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Radiation Safety Aspects of the Linac Coherent Light Source Project At SLAC[+]

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Abstract

The Linac Coherent Light Source (LCLS) is a Self-Amplified Spontaneous Emission based Free Electron Laser (FEL) that is being designed and built at the Stanford Linear Accelerator Center (SLAC) by a multi-laboratory collaboration. This facility will provide ultra-short pulses of coherent x-ray radiation with the fundamental harmonic energy tunable over the energy range of 0.82 to 8.2 keV. One-third of the existing SLAC LINAC will compress and accelerate the electron beam to energies ranging from 4.5 GeV to 14.35 GeV. The beam will then be transported through a 130-meter long undulator, emit FEL and spontaneous radiation. After passing through the undulator, the electron beam is bent to the main electron dump. The LCLS will have two experiment halls as well as x-ray optics and infrastructure necessary to make use of the FEL for research and development in a variety of scientific fields. The facility design will incorporate features that would make it possible to expand in future such that up to 6 independent undulators can be used. While some of the radiation protection issues for the LCLS are similar to those encountered at both high-energy electron linacs and synchrotron radiation facilities, LCLS poses new challenges as well. Some of these new issues include: the length of the facility and of the undulator, the experimental floor in line with the electron beam and the occupancy near zero degrees, and the very high instantaneous intensity of the FEL. The shielding design criteria, methodology, and results from Monte Carlo and analytical calculations are presented.

Key Words: Shielding, Accelerator, Design

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1. Introduction

The LCLS project will use several existing facilities at SLAC to create the world's first ultra fast, ultra short "hard" x-ray laser (Arthur, 2002 and Galayda, 2002). These facilities include: the last kilometer of the exiting three kilometer long SLAC Linac; the off-axis injector vault at sector 20 along the linac, and the Beam Switch Yard section of the Final Focus Test Beam (FFTB) tunnel. A photoinjector and a short pre-accelerator linac will be built in Sector-20 off-axis vault where a high brightness electron beam is generated. One nanocoulomb electron bunches at 120 Hz will be accelerated to 150 MeV in the pre-accelerator. Two chicane bunch compressors in the last kilometer of the linac will compress the electron bunches to 230 fsec FWHM duration. The electron bunches with 3400 ampere of peak current can be accelerated up to 14.35 GeV at the end of the linac. These electron bunches will then pass through a 122-meter undulator producing a burst of fully transversely coherent x-rays with peak brightness ten orders of magnitude higher than is presently available from the brightest third-generation storage ring sources (time averaged brightness 2- 4 orders higher). The brightness and coherence is the result of the "self-amplified spontaneous emission" (SASE) process. Figure 1 shows a schematic view of the LCLS and the main Linac at SLAC. Selected LCLS electron and x-ray beams, and the undulator parameters are listed in Table 1.

The new construction for the LCLS includes decommissioning and removal of the FFTB beam line from the end of 16.8 m muon shielding to the FFTB dump, and of the FFTB concrete tunnel in the Research Yards. A new Beam Transport Hall (BTH) will be built to transport and deliver the electron beam to the 130-meter long undulator. The first 62 m section of the BTH will flare out to allow for future installation of 2 and 4 degree beam lines (see Figure 2). A Single Beam Dump will be installed in the BSY section of the FFTB tunnel for tuning up the beam.

A new tunnel will be excavated to house the 130-meter long undulator. A tune- up dump will be installed shortly up-beam of the undulator. Electrons transported through the undulator emit Free Electron Laser (FEL) and spontaneous radiation. Then, the electron beam is bent to the e- dump line and delivered to the dump. The FEL and spontaneous radiation pass through the Front End Enclosure (FEE), where the x-ray optics system is located. Experimental hutches will be located at two halls. The Near Hall immediately downstream of FEE is 100 meters from the end of the undulator. The Far Hall experimental will be constructed 300 meters further. The LCLS will be constructed by a collaboration of US laboratories: Argonne National Labs, Lawrence Livermore National Lab, and SLAC.

2. Radiation Safety System

Most of the radiation protection issues for the LCLS are normally encountered at SLAC and in most of the high-energy electron linacs and synchrotron radiation facilities.

The SLAC Radiation Safety Program is designed to ensure that radiation doses above background received by workers and the public shall be As Low As Reasonably Achievable (ALARA), as well as to prevent any person from receiving more radiation exposure than is permitted under federal government regulations. The main provisions of the ALARA program ensure that:

1. Access to high radiation areas is controlled.
2. The accelerator facilities and the associated detectors are provided with adequately shielded enclosures for times when the possibility exists for a radiation field to be present.
3. Designs for new facilities and significant modifications incorporate dose reduction, contamination reduction, and waste minimization features in the earliest planning stages.

Several technical, operations, and administrative systems exist to implement the program, as described in the SLAC Radiological Control Manual (ES&H, 1999) and the Radiation Safety Systems, Technical Basis Document (ES&H, 1998). The users of the LCLS who will be working in the experimental halls are expected to be classified as non-radiological workers.

The SLAC Radiological Control Manual specifies an annual total effective dose equivalent limit to workers from both internal and external radiation sources of 50 mSv. In addition, SLAC maintains an administrative control level of 15 mSv. The following radiation dose criteria are used for the design of the LCLS radiation safety systems:

1. The integrated dose equivalent to personnel working inside and around the experimental hutch shielding barriers must not exceed 1 mSv in a year for normal beam operation.

2. The dose equivalent-rate in the event of the Maximum Credible Incident is limited to less than 250 mSv/h , and integrated dose equivalent of less than 30 mSv (ES&H 1999).

3. The maximum dose equivalent rates in accessible areas at 30 cm from the shielding or barrier should not exceed 4 mSv/h for mis-steering conditions defined as conditions that are comprised of infrequent or short-duration situations in which the maximum allowable beam power, limited by Beam Containment System (BCS) devices is lost locally or in a limited area.

4. In addition to shielding (bulk and local), the LCLS radiation protection systems will have Beam Containment System (BCS) and Personnel Protection System (PPS) in the Tunnel, and the Hutch Protection System (HPS) in the beam lines to achieve the designed goals.

The BCS is designed to ensure that beam parameters do not exceed the preset values, and that the beam is delivered to the main dump with minimal loss. The PPS controls entry to the tunnel, ensuring that personnel are excluded from the tunnel during the LCLS beam operation and the HPS controls access to the experimental hutches. The description of these systems will not be covered in the present work.

3. Radiation Sources

During machine operation, high energy bremsstrahlung and particle radiation is generated from the interaction of the primary electron beam with protection collimators, beam diagnostic devices, main LCLS dump and the tune up dumps. The radiation generated in these reactions as well as the forward directed and scattered coherent x-ray and synchrotron radiation are the main sources of radiation that have been considered in the design of the shielding of the LCLS. The following beam parameters are used in the calculations: Electron beam: 15 GeV, 5 kW (unless differently specified) and a Maximum credible beam power: 15 GeV, 150 kW. Table 2 lists the radiation sources and their strengths used in the shielding calculations.

4. Shielding Requirements

Based on the calculations that define the radiation sources the following shielding requirements have been specified:

BTH Head House: The source of radiation is assumed to be 5 W (0.1% of the total average beam power) of beam loss at any point along the beam line; the analytical computer code, SHIELD11 (Nelson, 2005) is used in the calculations. Shield requirements (Mao, 2004) are 1.83 m to 1.70 m of ordinary concrete on the sides as the distance to the BSY wall increases from 0 m to 62 m. Non-occupied areas on the roof require 1.09 m of concrete. Occupied areas on the roof require 1.60 m of concrete and will be shielded to 5 μSv/hr; for non-occupied a limit of 30 μSv/hr is assumed due to low use factor.

End of the Flared Sections of BTH Head Hall (end-plug)

The shielding requirements for the end-plug are dominated by accident cases. It is assumed that a 15-GeV and 2-kW nominal beam hits the end-plug requiring 2.13 m of concrete

BTH Tunnel: 1.83 m on the sides calculated based on loss of 5 W of beam. Requirements for the roof are the same as the BTH house.

Single Beam Dump (SBD): Local shielding consisting of 2.74 m long, 0.01 m Inner Diameter (ID), 0.20 Outside Diameter (OD) , lead collimator downstream of the SBD (Keller, 2004).

Tune-up Dump: 0.91 m long, 0.006 m ID, 0.30 m OD, lead collimator upstream of the undulator (Keller, 2004).

Main Electron Beam Dump: Above the dump, 0.61 m iron + 0.91 m concrete, 0.61 m concrete tunnel roof, 2.44 m earth above the roof. The occupied areas close to the dump are Near Hall and a service building above the hill (Mao, 2004).

Muon Shielding: The experimental floor in the Near Hall is in line with the electron beam and there will be occupancy near zero degrees with respect to the electron beam while the full power beam is being transported to the main dump. High energy bremsstrahlung and particle radiation, including muons, are generated from the interaction of the primary electron beam, or resulting secondary radiation with protection collimators, beam diagnostic devices, the main LCLS beam dump, and the tune up dumps. Unplanned and large beam losses will be terminated promptly by BCS devices. For known sources like the Single Beam Dump (SBD) in the BSY and the Tune-up Dump , relatively compact local muon shielding was specified, so that the thickness of the full-tunnel muon shields could be minimized. In general it was assumed that 0.1% of the 5 kW beam (5 W) could be lost anywhere along the beam line. However, accurate knowledge of all potential losses is difficult, thus, it was conservatively assumed that 30 W, i.e. 5 W with a safety factor of six, could be lost anywhere in the straight-ahead (zero degree) direction downbeam from the undulator.

To reduce the dose rate to less than 0.5 μSv/h limit in the Near Hall, it was decided to insert a magnetic, toroidal spoiler between the electron beam dump magnets and the muon shield to disperse muons from sources near the dump magnets. A 0.91 m long magnetic spoiler was used in the calculations. It consists of an iron "doughnut" with a small hole for the x-ray beam pipe and a current winding which produces a toroidal magnetic field in the iron. Spoilers of this type were used in the SLAC Linear Collider to shield the large experiment detectors from muons produced in collimators near the Experiment Hall.

Requirements: a 0.91 m long toroidal magnetic spoiler is located downstream of the dump magnets. The outside diameter of the spoiler is 0.61 m, the inside diameter is 0.015 m including the current winding. The distance from the front face of the spoiler to the Near Hall is 50 m. A 0.91 m thick steel muon shield which fills the tunnel is located downstream of the electron dump. The beam hole through the muon shield is 3 cm diameter. The distance from the front face of the muon shield to the Near Hall is 33 m. Additionally, a 1.22 m thick steel wall and a 0.91 m concrete wall which fill the tunnel are needed as up-beam wall of the Near Hall hutch. The muon calculations were performed using both MUCARLO and a special version of the FLUKA Monte Carlo computer programs (Keller, 2004, Fasso, 2004).

Experimental Hutches

Experiments for LCLS will be performed in two experimental halls, namely the Near Experimental Hall (NEH) and the Far Experimental Hall (FEH). The NEH is located 100 m down beam of the last girder of the undulator and the FEH is located 250 m down beam of the NEH; both halls will house experimental hutches. The shielding for the hutches was designed to satisfy an annual dose limit to personnel working inside or around the experimental hutches of 1 mSv.

The radiation shielding requirements of these hutches are based on considering high energy bremsstrahlung from beam halo interactions with a collimator upstream of the LCLS undulator, as well as spontaneous synchrotron radiation. Unlike synchrotron radiation facilities, gas bremsstrahlung in the single pass LCLS is negligible (Rokni, 2002). The bremsstrahlung is produced by interaction of electron beam halo with beam components and will be stopped on PPS stoppers in the experimental hutches. The energy deposition in a PPS stopper was calculated for a 20 W beam electron loss on a collimator upstream of the undulator and was found to be 12 mW (Nelson, 2002). The energy deposition in the stoppers was used as input in the SHIELD11 code to calculate the dose rate around the experimental hutches due to high energy bremsstrahlung, and specify the shield requirements.

The FLUKA Monte-Carlo code was used to determine the effective dose due to interaction of the spontaneous x-ray spectrum with optical components (Vincke, 2004). The spectrum of spontaneous x-rays generated by the LCLS undulator (K=3.5) is shown in Figure 3. The average power up to the 180th harmonic is 2.78 W (2.73×10^{14} photons/s) with a critical energy of 140 keV. The following beam parameters were used to calculate the spectrum: 14.35 GeV, 0.95 nC/pulse, 120 Hz, e-beam power of 1.64 kW, and 4000 periods in the 130-m long undulator. In the FLUKA calculation, the x-rays hit a 0.01 m thick Si mirror inclined by 1° with respect to the beam axis.

The results show that the contribution from high energy bremsstrahlung photons dominates the dose levels around the hutches (Vincke, 2004). High energy bremsstrahlung photons impinging on the PPS stopper in the hutch produces neutrons. Iron and lead are inefficient to shield neutrons, therefore concrete was chosen as the appropriate shielding material.

Near Hall Hutch

Requirements: 0.61 m concrete wall on the north side, 0.91 m concrete wall down beam plus 0.10 m iron local shielding after the PPS stopper, 0.91 m concrete on the roof (Vincke, 2004), see figure 4.

Far Hall Hutches

Zero Degree Hutch: Requirements are similar to the near experimental hutch. Note that like for the NEH hutches 12 mW of bremsstrahlung was assumed in calculating the radiation levels around the Far Hall hutches.

Off-Side Hutches: The LCLS spontaneous spectrum was folded with reflection coefficients for a Rhodium coated mirror with a 23 keV cut-off. The reflected x-ray spectrum has been used in FLUKA for dose calculation for the off side hutches. Again, three different materials have been chosen, namely concrete, iron and lead. Contribution from high energy bremsstrahlung is negligible for off-side hutches.

Requirements: 6 mm of iron or 1.2 mm of lead or 82 mm of concrete on the sides, 2 mm of lead in the down-beam wall with a thick plate (1 m × 1 m × 70 mm iron or 9 mm lead) and a photon dump in place. 1.0 mm of lead on the roof (Vincke, 2004).

5. Summary

Radiation sources for various modes of LCLS electron and photon beam operations have been calculated. Using both analytical and Monte Carlo computer codes shielding requirements for the electron beam tunnel, and experimental hutches are specified. While the shielding methodology for the electron beam tunnel is similar to the shielding of other high-energy electron facilities, the x-ray hutches pose new challenges for the shield designers. The current lay-out of the LCLS in which some of the experimental hutches are in line with the zero-degree electron beam requires special attention to potential electron beam losses that could send high-energy bremsstrahlung radiation into these hutches. Additionally, most of the analytical computer codes that are currently used for x-ray shielding have not been benchmarked at high critical energies generated in the LCLS. Therefore, use of Monte Carlo methods in calculating the shielding requirements for the experimental hutches is essential.

Acknowledgments

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Figure Captions

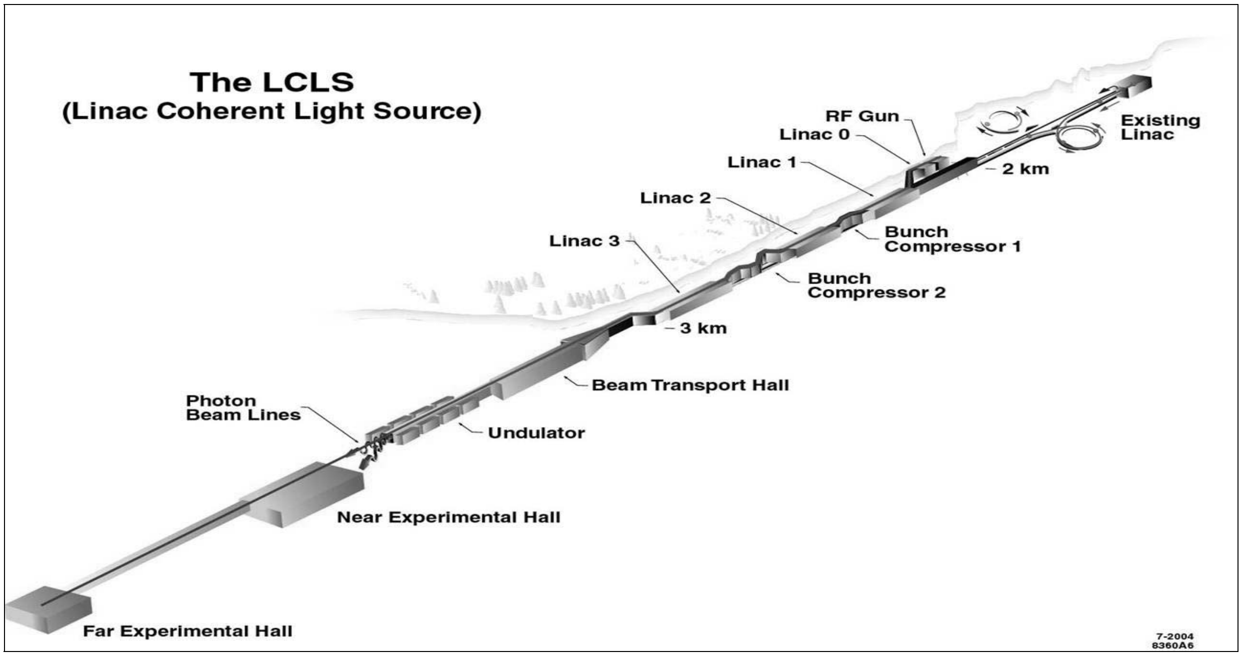
1. Schematic view of the LCLS at SLAC.

2. Schematic view of Beam Transport Hall.

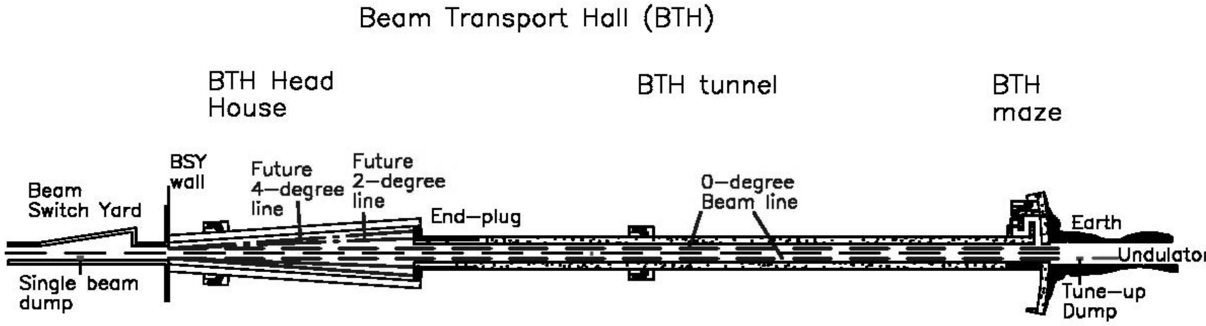
3. Spontaneous x-ray spectrum produced by 14.35 GeV electrons through the LCLS undulator.

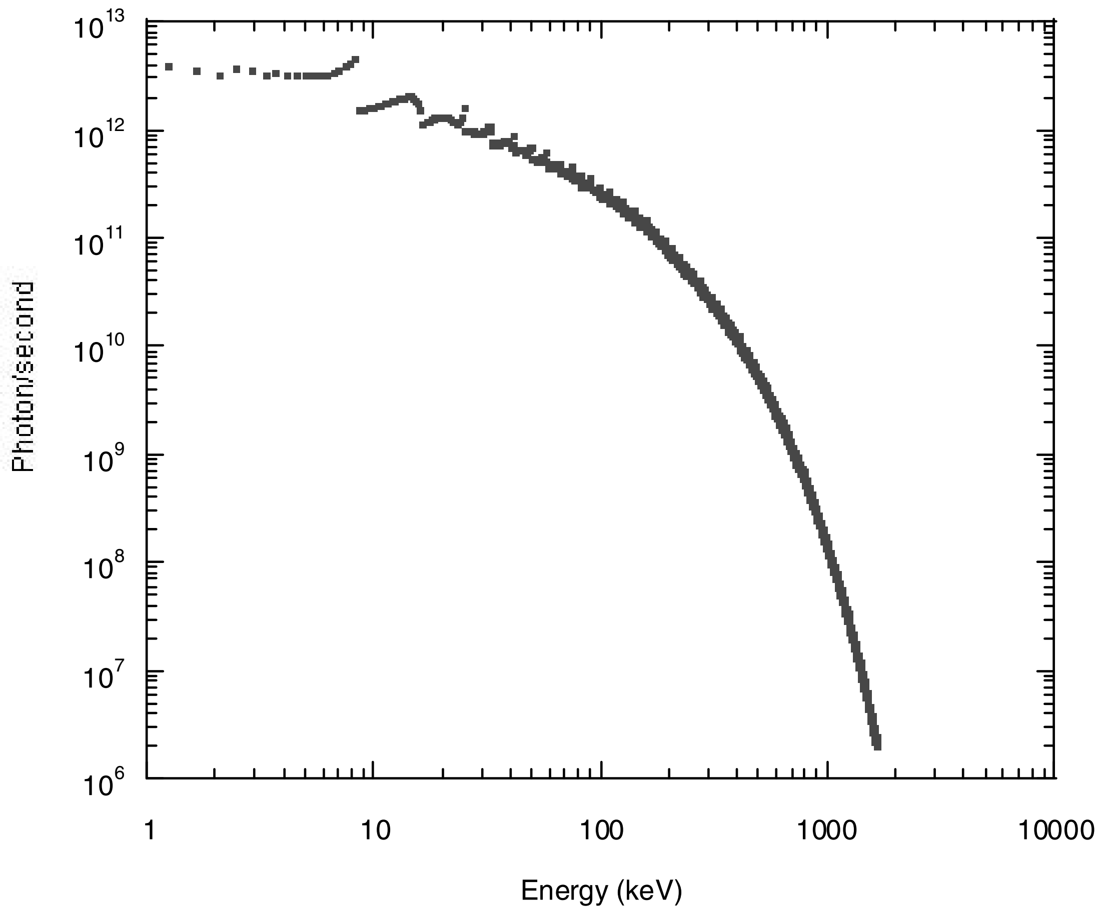
4. Schematic view of the Near Experimental Hall.

5. Schematic view of the Far Experimental Hall.

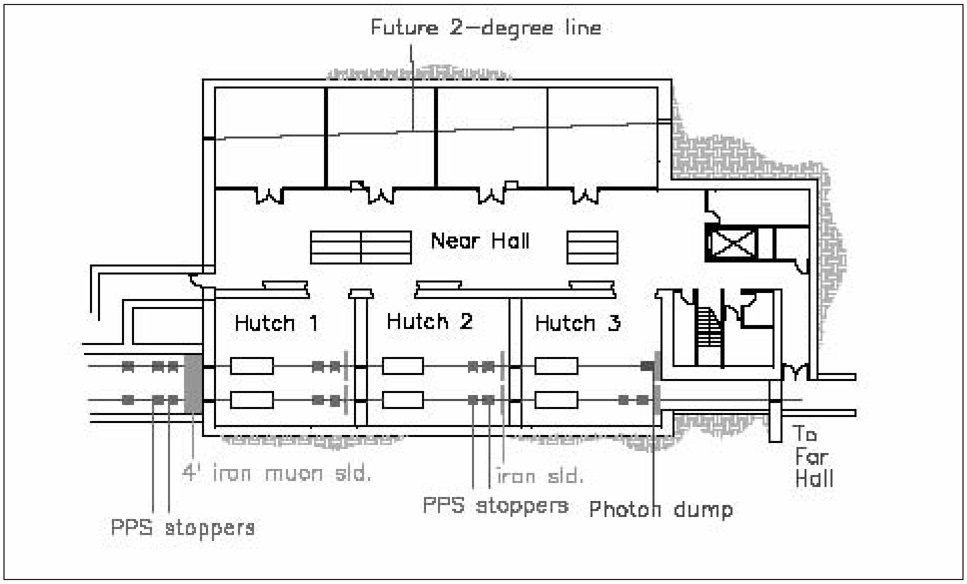


The LCLS
(Linac Coherent Light Source)
RF Gun
Linac 0
Existing Linac
Linac 1
2 km
Linac 2
Bunch Compressor 1
Linac 3
Bunch Compressor 2
3 km
Beam Transport Hall
Photon Beam Lines
Undulator
Near Experimental Hall
Far Experimental Hall
7-2004
8360A6

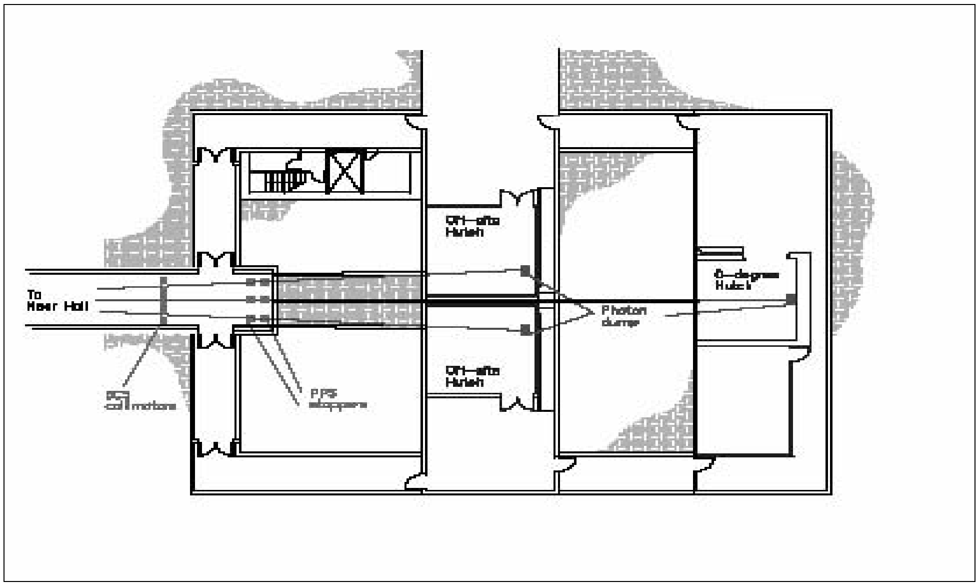

Beam Transport Hall (BTH)
BTH Head House
BTH tunnel
BTH maze
Beam Switch Yard
BSY wall
Future 4-degree line
Future 2-degree line
End-plug
0-degree Beam line
Earth
Undulator
Single beam dump
Tune-up Dump



10^{13}
10^{12}
10^{11}
10^{10}
10^{9}
10^{8}
10^{7}
10^{6}
Photon/second
1
10
100
1000
10000
Energy (keV)



Future 2-degree line
Near Hall
Hutch 1
Hutch 2
Hutch 3
4' iron muon sld.
iron sld.
PPS stoppers
PPS stoppers
Photon dump
To
Far
Hall


To
Near Hall
Off-axis
Hutch
Photon
dump
0-degree
Hutch
Off-axis
Hutch
PPS
stoppers

Electron Beam Energy	14.3	4.5	GeV
Fundamental FEL Radiation Wavelength	1.5	15	A
Peak Current	1,9	3.4	kA
Bunch Length (FWHM)	472	254	fs
FEL Fundamental Saturation power at exit	4	8	GW
FEL Photons per Pulse	1	29	10^{12}
Peak Brightness	0.08	0.06	10^{33} [a]

[a] photons/sec/mm^2/mrad^2/0.1%-BW

Table 1. Undulator parameters at 14.3 and 4.3 GeV electron energy

Radiation source	Power	Explanation
Single beam dump (SBD)	5 kW	5 kW beam parks on SBD during tuning up the beam
e- beam transport line	5 W	5 W could be lost at any point of e- beam transport line
Bremsstrahlung from beam-halo collimators	12 mW	20 W of beam loss on a 0.45 cm (ID) collimators upbeam of the undulator is assumed
Tune-up dump	417 W	417 W beam parks on Tune-up dump during tuning up the beam
Bremsstrahlung from on-axis diagnostic devices	540 mW	167 W of beam (10 Hz) on an X-ray monitor in the last section of the undulator is assumed
Gas bremsstrahlung	Negligible	It is negligible because the average e- beam current is low
Beam loss in dump line	30 W	30 W could be lost in any point of the dump line
Electron beam dump	5 kW	5 kW beam parks on the dump during operation
Spontaneous radiation	2.78 W	The average power up to the 180th harmonic is 2.78 W (2.73 × 1014 photons/s). The critical energy is 140 keV
Free electron laser	0.31 W	Not included since the energy of the FEL is only 8.2 keV

Table 2. Radiation source terms used in the shielding calculations