in LCLS Physics Requirements Document # 1.1-011-r1, “Electron Beam Loss in the LCLS” [1]. Table 9 lists the maximum credible beam power in various locations.

Table 9 The maximum credible beam power in various locations

Location	BX01 /02	BXS SDMP	X-iris	BC1/CE11	TD11
Beam energy and maximum credible power	0.11 GeV 5 kW	0.11 GeV 5 kW	0.25 GeV 1.5 kW	0.250 GeV 1.5 kW	0.25 GeV 1.5 kW

Table 10 lists the dose rates outside penetration 21-1 in the normal, mis-steering and maximum credible beam loss conditions. The main source is the beam losses in magnets BX01/BX02.

Table 10 The dose rates outside penetration 21-1

Penetration	Dose rate normal running conditions	Dose rate mis-steering conditions	Dose rate maximum credible beam loss
21-1	0.135 GeV 2 W	0.135 GeV 100 W	0.110 GeV 5 kW
	0.9 µSv/hr	0.045 mSv/hr	2.3 mSv/hr

Table 11 lists the dose rates outside penetration 21-2 in the normal, mis-steering and maximum credible beam loss conditions. The main source is the beam losses in the region of magnet BXS and dump SDMP.

Table 11 The dose rates outside penetration 21-2

Penetration	Dose rate normal running conditions	Dose rate mis-steering conditions	Dose rate maximum credible beam loss
21-2	0.135 GeV 16 W	0.135 GeV 100 W	0.110 GeV 5 kW
	2.4 µSv/hr	0.015 mSv/hr	0.75 mSv/hr

Table 12 lists the dose rates outside penetration 21-3 in the normal, mis-steering and maximum credible beam loss conditions. The main source is the beam losses in X-iris region.

Table 12 The dose rates outside penetration 21-3

Penetration	Dose rate normal running conditions	Dose rate mis-steering conditions	Dose rate maximum credible beam loss
21-3	0.250 GeV 0.5 W	0.250 GeV 100 W	0.250 GeV 1.5 kW
	0.3 µSv/hr	0.06 mSv/hr	0.9 mSv/hr

Table 13 lists the dose rates outside penetration 21-4 in the normal, mis-steering and maximum credible beam loss conditions. The main source is the beam losses on Collimators CE11 in BC1 chicane region.

Table 13 The dose rates outside penetration 21-4

Penetration	Dose rate normal running conditions	Dose rate mis-steering conditions	Dose rate maximum credible beam loss
21-4	0.250 GeV 0.1 – 30 W Nominal = 0.1 W	0.250 GeV 100 W	0.250 GeV 1.5 kW
	7.3 µSv/hr /30 W	0.024 mSv/hr	0.36 mSv/hr *

* Maximum credible beam (0.250 GeV and 1.5 kW) is bent by magnet BC1 and hit collimators CE11. It will produce 0.36 mSv/hr outside the penetration 21-4.

Table 14 lists the dose rates outside penetration 21-5 in the normal, mis-steering and maximum credible beam loss conditions. The main source is the beam losses on dump TD11.

Table 14 The dose rates outside penetration 21-5

Penetration	Dose rate in normal running conditions	Dose rate mis-steering conditions	Dose rate maximum credible beam loss
21-5	0.250 GeV 30 W	0.250 GeV 100 W	0.250 GeV 1.5 kW
	4.4 µSv/hr	0.015 mSv/hr	0.23 mSv/hr*

* Maximum credible beam (0.250 GeV and 1.5 kW) is lost in the dump TD11, and produce 0.23 mSv/hr outside the penetration 21-5.

III. CONCLUSIONS

In Sector-20 Alcove, the total dose rates above the laser penetration, unused penetration, ventilation and around the PPS barrier surrounding the stairway are about 5 µSv/hr during normal operation. The highest dose rate is 1.75 mSv/hr, which would occur if the maximum credible beam were lost in Faraday Cup FC01. Two BSOICs are required to be installed in the Sector 20 alcove, and set to trip at 0.1 mSv/hr.

In the existing LINAC sector-21 area, the dose rates above and outside the penetrations 21-1, 21-2, 21-3, 21-4 and 21-5 are less than 20 µSv/hr and less than 5 µSv/hr with required shielding in place, respectively.
The dose rates outside the penetrations 21-1, 21-2, 21-3, 21-4 and 21-5 are less than 5 µSv/hr, 0.06 mSv/hr and 2.3 mSv/hr in normal, mis-steering condition, and maximum credible beam loss , respectively.

ACKNOWLEDGMENTS

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