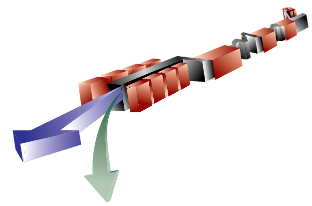
14 Radiological Considerations



Technical Synopsis

The radiation protection issues for the LCLS are normally encountered at both high-energy electron linacs and synchrotron radiation facilities. The SLAC Radiological Control Manual [1] specifies an annual total effective dose equivalent limit to workers from both internal and external radiation sources of 5 rem. In addition, SLAC maintains an administrative control level of 1.5 rem.

Radiation dose criteria used in design of the LCLS radiation safety systems are those required for SLAC facilities.

The integrated dose equivalent outside the surface of the FFTB shielding barriers must not exceed 1 rem in a year for normal beam operation [1].

The integrated dose equivalent to personnel working inside and around the experimental hutch shielding barriers must not exceed 0.1 rem 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 25 rem/h , and integrated dose equivalent of less than 3 rem [1].

The maximum dose equivalent rates in accessible areas at 1 foot from the shielding or barrier should not exceed 400 mrem/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.

The dose equivalent for the maximally exposed member of the public exposed to ionizing radiation from SLAC produced pathways must be less than or equal to 10 mrem/yr [3]. The dose equivalent at the site boundary from the operation of the LCLS must be a small fraction of that total for normal beam operation.

The expected radiation sources have been identified and analyzed to determine the required radiation safety systems. These sources produce high energy bremsstrahlung and particle radiation from the interaction of the primary electron beam with protection collimators, beam diagnostic devices, main LCLS dump, and interaction with the residual vacuum.

A radiation safety system comprised of shielding, Beam Containment System (BCS), Personnel Protection System (PPS) and Hutch Protection System (HPS) [1] has been designed for the LCLS. The issues considered in the design of these systems are described in this chapter.

14.1 Introduction

Most of the components of the LCLS beam line are installed in the FFTB tunnel, a shielded enclosure in the straight-ahead channel at the end of the SLAC linac (**Figure 14.1**). This tunnel is composed of two sections. The first section (107 m) is in the beam switchyard, which is a large, two-level structure shielded on the roof by more than 12.2 m of concrete and earth, located at the end of the linac. The second section is a shielded structure that extends 150 m to the east beyond the beam switchyard. This section is shielded with 1.2 m of concrete laterally and 1m of concrete on the roof [4].

Since the LCLS electron beam power, energy and beam losses are comparable to that of the FFTB, the existing enclosure shielding should be adequate without major modifications. For the LCLS, new designs of the safety systems are required for the injector at sector 20 of the linac, Front End optics enclosure that will be added to the structure in the research yard, the new beam dump enclosure, and experimental hutches downstream of the electron beam dump.

14.2 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 interaction with the residual vacuum.

The radiation initiated in these reactions as well as the forward directed and scattered coherent x-ray and synchrotron radiation are the main sources of radiation that need to be considered in the design of the shielding for the new areas downstream of the undulator. The particle radiations of concern are neutrons and muons.

14.2.1 Beam Parameters

The electron beam will be delivered at energies up to 15 GeV at 1 nC and 120 Hz.

14.2.2 Bremsstrahlung from Collimators

Two copper collimators, each 10 cm long and with an internal diameter of 0.2 cm, will be placed up beam of the undulator (**Figure 14.2**). The purpose of the first collimator is to reduce the electron beam halo, while the second should intercept any mis-steered beam that could hit and damage the undulator. The first collimator, continuously intercepting about 1% of the beam, will be a constant source of forward-directed bremsstrahlung and muon radiation. The second collimator should interact with the beam only in exceptional cases and is not expected to contribute substantially to the radiation field under normal operating conditions.

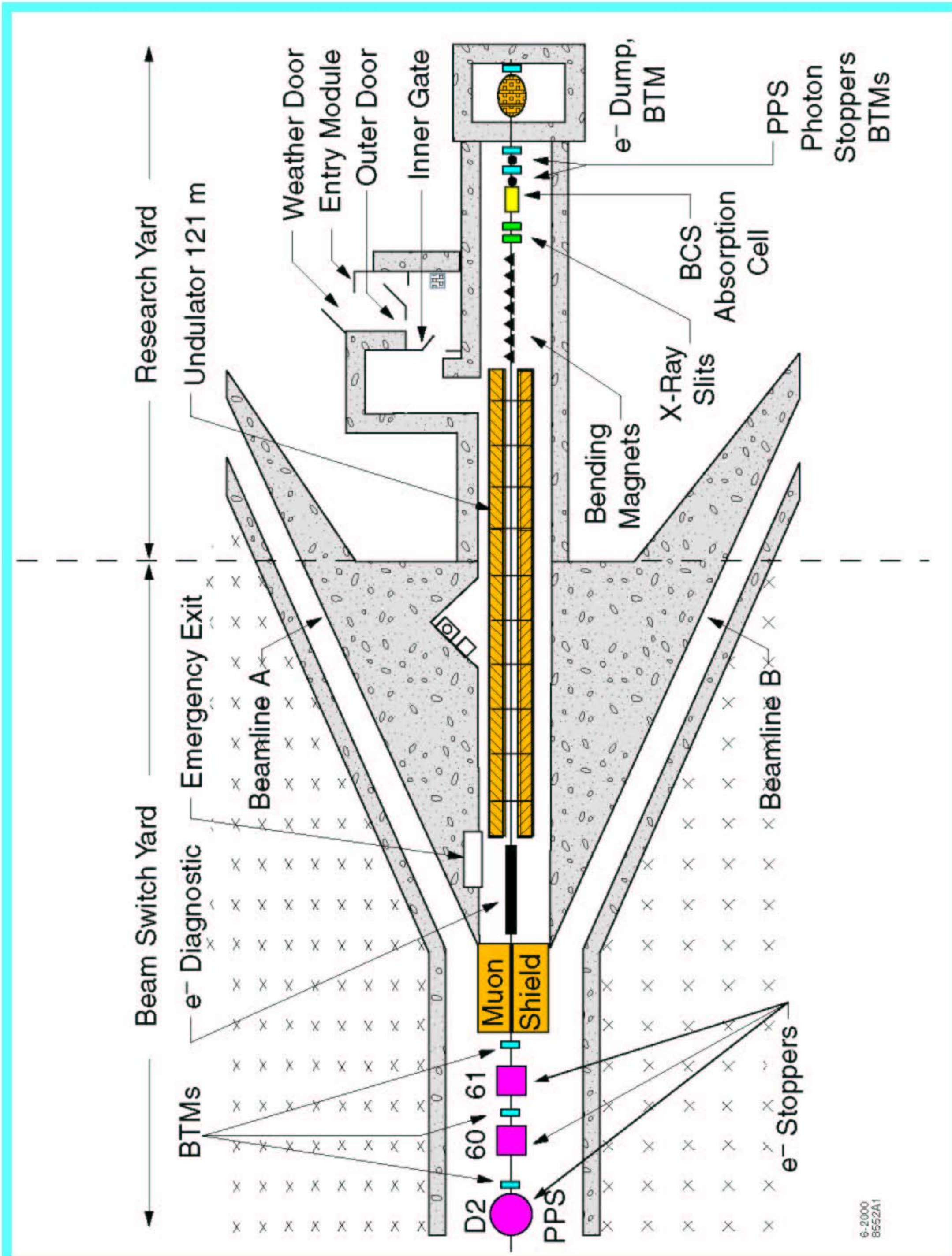


Figure 14.1 Electron Beamline for LCLS

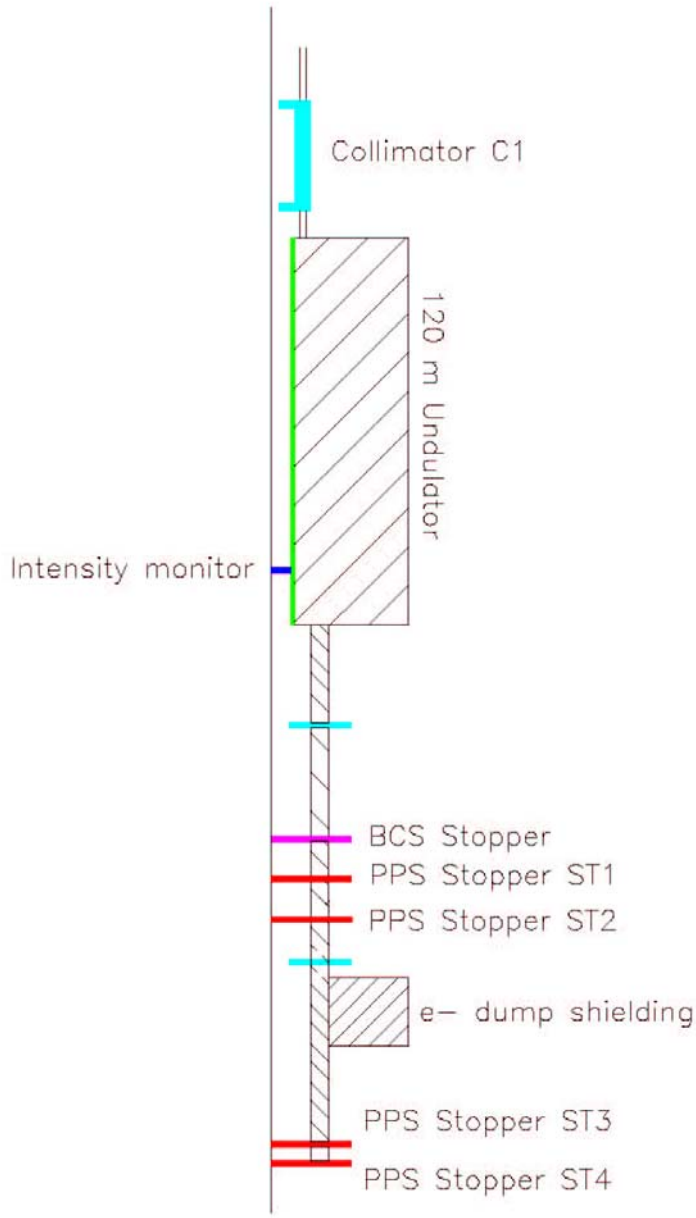


Figure 14.2 LCLS Beamline showing various BCE and PPS devices

Bremsstrahlung radiation produced in the first collimator will present a hazard to personnel in downstream experimental areas. Consequently photon stoppers are required as part of the Personnel Protection System (PPS, **Section 14.3.3**). The first of these stoppers, which must be inserted into the beamline when access is allowed in any downstream enclosure, will intercept this bremsstrahlung radiation.

Details of the calculation are given in [5]. For a 1% loss of a 15-GeV, 2-kW electron beam the energy deposition in the PPS stopper ST1 (see Fig. 14.3), which must be inserted into the beamline when access is allowed in Hutch 1, was 17 mW, calculated using the EGS4 code. The energy deposition in the PPS stopper ST3, which must be inserted into the beamline when access is allowed in Hutch 2, was 12 mW [6].

However, bremsstrahlung from collimators is neither the only nor the main source of radiation to be considered for shielding design: other radiation components (bremsstrahlung from profile monitors, neutrons, muons, x-rays) must also be taken into account.

14.2.3 Bremsstrahlung from On-Axis Diagnostic X-Ray Stations

The electron beam will be intercepted by monitoring devices at several locations in the on-axis diagnostic x-ray stations along the undulator. There will be 10 or 12 of these stations, but calculations have been made for the one located in the last 10 m section of the undulator. The material is diamond, 0.5 mm thick, but because the beam strikes it at an angle of 45˚, the effective thickness traversed is 0.707 mm. For a 15-GeV and 2-kW electron beam the energy deposition in the BCS stopper, which is interlocked with the monitor, was 6.5 W calculated using the EGS4 code [5,6]. If it is assumed that the monitor will be used about 10% of the beam time, this is equivalent to a continuous energy deposition of 650 mW in the BCS stopper.

14.2.4 Synchrotron Radiation

The synchrotron x-rays will be absorbed in the BCS or PPS stoppers when they are inserted to the beam. The total power in the LCLS synchrotron spectrum was calculated to be 2.78 W [6]. When the beam line is open, this power will be absorbed in the hutch stopper.

14.2.5 Electron Deam Dump

The distance from the front face of the first bending magnet to the front face of the dump will be 28 meters. The distance from the center of the dump to the ground level will be 1.5 meters. The shielding design for the dump was based on this arrangement, shown in **Figure 14.4**.

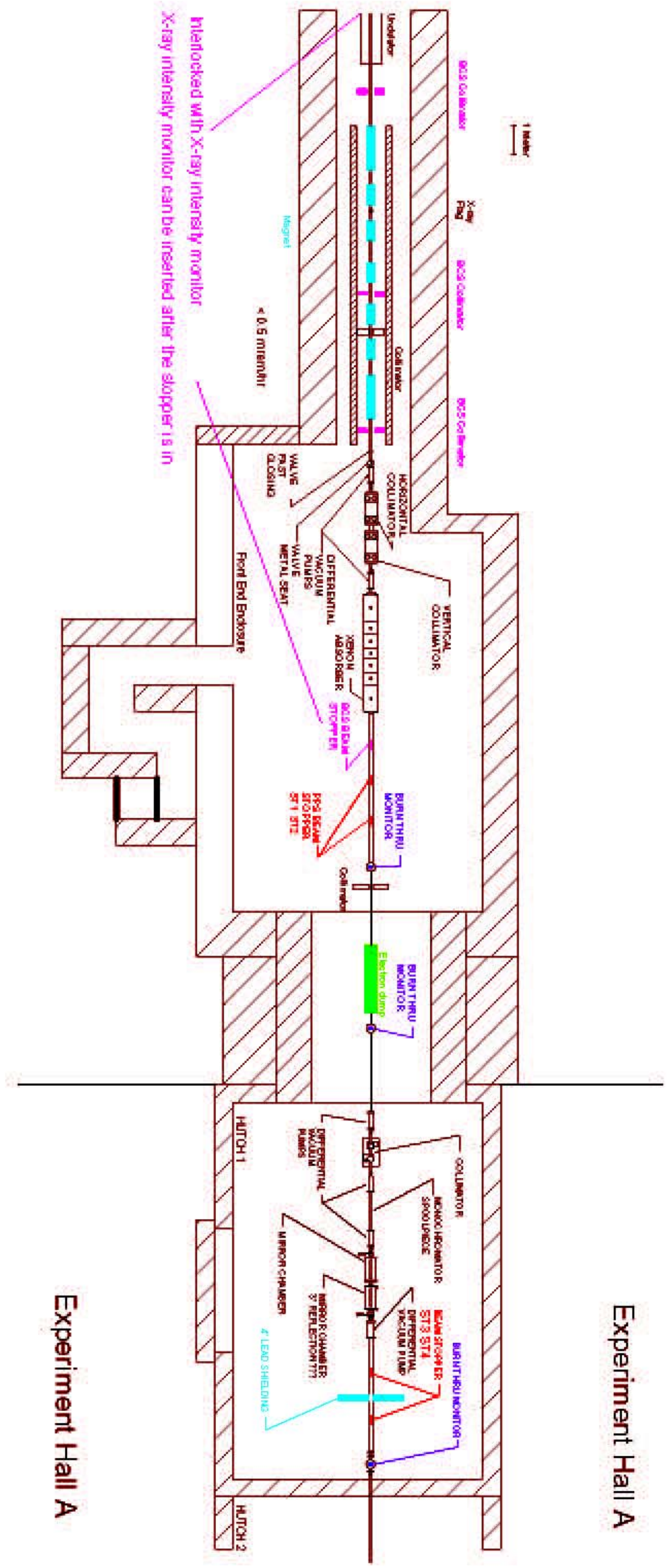


Figure 14.3 Schematic View of LCLS x-ray beam line showing details of the front end and experimental hall BCS and PPS devices.

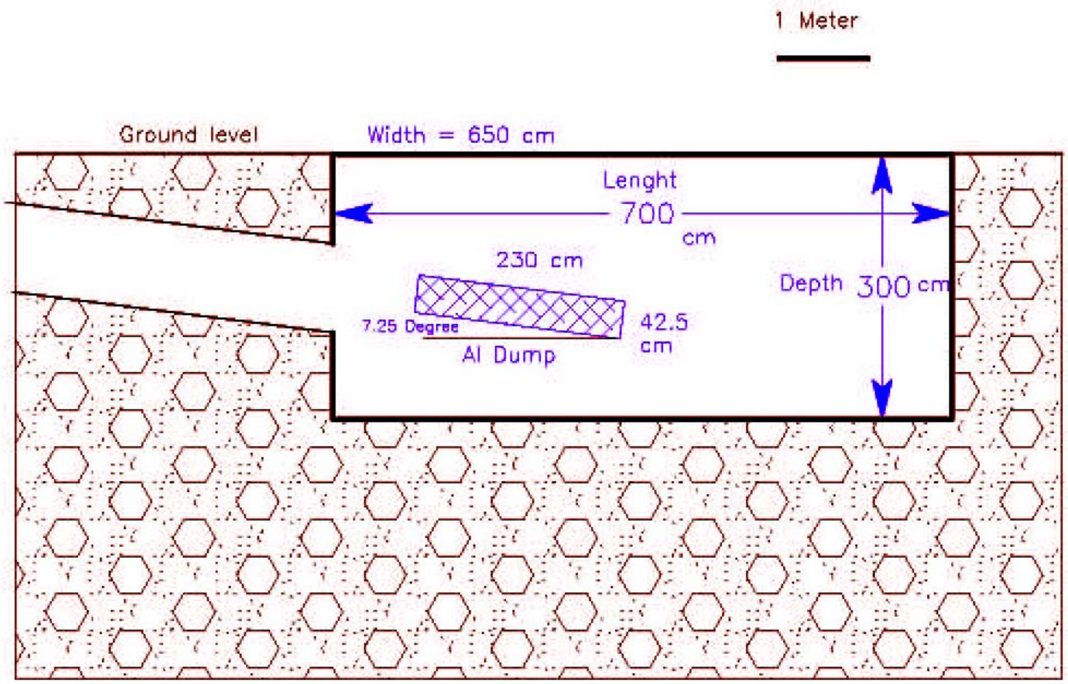


Figure 14.4 Electron Beam Dump

14.2.6 Gas Bremsstrahlung

Interaction of the electron beam with residual low-pressure gas molecules in the vacuum pipe will give rise to forward-directed gas bremsstrahlung. This type of radiation has been thoroughly investigated at circular storage rings, where the beam current is much more intense. However, at LCLS the straight length over which bremsstrahlung is produced will be much longer (120 m between the dog-leg and the first bending magnet before the electron dump). The residual gas pressure and the electron energy will also be higher.

Radiation levels from the interaction of gas-bremsstrahlung photons generated in the LCLS undulator with a tungsten stopper were calculated using the FLUKA code and compared with results from two analytical methods [7]. The total dose rate at a distance of 1 meter from the stopper was estimated at 6.3 μrem h^{-1}, dominated by secondary photons from the stopper.

14.2.7 Muons

Muons produced by electron interactions in the Beam Switchyard and upstream of it are ranged by 55 feet of iron and cannot constitute a concern. Muons can be created in the diagnostic area (by losses upstream of and inside the dog-leg, in the collimators and in the profile monitors); there are other possible muon sources inside the undulator (x-ray intensity monitors) and the electron dump. These muons will be either bent away by magnets downstream of the undulator or shielded by iron shielding located on the top of the electron dump.

However, persons accessing the on-line hutches and the research yard downstream of the Near-Field Hall and possibly the Far-Field Hall could be exposed to several other muon sources, which are produced when high-energy bremsstrahlung hits the photon stoppers. Muons can also constitute an important radiation background for experiments. The radiation levels for this source have been calculated using the codes MUCARLO [8] and MUON89 [9,10]. The expected dose rates in the vicinity of experimental hutch 1 are of the order of microrem per hour [11].

14.2.8 Neutrons

Photo-neutrons can be generated on the zero-degree line in any object hit by electrons and by bremsstrahlung. Such objects include the electron dump, the transport line to the dump, photon stoppers outside and inside the experimental Halls, and any optical device in the x-ray line. Neutrons generated outside the Near-Field Hall can penetrate to the Hall through the concrete shielding or streaming through the x-ray beam pipe. A preliminary analysis of the neutron radiation levels has been made using the analytical code SHIELD11 [12].

14.3 Radiation Safety System

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 access to high radiation areas is controlled; 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; and 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 [2] and the SLAC Guidelines for Operations [13] and Radiation Safety Systems, Technical Basis Document [1].

Almost all the users of the LCLS working in the experimental halls are expected to be classified as non-radiological workers, General Employees or Visitors.

The SLAC Radiological Control Manual [1] (ES&H, 1998) specifies an annual total effective dose equivalent limit to workers from both internal and external radiation sources of 5 rem. In addition, SLAC maintains an administrative control level of 1.5 rem.

The following radiation dose criteria are used in design of the LCLS radiation safety systems. The integrated dose equivalent outside the surface of the FFTB shielding barriers must not exceed 1 rem in a year for normal beam operation [1].

1. The integrated dose equivalent to personnel working inside and around the experimental hutch shielding barriers must not exceed 0.1 rem in a year for normal beam operation [2].

2. The dose equivalent-rate in the event of the Maximum Credible Incident is limited to less than 25 rem/h, and integrated dose equivalent of less than 3 rem [1].

3. The maximum dose equivalent rates in accessible areas at 1 foot from the shielding or barrier should not exceed 400 mrem/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. The dose equivalent for the maximally exposed member of the public exposed to ionizing radiation from SLAC produced pathways must be less than or equal to 10 mrem/yr [3]. The dose equivalent at the site boundary from the operation of the LCLS must be a small fraction of that total for normal beam operation.

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 FFTB beam operation and the HPS control access to the experimental hutches.

The components that have been designed for the LCLS are: lateral shielding walls of the optical front end (**Figure 14.5**), front back and lateral shielding walls for the beam main dump (**Figure 14.6**), the experimental hutches shielding and HPS (**Figure 14.7**), front end beam stoppers (**Figure 14.5**), the stoppers between hutches (**Figure 14.7**).

Additionally, the injector vault shielding has been designed assuming losses in sector 20 of the linac.

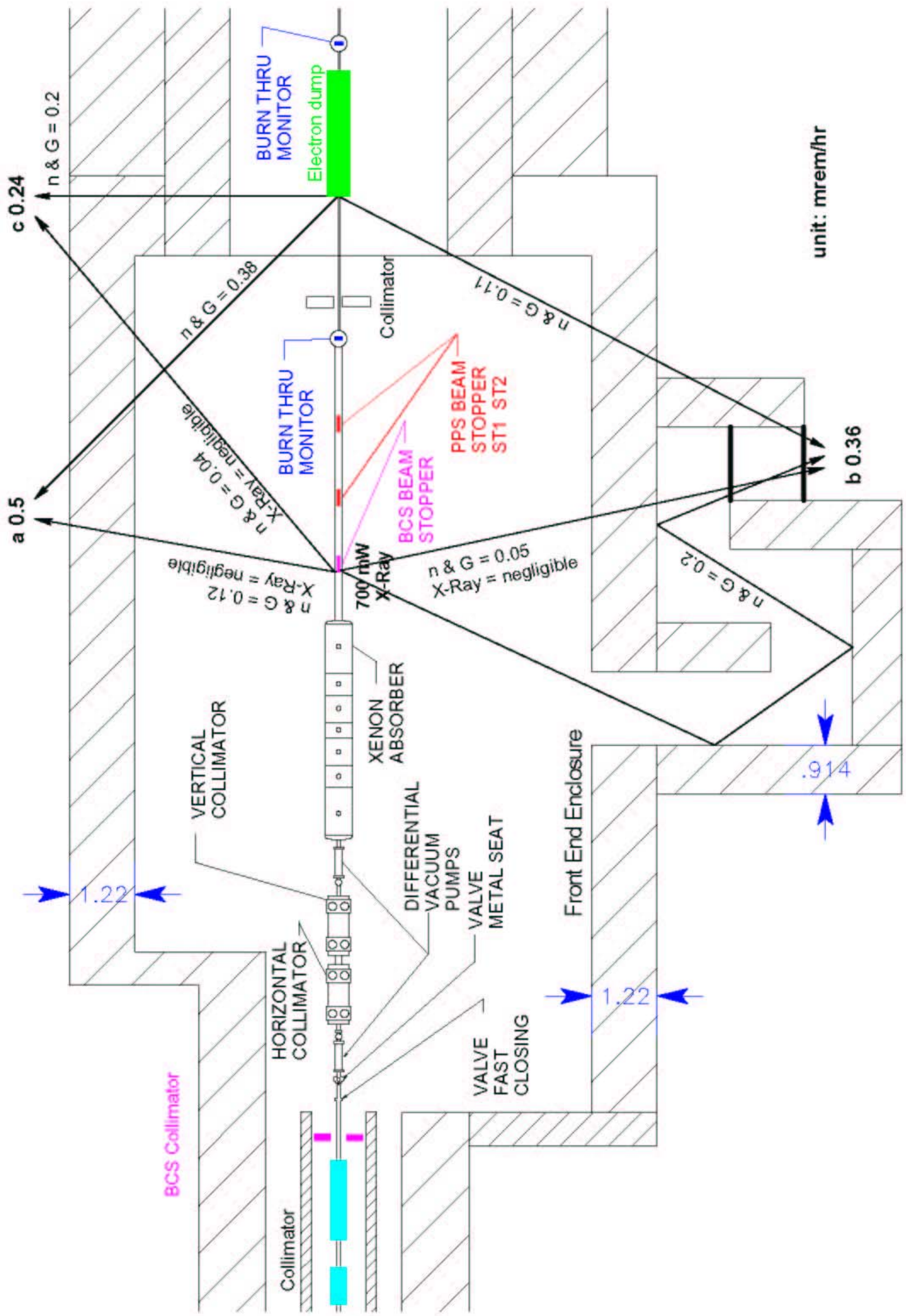


Figure 14.5 Shielding and Radiation Safety System Components for the Front End

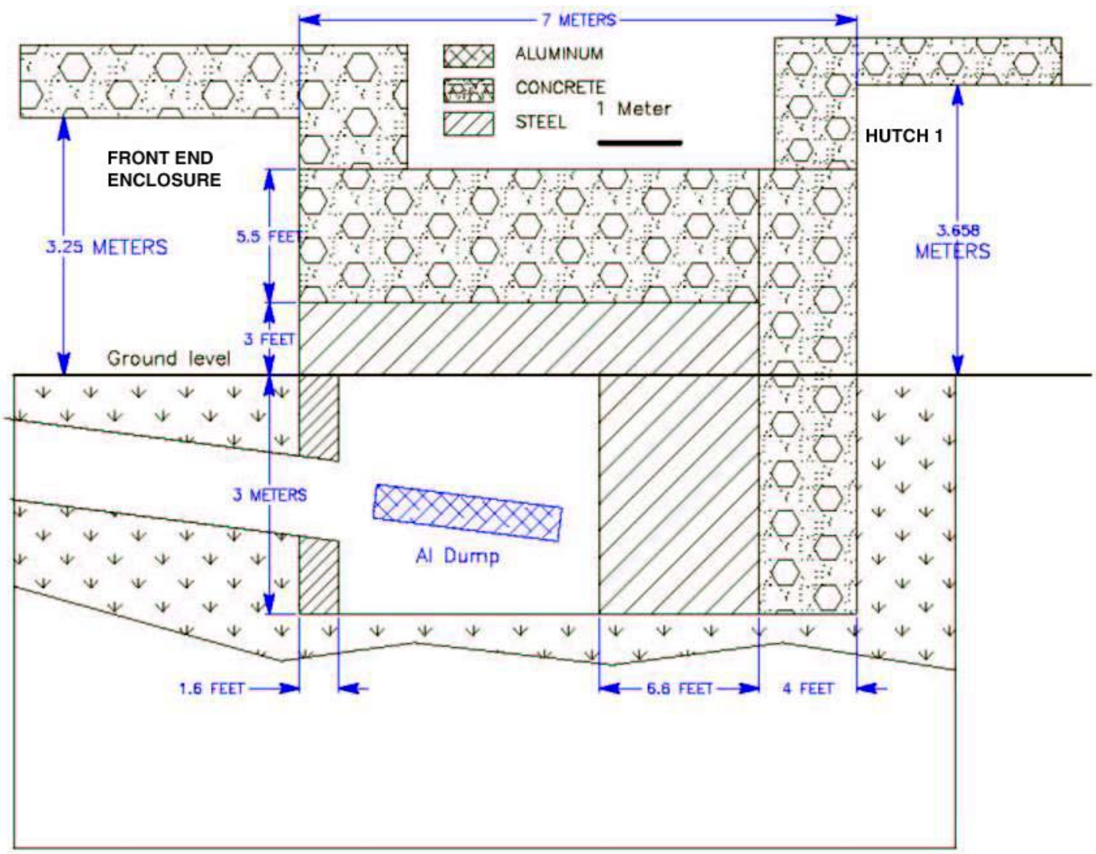


Figure 14.6 Shielding for the Electron Beam Dump

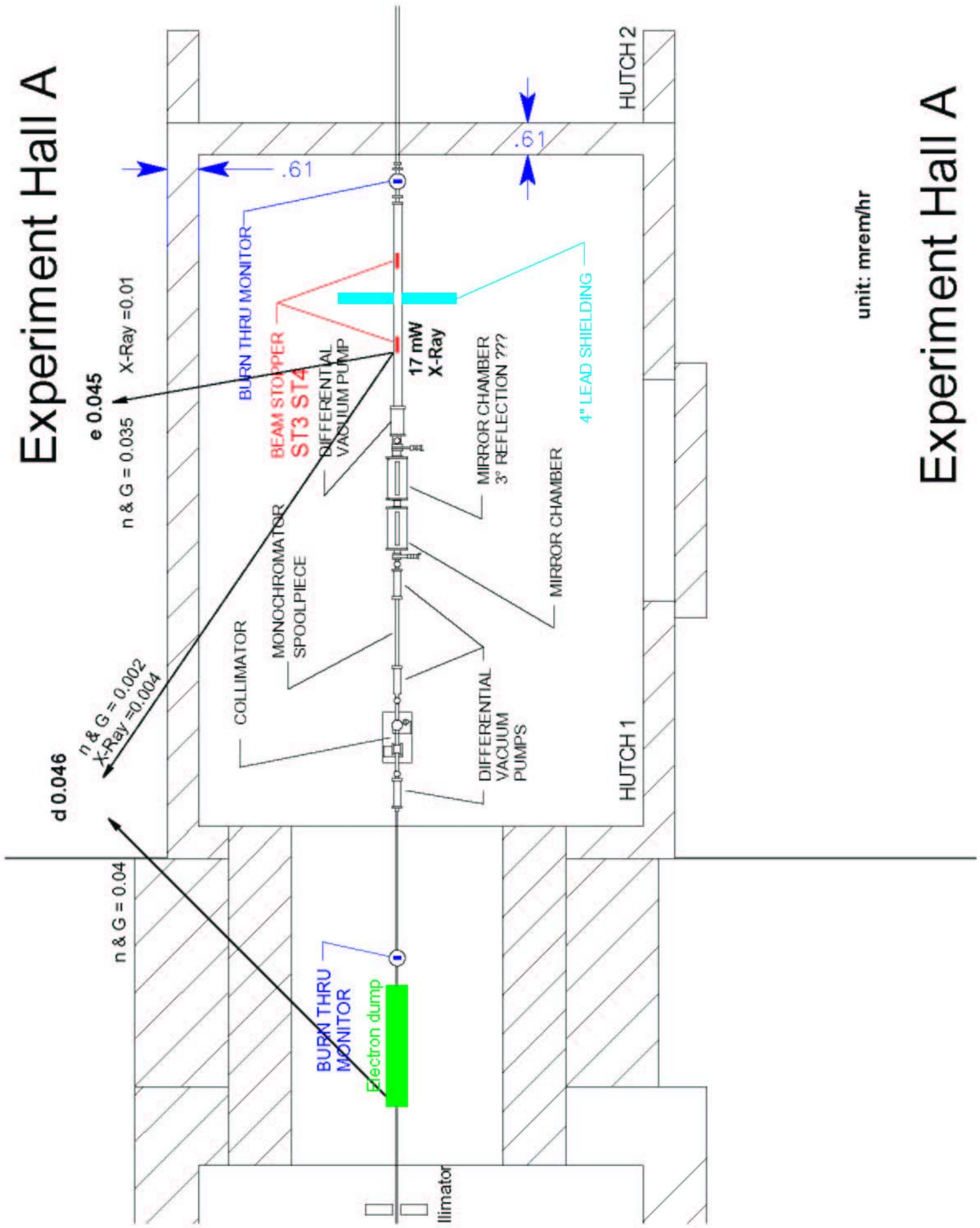


Figure 14.7 Shielding and Radiationo Safety Components for the Experimental Hutches, Hall A

14.3.1 Minimum Shielding Requirements

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

Front End Shield:

Lateral walls: 4.1 ft. iron plus 4.0 ft. concrete.

Roof: 3.0 ft. iron plus 5.5 ft. concrete.

Dump Shield:

Lateral walls: 4.1 ft iron plus 4.0 ft. concrete.

Front (exit) wall: 6.6 ft. iron plus 4.0 ft concrete.

Back (entrance) wall: 1.6 ft. iron.

Roof: 3.0 ft iron (minimum) plus 5.5 ft. concrete.

Experimental Hutches Shield:

Lateral walls: 2.0 ft concrete.

Front and back walls: 2.0 ft concrete.

Roof: 2.0 ft concrete.

Local: 4 in. lead to shield down beam of the first stopper.

14.3.2 Beam Containment System

SLAC's beam containment policy requires that beam lines be designed to contain the beam, limit the incoming beam power to the beam line, and limit the beam losses to prevent excessive radiation in occupied areas [1]. The containment of the beam in its channel is achieved by implementing a system of redundant, tamper-proof, and fail-safe electronic and mechanical devices that are enforced by strict operational requirements. The BCS for the LCLS will use most, if not all, of the FFTB BCS, which is comprised of devices that limit the incoming average beam power to less than the allowed beam power (torroids of current monitors 14 and 15); devices that limit normal beam loss to 1 W (torroids 16 and 17, long ion chambers); protection collimators that ensure that errant beams do not escape containment; and devices that protect collimators, stoppers and dumps (ion chambers and flow switches). The permanent dipole magnets in the beam line that assure that the electron beam reaches the main dump are the final component of the BCS.

For the LCLS, the following BCS devices will be added to the existing FFTB BCS down beam of the undulator and in the front end enclosure (Fig. 14.3).

A collimator after the undulator with two ion chambers and one BTM.

A collimator between the third magnet and the fourth magnet of the electron beam dump with two ion chambers and one BTM.

A collimator after the last dump magnet with two ion chambers and one BTM.

A beam stopper upstream of PPS stopper ST 1, which is interlocked with the x-ray intensity monitor.

One BTM after PPS stoppers ST 1 and ST 2.

One BTM after the electron dump.

One BTM after PPS stoppers ST 3 and ST 4.

14.3.3 Personnel Protection System (PPS) and Hutch Protection System (HPS)

The PPS and HPS are designed to prevent access to experimental areas when beams are present and to prevent beams from entering an area during personnel access. Thus, the PPS and HPS function as access control systems and are based on standard designs at SLAC.

The PPS is composed of beam stoppers, entry module, and emergency shutoff buttons. Entry to the tunnel requires that all three PPS stoppers (D2, ST60 and ST61) be in the IN state. The main entrance to the FFTB tunnel is through a maze in the research yard. It is equipped with the standard access module of an outer door, an inner door, a key bank, an access enunciator panel, door control boxes, search reset boxes, a telephone, and a TV camera. The outer door has an electromagnetic lock and two door-position sensing switches that are used to monitor the status of this door and to activate a relay that permits or prevents a beam. The inner door provides redundancy and has two position sensing switches as well. A similar maze will be added at the entrance to the front end.

The experimental hall shielding, which prevents access to beam areas, will consist of fixed and moveable parts. The experimental hall perimeter walls and central beamline walls are planned to be fixed shielding consisting of appropriate material for the energy spectra of expected radiation. The experimenter hutches may have movable walls to adjust for experimental requirements. The moveable wall configuration will activate the current radiological configuration control system when changing the hutch shielding [13]. The experimental walls will have the capability of adjusting to the different angles of any hutch branch lines. The access control system (PPS and HPS) will be capable of retaining integrity and reliability, while compensating for wall placement.

The HPS will control access to the experimental hutches and will be modeled after existing SSRL HPS. The key parts of the HPS are a keyed access door, photon stopper interlocks, and area security system. The HPS allows either permission for personnel access or for beam to enter the hutch. It contains the logic interlock circuits that govern the sequence of access operations centered on the status of the stoppers. It also captures or releases the hutch door keys, acknowledges completion of a personnel security search, and keys the experiment enclosure on-line or off-line. Access to the hutch is permitted only if all photon stoppers are closed.

For access permission to any experimental hutch, the LCLS HPS will control the operation of photon stoppers in other areas or hutches that are required to be in. Two ion chambers and a burn-through monitor are required to protect each stopper.

14.3.3.1 Stoppers

Two up beam PPS beam stoppers will be required to allow entry into an experimental hutch to make changes that require disruption of the x-ray beam line while the e^- beam is being delivered to the undulator and deflected into the dump. The function of these stoppers is to block and absorb any coherent or incoherent γ or X-radiation from the undulator, as well as bremsstrahlung from anywhere in the beam transport system. These stoppers are patterned after an SLC design used in Sector 10 of the SLAC linac and in the PEP-II extraction lines [14]. The design energy is 12-15 GeV and the assumed power for continuous exposure is P_{av} ~5 kW. The absorbing element in each stopper provides 30 cm copper, or the equivalent in radiation length of other material. The stoppers will be designed to meet the safety criteria.

14.3.3.2 Burn-Through Monitors

A built-in burn-through monitor is located at the depth of shower maximum in each stopper. It consists of a pair of cavities separated by a Cu diaphragm. The first cavity is pressurized with dry N_2. Its return line contains a pressure switch with the trip level set to 15 psig. Should excessive beam power be deposited in the stopper block, the diaphragm will perforate, allowing the N_2 to escape into the second cavity, which is open to atmospheric conditions on the outside. The pressure switch will interrupt beam delivery within 2-3 linac pulses.

14.4 Induced Activity

Personnel exposure from radioactive components in the beam line is of concern mainly around beam dumps, targets, or collimators where the entire beam or a large fraction of the beam is dissipated continuously.

Another source of potential exposure is to personnel working on the undulator after it has been in service for a period of time. Calculations based on methods developed by [15] and on [16] Swanson's (1979) tabulations express the rate of radionuclide production in terms of saturation activity A_s, i.e., the activity, at the instant that the irradiation has stopped, of a target that has been steadily irradiated for a time long compared with the half-life of the produced radionuclides. For these calculations, it was assumed that the permanent magnets are made of natural iron and natural cobalt, 50% each. To calculate the exposure rate, A_s is multiplied by γ, the specific gamma ray constant which gives the exposure rate in air at a fixed distance (1 m) per unit of activity (Ci).

Natural iron is comprised of ^{54}Fe, ^{56}Fe, ^{57}Fe, ^{58}Fe isotopes. Reactions (γ,n) (γ,2n) (γ,np) (γ,p) (γ,spallation) were considered. The product radionuclides that contribute the largest fraction of the dose are Mn isotopes. Natural cobalt is 100% ^{59}Co, and the reactions (γ,n)^{58}Co, (γ,2n)^{57}Co were considered. Reactions (γ,p), (γ,pn), (γ,p2n) (γ,p4n) all lead to stable iron isotopes, and (γ,p3n) leads to Fe with a 5.9 keV x-ray which would be self shielded in the target.

The total exposure rate from an activated magnet immediately after shut-down is conservatively estimated to be 5 mrad hr^{-1} W^{-1} at 1 m. The exposure is dominated by a 0.8 MeV gamma from ^{58}Co with a half-life of 71 days. With the expected low level of beam losses in the undulator, the activation of the unit and resulting personnel exposure are expected to be very low.

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