SOURCE DEVELOPMENT LABORATORY

Safety Assessment Document

Building 729, Site of the BNL Deep Ultra-Violet Free Electron Laser (DUV-FEL)

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Source Development Laboratory Safety Assessment Document

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INTRODUCTION 1

1.1 Motivation and Scope

By 2010 or sooner, it is believed that the next major DOE light source facility will be operational, and that it will likely be based on some type of single-pass free electron laser (FEL) technology. Since the early 1990's BNL has been a key laboratory in the development of technology and theory that will support such a machine. The Source Development Laboratory (SDL) was established as a dedicated experimental platform to pursue research for this type of 'Fourth Generation' synchrotron radiation source.

A major element of the program includes development of a high peak power FEL operating in the vacuum ultraviolet. Known as the Deep Ultra-Violet Free Electron Laser (DUV-FEL), the objective of the program is to develop the source and experimental technology together to provide the greatest impact on UV science, and the broadest possible insight into the virtues and limitations of the technology at yet shorter (x-ray) wavelengths. The concept for the DUV-FEL is an extension of the High Gain Harmonic Generation (HGHG) FEL recently demonstrated in the infra-red at the BNL Accelerator Test Facility (ATF).

The basic configuration of the FEL requires a high peak current, low emittance electron beam that can be made to interact with light from a seed laser in a periodic magnetic structure (wiggler or undulator). The resulting energy modulation in the electron beam can be converted to a spatial modulation which then radiates and is amplified in a longer undulator. The radiation produced can be either at the fundamental of the seed laser (same wavelength output) or can be arranged for a higher harmonic. From the experimentalists' standpoint, the essence of the approach is to capture the properties of the high quality seed laser (stability, bandwidth, pulse duration, chirp &c) and express them at shorter wavelengths than can be obtained from laser itself.

In the case of the DUV-FEL a Titanium:Sapphire system (ca 800 nm) provides the seed, and operation at wavelengths well below 200 nm are anticipated.

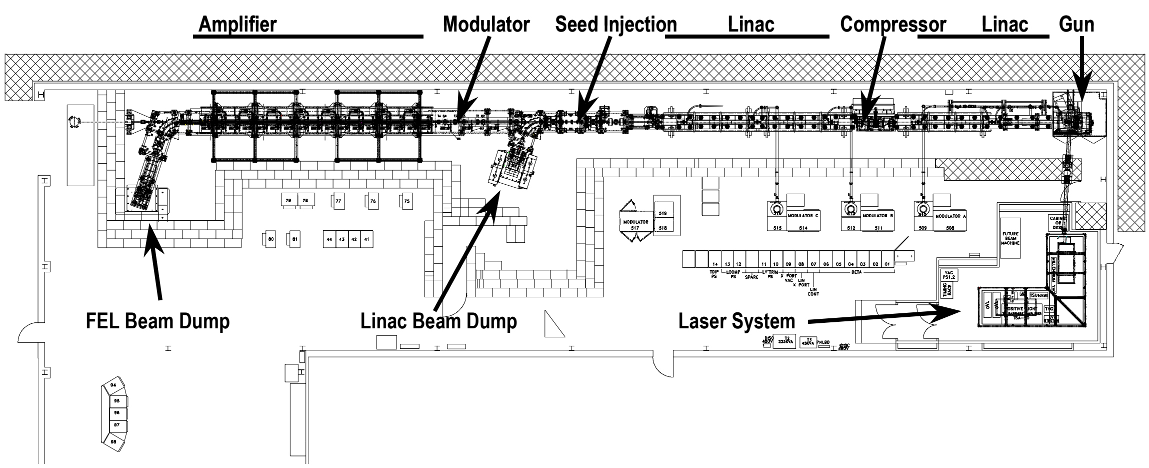
The SDL builds on technological developments pioneered at the ATF in creating the DUV-FEL and experiments involving coherent synchrotron radiation. Therefore, in the creation of this Safety Assessment Document (SAD), much use was made of the previous operational experience at the ATF which shares much of the hardware complement to be installed at the SDL. The SAD analysis also takes advantage of the fact that the linac was originally procured as part of the superconducting x-ray lithography source (SXLS) program. The linac was assembled and tested as part of the procurement process, so experience from the earlier electron linac facility (ELF) installation was factored into the design of the SDL and the creation of this SAD.

The Source Development Laboratory is being assembled in stages, which is reflected in the scope of the SAD through each revision. The initial phase of the program was covered in revision B of the SAD, and was centered on the creation and characterization of the bright electron beam required by the DUV-FEL. Revision C of the SAD expands the scope of the document to include the DUV-FEL experiment and its equipment. The structure of the SAD is meant to provide an understanding of the project so that the efficacy of the design to ensure the protection of the environment, workers and the public can be fully evaluated. In this revision, the content of the document has also been rearranged to follow the guidance provided in the BNL SBMS subject area on Accelerator Safety.

Section 1 describes the basis for the project and provides a brief description of the facility. Section 2 provides a high level summary of the conclusions of the Safety Assessment Document. Section 3 involves a more detailed description of the facility, its components, and the operating procedures which will be in place when operations are approved. Section 4 concerns itself with an analysis of the safety issues, with particular emphasis on radiological safety. The remaining sections are concerned with Quality Assurance (5), Decommissioning (6), and a listing of References and Associated Documentation used to establish design criteria (7). As outlined in the SMBS subject area, the Accelerator Safety Envelope (ASE) has been removed and is now a stand alone document (LS-SDL- 0019) that defines the boundaries established for safe operation of the facility described in the SAD.

1.2 Description of the Facility

The goal for the SDL Linear Accelerator is to provide intense electron pulses for subsequent experiments. The average beam power as presently configured is actually comparatively low; 6 W at full machine capability. These characteristics have influenced many aspects of the design of the SDL including the machine, shielding, and distribution of equipment throughout the building. This thumbnail sketch emphasizes the major features of the facility, and the location of the accelerator within building 729.



The electronic characteristics of the SDL linac are shown schematically in Figure 1. It consists of a high brightness RF photocathode electron gun followed by a 230 MeV pulsed linac (~1.5 μsec radiofrequency pulse length) operating at a pulse repetition frequency of up to 10 Hz. The linac incorporates a magnet chicane for bunch compression of the short (~7ps), high peak current (~130A) electron bunches, produced by the electron gun.

The gun cathode is illuminated by the beam from a wide bandwidth Ti: Sapphire regenerative amplifier capable of pulse shaping and lengthening. The pulse length is adjustable from 0.3 ps to 20 ps. With pulse compression peak bunch currents of up to 10kA are feasible with a corresponding bunch length of ~50 μm.

Following the linear accelerator is a transport line that has a diplole magnet to direct the electron beam to a shielded beam dump. This line constitutes an energy spectrometer that can be used to characterize the beam. The field in the dipole magnet can be reduced to zero so the electron beam is not deflected and it can pass directly to the DUV-FEL experiment. There the beam passes through a transport line that includes an energy modulation wiggler, a dispersive magnet chicane, and the amplifier wiggler where the FEL light is produced and amplified. To separate the optical beam from the electron beam, a second diplole magnet and beam dump are provided. The optical beam is deviated down with mirrors to pass through a penetration in the concrete shielding wall that is below the nominal electron beam height, to minimize the potential for radiation leakage from the accelerator enclosure.

The components of the DUV-FEL will be installed and commissioned in stages starting with an initial configuration that includes only the amplifier wiggler and beam dump. The modulator and dispersion section will then be added. In addition, this safety analysis anticipates an upgrade of the linac energy from the presently installed 230 MeV to 300 MeV. The equipment configuration for the analysis and utilization of the FEL light will be reviewed by the NSLS Beamline Review Committee. Individual experiments will be reviewed through the NSLS experimental approval process.

1.3 Environment, Worker and Public Safety

Although the SDL will incorporate and explore very advanced technology in the accelerator physics field, the operations, energies and beam currents associated with this facility are well within those commonly in use at the NSLS and other accelerators at BNL and elsewhere. As a result, the potential hazards associated with the operation of this facility have been successfully addressed at NSLS for a number of years.

The ESH requirements and practices in place at the NSLS will be incorporated into those implemented at the SDL. The ESH design and operational program requirements are described in this document and are subject to the review and approval of the NSLS Department, as well that of the BNL ESH/Q Directorate and the Laboratory ESH Committee.

An Accelerator Safety Envelope which defines the operating requirements for the facility has been prepared for the SDL based on this analysis and will require approval from the Department of Energy prior to operation. Prior to initial operation of the facility, an accelerator readiness review will be conducted to ensure that the necessary ESH program elements are in place and are functional.

SUMMARY/CONCLUSIONS 2

This SAD describes all significant environmental, safety and health hazards created by the facility and its operations. Section 4 reviews the risk associated with environmental and hazardous waste issues, ionizing and non-ionizing radiation, electrical, fire, and hazards associated with natural phenomena. Appropriate design and controls have been put into place to mitigate and control these hazards, and it is demonstrated that the facility can operate with a minimum level of risk to the environment, workers, and the public.

The shielding design together with the radiation security interlocks and search and secure procedures ensure that no personnel are exposed to any significant levels of radiation. NSLS workers will receive < 100 mrem/year and the general public will receive less than 25 mrem/year by the measures outlined in this document. This includes normal operation of the Source Development Laboratory at the maximum operational levels given in Accelerator Safety Envelope (LS-SDL-0019), as well as for accident scenarios. This also conforms to or is less than the criteria in 10CFR835.

Design and construction of electrical equipment ensures that no exposed high voltages are present anywhere in the facility. High voltage enclosures are either locked or fully interlocked. Normal NSLS policy prohibits “working hot” on electrical equipment; any deviation from this requires a permit and a working hot procedure. Staff members are trained in these policies and in Lockout/Tagout (LOTO) procedures.

Non-hazardous fluids are used for cleaning purposes where possible and all chemical inventories are kept to a minimum. Generation of hazardous wastes at the facility will be quite low (< 5 gallons/year). Releases to the environment are minimal and no permits or monitoring for environmental releases are needed. Generation of radiological waste materials will also be limited. Small quantities of activated copper, aluminum or stainless steel will need to be disposed of as part of a decommissioning plan. The total volume is estimated to be < 10 cubic feet over the life of the project.

The building has been designed to conform with the National Fire Protection Association "Life Safety Code" No. 101 and DOE Order 420.1 Facility Safety 10/13/97. Automatic sprinklers and smoke detectors are installed in the facility. The facility is compliant with the DOE "Improved Risk" criteria for fire protection purposes.

The high power, pulsed, laser beams are contained in interlocked enclosures and are transported inside opaque beam tubes. Entry into or occupancy of laser areas while the lasers are operational shall be only by trained or properly escorted personnel who are required to use suitable protective eyewear.

An Accelerator Safety Envelope (ASE) has been established to ensure the facility operates as defined in this document. The Source Development Laboratory (SDL) facility has been designated as a 'low hazard' under DOE order 5480.25 "Safety of Accelerator Facilities". This facility, as described in this document, is compliant with the NSLS, BNL and DOE ESH requirements. This Safety Analysis Document (SAD) has been developed to meet the requirements of DOE Order 420.2A "Safety of Accelerator Facilities" and its predecessor document, DOE Order 5480.25 as well as the guidance contained in 10CFR835(paragraph in the CFR as a reference), the Brookhaven National Laboratory Radiological Control Manual, and the Accelerator Safety Subject Area.

FACILITY AND OPERATIONS DESCRIPTION 3

3.1 Introduction

The SDL is housed in Building 729, which was built in 1993. The structure consists of a steel exterior and frame on a slab and a single high bay story. The building was extended in 1996 to allow for more experimental space and for a new injection and laser system. The building extension is of a similar construction to the original building. The structure was built to all applicable Uniform and State Building Codes in force at the time of its construction. The facility is located northeast of the intersection of Brookhaven Avenue and Railroad Street and east of the existing NSLS Building 725 as shown in the site plan (Figure 2). The Mechanical Equipment Room is situated in an area connected to existing Building 726 at the west end of the Building 729 and is separated from both buildings by one low rated fire wall. A cleanroom to house the class IV laser systems used in SDL operations is located at the east end of the building. The detailed description of the conventional facilities is provided in section 3.2.

The 230 MeV linac utilized as the electron source for the SDL was fabricated, installed and tested by an outside vendor, Beta Development Corporation, as part of an earlier project (ELF) in 1993. It has been modified and is housed in Building 729 as shown in Figure 3. The accelerator, a conventional S-Band (2856 MHz) RF electron linac of overall length ~ 60 ft. is located along the north wall of Building 729. The electron gun is located at the east end of the building. The laser system used to produce electrons from the gun is just south of the gun. The DUV-FEL optical systems are located at the west end of the building. These accelerator systems are detailed in section 3.3.

To provide radiological shielding, lead, concrete and borated polyethylene are used to enclose the accelerator. The principal enclosure for the accelerator is comprised of 8 ft. high concrete walls. Inside the building the wall is 32” thick along the south side of the linac, and 48” thick in all other interior locations. The exterior wall is 48” thick running the length of the building on the north side and lapping the corners of both the west and east ends of the building. The accelerator and other critical accelerator components are covered on top and sides by lead shields at least 2" thick. Access to the machine is controlled by interlock systems that prohibit entry to the enclosure when the machine can operate. Details of the radiological protection systems are provided in section 3.4.

Environmental, Worker and Public Safety is an integral part of the design process for SDL equipment. Electrical, radiation (ionizing and non-ionizing) and general safety issues were reviewed and preventative measures such as interlocked enclosures with controlled entry or adequate shielding have been provided based on both normal and unusual or accidental modes of operation anticipated. Various organizational, training and program review policies have been put in place that form the basis of the SDL Safety Program described in section 3.5.

3.2 Conventional Facilities

3.2.1 Building 729

Building 729 is a one story high, butler type building. The concrete slab construction is used for the floor and the walls are insulated metals panels on steel beams. All building materials are considered non-combustible. The plan view of figure 3 shows an L-shaped structure of approximately 160 feet length and 40 feet wide with the west end extended an additional 40 feet to join the existing Building 726. The elevation view of figure 4 shows a minimum inside building height of about 14.7 feet on the north side of the linac enclosure, sloping up to a maximum inside height of about 22.4 feet at the building center. There is a 2 ton bridge crane which covers the building area between the laser room and the west end of the building. .

The facility is designed to be in compliance with NFPA 101, Life Safety Code, and with BNL Environmental Safety and Health Standard 4.1.2. for an ordinary hazard, fully sprinklered, industrial occupancy. The occupancy is a standard accelerator, with metal beam line transport piping, concrete shielding, electrical power supplies, and cable trays. The occupancy load within the building is low (>100 sq. ft./person). The access and egress doors and gates are indicated on building plan view Figure 5. The primary access and egress for personnel will be through doors located on the west and south side of the building. A roll-up door (door 4) intended only for equipment access will otherwise be closed. Additional egress can be made through a set of double doors into Building 726. The mechanical equipment room is provided with one emergency exit door.

Standard outdoor lighting and concrete walkways for personnel are provided for doors 1 and 2. Doors 1, 2 and 3 are provided with the standard controlled access entry system in effect throughout the NSLS, with entry enabled by a BNL ID card reader. These standard industrial security measures do not conflict with egress from the facility. Emergency lighting is provided within the building by battery-operated units. All exits are marked with appropriate signs. The building is protected with a combination of automatic sprinklers, automatic heat and smoke detectors and manual fire alarm pull stations. Smoke detectors are provided in the air handling system in compliance with NFPA 90A. Alarms and supervisory points are connected to the BNL Fire Rescue Group annunciators.

Combustible loading within the building is light. Previously stated the building is constructed of non-combustible materials. Equipment within the building contains combustible wire insulation as well as interconnecting power and signal cables. This is an acceptable risk given the presence of automatic sprinkler protection in the facility and the open configuration of the cable trays.

Apart from the klystron insulating oil (~450 gallons in well controlled tanks), no significant quantities of combustible gases or fluids are anticipated. Klystron oils are combustible mineral oil types. However, they are within metal containers, within secondary containment, and protected by ceiling level sprinkler systems. For neutron shielding, polyethylene containing 5% boron is used. The both green and white colored borated polyethylene is used. This type of shielding is considered non-combustible and acceptable for sprinklered occupancies. No high hazard operations are associated with the operation of the SDL systems. A detailed “Life Safety Code Analysis” and a Fire

Assessment/Fire Analysis Report generated by the BNL Fire Protection personnel is available [A1] (Appendix I).

3.2.2 Electrical Power

The electrical power for the Source Development Laboratory is distributed at 480 volts, 3 phase with a grounded wye system. Some equipment requires the 480 line voltage such as the overhead crane, linac modulators, klystron magnets, and transport magnet power supplies. The 120/208 volt system is derived from the 480 feed for smaller equipment. Examples of loads on this system include building lighting, heating and ventilation pumps, water system pumps and other small equipment needs such as control console components, fire safety monitors, alarms and communications equipment. The installation and operation of this power distribution system is according to standard industrial practice for this type of equipment. The safety codes used for guidance included ANSI spec #39.5 (electrical and electrical measurement and controlling instrument safety requirements), the National Electric Code, Department of Energy Order 440.1A "Worker Protection Management for DOE Federal and Contractor Employees", DOE/EV-0051-1 electrical safety criteria for research and development activities, and BNL Environmental, Health and Safety Standards 1.5.0 and 1.5.2.

All equipment is enclosed in grounded dead front cabinets. All systems operating at exposed voltages above 24 volts RMS are contained inside secured enclosures with locked or interlock protection, or bolted access according to the serviceability of the equipment and the potential hazard. In equipment where stored electrical energy may be present a system of discharge bleeders, automatic shorting bars and manual grounding sticks are provided.

The A.C. Power Distribution System uses conventional design practice and provides for lockout and tagging of all equipment for which these rules are applicable. The electrical system contains no unusual features when compared to similar Laboratory facilities such as the NSLS and ATF linacs and, as such, hazards are judged to be marginal in terms of occurrence probability and potential consequences as defined in the Brookhaven National Laboratory Environmental Safety and Health (BNL ES&H) Standards Manual. Electrical hazards are discussed in Section 4.4.

3.2.3 Water Cooling Systems

An air-cooled chiller is located outside the northeast corner of Building 729, and provides the capacity for the water system which circulates up to 435 GPM of glycol/water at a temperature of 45°F. The chilled water system contains approximately 400 gallons of 40% propylene glycol (Eastman Chill Guard 35) with a fresh water make-up line to an expansion tank. The location of the circulation pumps is such that about half of the volume of the glycol/water coolant (200 gallons) could be lost in unlikely event of a catastrophic failure of the piping system. Low flow and temperature excursion alarms immediately enunciate at the Plant Engineering Central Chilled Water facility where the functioning of the cooling system is continuously monitored. Plant engineering personnel are on call 24 hours a day to respond to such alarms.

Approximately 90 GPM of the chilled water is used for the building air handler with the balance available for the other systems. These include the laser room and the linac temperature control systems. The machine systems are both closed loop deionized water systems using ion exchange beds that are removed for regeneration or disposal by a contractor off site. Discharge of contaminants to the ground or to the sanitary system is neither planned nor expected from either the HVAC or accelerator cooling systems.

One system (accelerator components) actually heats the linac sections to keep them operating on frequency. A 75 kW electric heater is used to elevate the temperature of the water for this loop and cooling is used only to damp the temperature against overshoot in the heater. Another system (power supplies) is provided to remove the waste heat from other accelerator components including power supplies, magnets, and auxiliary equipment. The operating parameters for the machine systems are summarized below:

Parameter/System		Power Supplies	Acc. Components
Design Pressure	[psig]	110	150
Design Temperature	[°F]	100	150
Operating Pressure	[psig]	97.5	133.5
Operating Temperature	[°F]	74	113±0.2
Flow rate	[gpm]	135	75
DI Resistivity	[Mohm cm]	<1	~1

3.2.4 HVAC

BNL Plant Engineering and the NSLS utilities group have specified the Heating, Ventilation and Air Conditioning systems. A closed loop propylene glycol/water system provides the cooling for the building air, the laser room, and the accelerator equipment. The building space has one large air handler (AHU1) that provides a minimum fresh air intake of 600 CFM. It is tied into the sitewide Energy Management Control System (EMCS) and provides heating from site steam to a setpoint of 70°F and cooling to a setpoint of 74°F. The laser room is a class 1000 clean room with a class 10,000 ante-room that runs with a separate HVAC system under local control. It is a recirculated air system that takes in 570 CFM of 'fresh air' from inside Building 729. A compressed air system is also located in Building 729 for air operated equipment such as HVAC control valves, valves on the accelerator, or pneumatic flags on the accelerator. It has a 10 hp 43 SCFM compressor operating at 100 psig filling a 120 gallon storage tank located in the mechanical equipment room.

3.2.5 Communication System

The PA system announcements for Building 729 can be made from the control console. Speakers are located throughout the building to keep personnel informed of any occurrence and status within the building. Additional communication through the Building 725 TV/Audio system will keep all personnel advised of the status of Building 725 and also may be used as a back-up for Building 729 communications.

3.3 Accelerator Systems

3.3.1 Linac

All of the accelerator and beam line components as well as the purchased equipment have been designed to conform to applicable guides, codes and standards. There are no deviations from current DOE design criteria outlined in the documents listed in section 7 of this SAD, 'References, Figures, and Associated Documentation'. Specifications for purchased equipment have undergone thorough design reviews prior to issuing of purchase orders and on site acceptance tests have been carried out.

The linac is a commercially built [1] (Beta Development Corp., Dublin, CA) RF electron linear accelerator of nominal installed maximum energy E_0 = 230 MeV, energy range 40-230 MeV, containing four 3 m SLAC, iris-loaded accelerating sections powered by three 45 MW peak pulsed power Thomson-CSF TH-2128 klystrons operating at the Standard S-band frequency of f_{rf}=2856 MHz. A block diagram of the complete system is reproduced here for convenience as Figure 1. The overall length, including electron gun as shown on Figure 3 is 60 feet and the diameter of the vacuum enclosure around the drift tubes is about 125 mm and the beam elevation is 1.4 m (55") above the building floor. The vendor's stated maximum energy performance capability is [1]222 MeV + electron gun energy. The nominal performance specifications for the machine are listed in the following table:

CHARACTERISTIC	VALUE
Beam Energy:	Variable from 40 to 230 MeV
Beam Pulse Width:	300 fs to 20 ps

Pulse Repetition Rate:	1-10 Hz in 1 Hz Steps
Energy Spread at 230 MeV:	±1%
Maximum Peak Beam Current:	10 kA (1nC; 100fs Compressed Pulse)
Maximum Average Beam Current:	100A at 10 ps, 10 Hz = 10nA/beam pulse
Vacuum Pressure:	$\approx 10^{-8}$ Torr at vacion pumps
RF Cavity Input Power Pulse Width:	1.2 μsec flat top
Klystron Peak Power:	45 MW x 3 tubes
Klystron Modulator Voltage:	48 kV
Klystron Modulator Peak Current:	13.0 kA
Maximum Gun Peak Current:	1 kA (eg. 1nC; 1ps)
Gun Energy:	Maximum 8 MeV, 5 MeV nominal

The linac is located along the north wall at the eastern end of Building 729. There is a 44" wide aisle between the linac and a 3 ft. thick shielding wall on the south side (see Figure 4). Modulators, magnet power supplies, beam diagnostic and monitoring equipment are located between this shielding wall and the south wall of the building. There is also a control console and a laser equipment room in this area.

The power is transmitted from the klystrons to the accelerating sections and electron gun via vacuum waveguide and therefore presents no hazard. The klystron tanks and the capacitors in the modulators are insulated with oil that has been certified as containing no PCB above the minimum detectable limits. The high voltage end of each klystron tube is immersed in a tank filled with approximately 150 gallons of mineral oil. The three klystron tanks each reside in secondary containment tanks large enough to contain all of the oil if it is accidentally drained from the klystron tank. The tanks have been registered with Suffolk County in compliance with Article 12 of the Suffolk County Sanitary Code, although modifications to the registration are in process.

Various high field magnets are used in the facility including electromagnets for focusing the beam inside the klystrons, and transport elements for the accelerator. Ion pumps are equipped with permanent magnets. These magnets are generally situated in areas not normally accessible to the general public. Their approximate fields have been measured and are posted as warnings for individuals who have pacemakers.

3.3.2 Laser Systems

The gun cathode is illuminated by the beam from a wide bandwidth Ti:Sapphire regenerative amplifier system. A Ti:Sapp oscillator (Spectra Physics Tsunami, 800 nm, 1.25 W cw) is operated at 81.6 MHz pulse repetition rate that is phase locked to the accelerator timing system. The pump energy for the oscillator is provided by a diode pumped $Nd:YVO_4$ laser (Spectra Physics Millennia, 532 nm, 5W cw). The light from the oscillator is used as the seed for the regenerative amplifier (Positive Light TSA-50, 50 mJ/pulse, ~800 nm, 50 fs). The pump energy for the amplifier is provided by two frequency doubled YAG lasers operating at 10 Hz (Quanta-Ray GCR 170/150, ~0.85J/0.65J per pulse@ 532nm, 6ns). The amplifier is based on chirped pulse technology, hence the pulse length is adjustable from 0.3 ps to 20 ps by adjusting the stretcher/compressor. The IR light from the amplifier is tripled in a BBO harmonic generation system. The resulting 266 nm UV light is used to stimulate the production of photoelectrons from the gun cathode surface.

The gun laser system is classified as a Class IV laser and is housed in an interlocked room. The light is transported to the electron gun in an opaque beam pipe. The electron gun and the final focus optics table are located in a light tight interlocked enclosure. A photon shutter is located in the laser room that intercepts the beam if the gun hutch door has been opened, or if the gun hutch laser interlock has not been satisfied. In addition to the gun laser, alignment laser systems are also used. Typically these are He:Ne lasers with integrated collimating and steering optics. The alignment laser heads may be up to Class IIIb with beam specifications of less than 5mW @ 633 nm cw.

The delivered beam power from the alignment laser systems will be lower than 5 mW due to attenuation in the delivery optics.

The laser and interlock systems have been designed to conform to BNL SBMS 'Laser Safety' subject area. A detailed description of the interlock systems [A7] is available and the hazards associated with the laser are outlined in the Risk Assessments provided in section 4 of the SAD. Safety goggles are required for those workers who need to enter the interlocked laser areas in order to make adjustments while the lasers are operating. Adjustments to the high power lasers or transport systems can only be made by personnel who have been trained in SDL site specific laser procedures. Only trained and authorized personnel may work in the laser areas while the lasers are in operation.

3.3.3 DUV-FEL Optical System

This section of the accelerator is where energy from the electron beam is converted into light. The properties of the light produced depend upon the mode of operation, and the characteristics of the electron beam and accelerator optics. For the range of parameters anticipated for the SDL, the DUV-FEL should be capable of producing light at wavelengths ranging from 1000 nm down to 200 nm (in the fundamental) with pulse energies of as much as 0.25 mJ in pulses as brief as 0.1 ps. Harmonic output (down to 66 nm) should be available with approximately 1% or less of the power contained in the fundamental. From the standpoint of safety analysis and facility design, the DUV-FEL output light is regarded as class IV laser light. The stringent precautions for class IV systems (as outlined in SAD section 3.3.2) are uniformly applied in enclosing the optical path, and utilizing the light produced by the DUV-FEL.

The DUV-FEL is based on sub-harmonic seeding of the electron beam with a laser to provide a controlled energy modulation in the electron beam. To accomplish this, light from the facility laser will be conducted inside an opaque beam tube from the gun hutch to a small optical table just upstream of the linac dipole spectrometer. The light is injected with an optical periscope and passes through the accelerator vacuum system to a focus inside of an energy modulation wiggler. There the electric field of the laser light couples with the electron beam as it passes through the wiggler. This imparts an energy modulation that must be converted to a spatial or density modulation in the electron beam, which is accomplished with a dispersive magnet, which is a small electromagnet chicane.

Once the beam is bunched it passes into the amplifier wiggler that is tuned to be resonant with the bunching, or a harmonic of the bunching. The light generated in the early part of the amplifier reinforces the bunching at the desired wavelength as the beams propagate through the amplifier. As the density modulation is increased, the intensity of light produced is increased. For this process to work correctly the alignment of the magnetic axis of the amplifier with the optical and electron beam trajectories is critical. For this reason extensive intercepting diagnostics have been built into the DUV-FEL which consist of a series of ‘pop-in’ monitors.

The energy modulation wiggler is the ‘mini-undulator’ with a new gap separation mechanism. This device was used in the NSLS X-ray Ring, and was the energy modulation wiggler for the original HGHG experiment at the ATF. It uses $SmCo_5$ magnet material and steel poles. The dispersion section is a purpose built electromagnet also recovered from the HGHG experiment. The amplifier wiggler is known as NISUS (Near Infrared Scalable Undulator System) and was originally built for an Army Strategic Defense Initiative program and transferred to BNL for use in the DUV-FEL. It uses $SmCo_5$ magnet material and vanadium Permadur poles. The properties of the undulators are provided in the following table:

PARAMETER	UNITS	MODULATOR	DISPERSION	AMPLIFIER
Period	mm	80	197	38.9
Number of Periods		10	1	256
Peak Magnetic Field	T	0.35	0.55	0.56
K (Max)		2.6	N/A	2.0
Minimum Gap	mm	31	15	14.4
Overall Length	m	0.8	0.3	10
Clear Aperture	mm	25	11.4	11.4

The amplifier wiggler presents the closest integration of machine and safety requirements in the machine. The gap of the device must be small and a large number of diagnostics must be available to monitor the trajectory, which can be corrected by steering coils embedded in the vacuum system chamber. The magnet structure is in 16 segments which can be adjusted to different gaps at each end using stepper motor driven gear boxes. The top and bottom magnet beams can be independently positioned. As a consequence, the NISUS undulator system includes 16 4-wire corrector magnets, 17 pop-in monitors, 34 stepper motors, 34 LVDT position sensors, and 134 limit switches. The device is complex with many requirements for stability, survey accessibility in addition to all of the connections and data channels. For this reason the shielding system is closely coupled to the undulator structure to minimize its size and weight. It consists of fitted lead and 5% borated polyethylene segments built around the undulator structure, and is described in more detail in section 3.4.

The light from the FEL will be coupled out of the radiation enclosure by a pair of mirrors that bring the optical beam well below the electron beam height before exiting the enclosure. The objective of this configuration is to contain any possible brehmsstrahlung within the radiation enclosure. Initially a pair of flat mirrors at 45° incidence will be used in a standard periscope configuration, bringing the optical beam from the electron beam height of 1400mm to 970 mm. As the light produced by the FEL progresses to shorter wavelengths, a grazing incidence system will be installed to improve the efficiency of the beam transport. The same nominal height displacements will be used.

The following table provides parameters for four representative operating configurations of the

DUV-FEL.

PARAMETER	UNIT	I	II	III	IV
FEL Output Wavelength	nm	400	400	200	100
Seed Wavelength	nm	-	800	400	300
Linac Energy	MeV	145	145	205	290
Operation Mode		SASE	HGHG	HGHG	HGHG

Operation at wavelengths shorter than 200 nm will require implementation of the linac energy upgrade by the addition of a new accelerating structure and additional RF power. The space for these devices is anticipated by the current machine configuration.

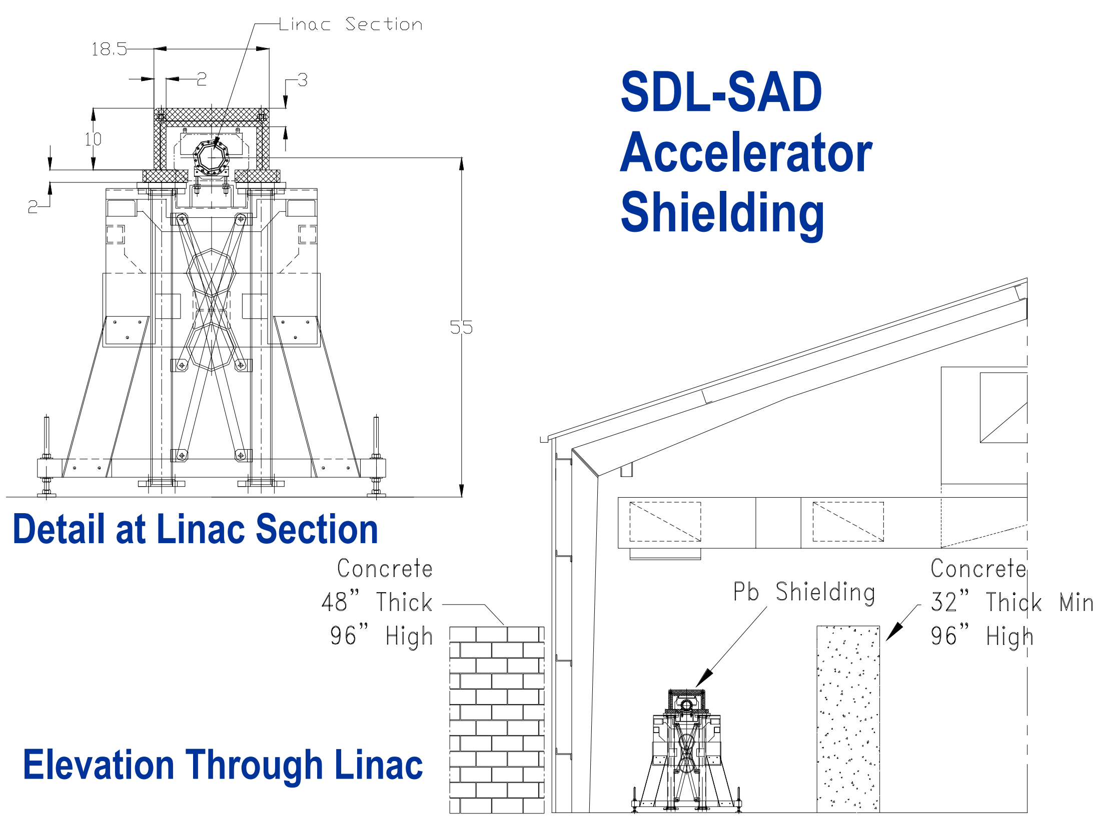
3.4 Radiation Protection Systems

3.4.1 Shielding

Shielding requirements for the facility are based on a maximum average current of 20 nA (1.2×10^{11} electrons/sec) at a maximum energy of 300 MeV. Radiation loss modes are discussed in Section 4.6 of this report and shielding requirements were determined as part of this analysis. This section provides a detailed description of the shielding in place as shown in Figures 4 and 5. For lead shielding standard bricks (2x4x8") are used along with several types of precast lead structures. All of the lead castings were manufactured and painted by Nuclear Lead (Oak Ridge TN). They are also stenciled with the corresponding drawing numbers and their lifting weight. Installation and handling of lead in the SDL will be performed using methods consistent with the ES&H guidance from the NSLS PRM 6.2.0 Lead Working Guidelines.

For long runs of relatively small cross-section, inverted “U” shaped lead covers at least 2" thick on the sides and 3" thick on the top are used. These covers have interlocking ledges on the open ends, so when stacked end to end they form a continuous shielding tunnel. Threaded sockets were cast into the covers so they can be lifted with the building crane (they weigh approximately 400 pounds each). Stands with aluminum plate shelves were built along side of the accelerator to hold these covers. Depending on the height of the components they cover, lead bricks were stacked underneath the covers to adjust the elevation as required. In all locations at least one layer of brick is used beneath the covers on each side (2" high) with the bricks placed facing the centerline of the accelerator. This allows only x-rays directed to the floor to escape the lead shielding assembly. The configuration is illustrated in the thumbnail sketch below.

This shielding strategy is used over the full length of the accelerating linac structures and the small cross section transport lines. In locations where the accelerator cross-section is larger, frames were



erected to support precast sheets of lead that are at least 3" thick. In several instances the thickness of the lead is more than required for shielding and was determined by structural strength requirements of the cast plates to avoid sagging or deformation when installed.

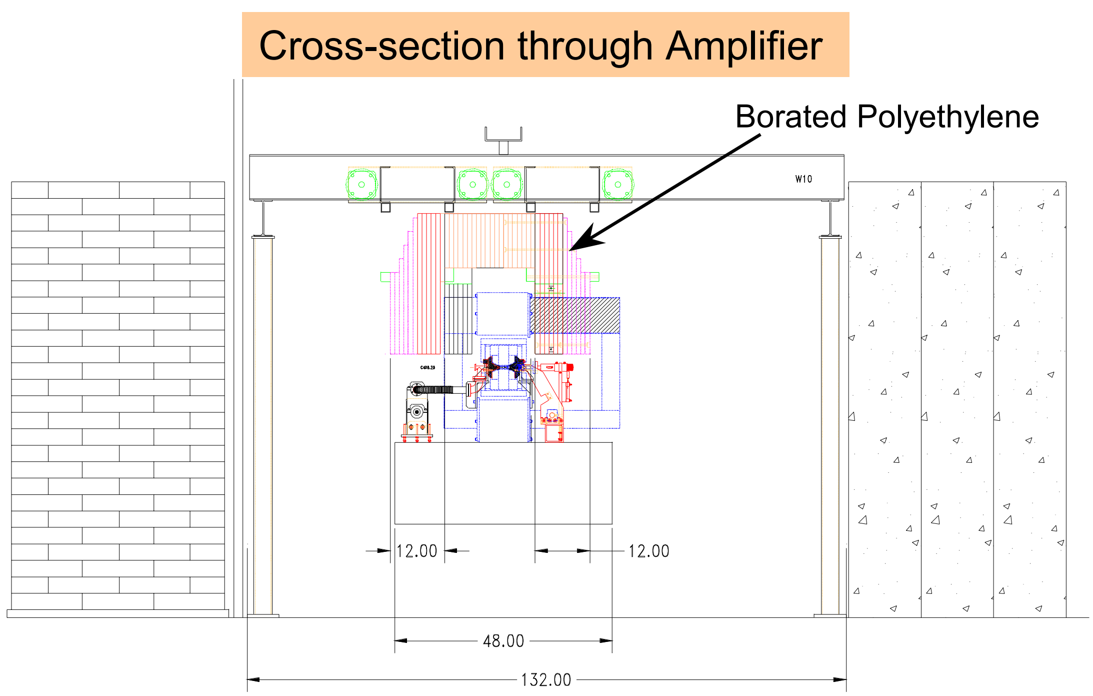
These larger tunnel structures are built around the bunch compressor and the area downstream of the linac that includes the transport line, beam dump dipole magnet, energy modulator, and dispersion section. Each of the plates or assemblies was sized to be within the load limit of the building crane (2 tons). Special lifting fixtures were used to install the sidewalls of the enclosures that extend north of the linac centerline (past the crane hook limit). Essentially a pair of sidewall panels are lifted simultaneously with their center of gravity at, or south of the linac centerline. Three other areas of the linac have unique shielding configurations; the gun, the Faraday cup beam dumps, and the amplifier undulator.

A lead shielding enclosure has been built around the electron gun area. Inside the gun hutch, a separate support structure has been installed that has an aluminum roof with a layer of lead bricks on it over the gun, solenoid, and diagnostic area extending over the start of the first accelerating tank which is shielded with the precast covers. This insures a minimum of 2" of lead shielding above the gun. The north wall of the enclosure is shielded with an assembly of strips of lead 1" thick with overlapped seams to provide a minimum transverse lead thickness of 2" on this wall.

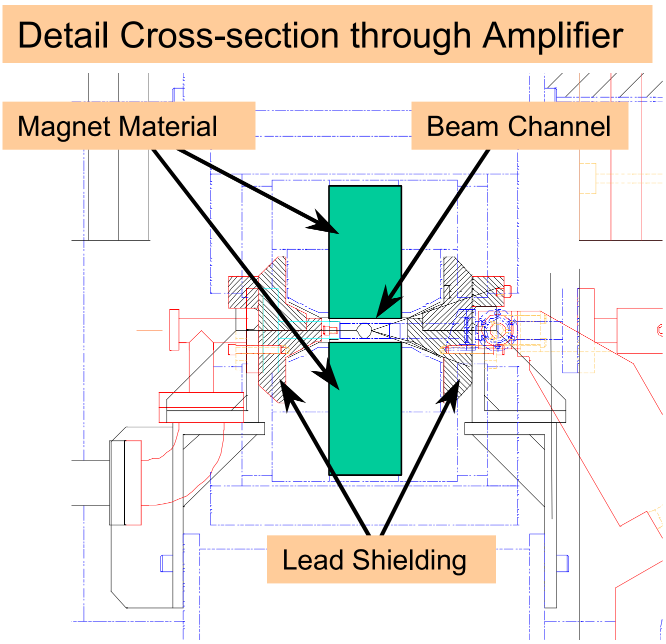
The south wall and east (back) walls of the gun enclosure are actually buckets on rails that can be lowered to ground level to allow servicing of the gun area from two sides. The buckets are filled with lead bricks arranged to provide at least 2" of lead shielding. The lifting is accomplished by permanently installed screwjacks that run through a gear reduction box. To move the shield walls a drill motor is employed. The reduction ratio is sufficiently large that the shielding can not lower itself from its own weight. When the lead curtains are in place, cross pins are installed through the support stand to protect against accidental lowering of the shielding. The east gun shield wall also has a shelf with a stack of lead bricks (12" by 12" by 8") centered on the beam to attenuate any high energy x-rays that might be produced in the accelerator and directed back toward the electron gun. The longitudinal lead thickness provide by this arrangement 10".

The beam dumps for normal operations are identical aluminum Faraday cups that are very heavily shielded with lead. At each Faraday cup, an extra layer of lead brick is stacked underneath the transport line covers (inverted U castings) providing an additional shielding thickness of at least 2 inches (transverse and longitudinal). In the forward direction another large stack of lead brick (12" thick, 24" wide, 16" high, centered on beam) is installed to provide a total thickness of 14" longitudinal lead for attenuation of x-rays.

The radiation shielding around the amplifier undulator includes fitted lead castings and large borated polyethylene blocks as shown in the cross section sketch's below.



On each side of the undulator, the fitted lead castings are in an upper and lower part supported by the table. The magnetic structure is comprised of Samarium Cobalt magnets and Vanadium Permadur pole pieces. Since these are high Z materials, their value as x-ray attenuators was included in the shielding analysis. To provide neutron shielding above the amplifier, large blocks of borated polyethylene were assembled from sheet stock and supported by an overhead rail system. These blocks can be shifted away from the amplifier for servicing.



The general philosophy of using large structures to accomplish the lead shielding was based on the desire to make servicing less difficult, since large areas of the shielding can be easily removed. Their size and therefore comparatively small number also makes it more readily apparent when a piece is missing or out of place. This helps to ensure that the shielding checklist can be easily and correctly followed.

The design for the concrete enclosure follows a similar design philosophy. Rather than using individual blocks stacked by hand, large precast shielding blocks are used for most of the accelerator vault wall. The shield blocks are 16" by 30" by 96" and made from 'normal' structural concrete. They have internal reinforcing rods and metal edges on the two smallest surfaces.

Lifting knobs (attached to the rebar) are cast in sockets in these small surfaces on both ends as are a pair of threaded steel sockets (a total of four holes). A special lifting fixture is used to place the blocks with the building crane. Their odd size was set by the need for an 8 foot high wall and weight restriction set by the 2 ton building crane.

When they are used to form the wall several layers are used, and the joints between them are bond stacked so there are no direct gaps through the entire shield wall. The blocks are secured to each other on top with steel straps that are bolted to the blocks using the cast in place threaded sockets. This significantly improves the resistance of the wall to upset (tipping over). Four of these blocks are also placed around each beam dump to provide attenuation of neutrons from the routine loss of beam at this location.

For the eastern 20 feet of the shielding inside the building, hand stacked concrete block was used to build the wall, since this area is beyond the reach of the crane. Hand stacked block was also used to form the exterior shield wall which has a minimum thickness of four feet, and is stacked to a height of eight feet.

3.4.2 Radiation Security

A number of measures have been taken to ensure that workers are not exposed to radiation fields produced by accelerator operations. The concrete shield wall is fitted with a system of interlocks and warning indications that, when coupled with personnel training, will prohibit access to the accelerator when it is possible to operate the machine and potentially produce radiation. Entry to the linac/experimental region is through one of two doors, each of which gives entry via a labyrinth. One door is near the electron gun at the east end of the building and the other near the beam analysis system near the middle of the building. Two separate interlock chains are provided that turn off the power to the electron gun and linac modulators if either of the doors are opened.

The doors are also provided with a Kirk key system. In order to gain access to the area, the Door key(s) must be rotated and removed from the Solenoid Release Unit. This key can only be removed if the linac high voltage power supply is turned off. The key is then used to unlock the area door and is held captive in the lock until the door is again closed and locked. The interlock system is tested and certified at 6-month intervals.

Prior to operation the operators will be required to secure the linac and experimental area utilizing a formal search and secure procedure [A6]. In order to insure a proper search, reset buttons are provided which require that the person carrying out the search covers all regions of the search area. The buttons must be reset in a prescribed sequence and in a prescribed time. The person carrying out the search will enter and exit through the door situated adjacent to the electron gun. After exiting and locking the door, the Kirk key for the entry door must be returned to the Solenoid Release Unit and rotated which sets off an annunciator in the areas for 15 seconds. If anyone for any reason wishes to stop operation, they may do so by depressing any of a number of emergency stop buttons situated through the facility at convenient and clearly marked locations. Both doors are interlocked and keyed in the same way and both are provided with an emergency panic release system to allow fast exit in an emergency. If either of the entry doors is opened while the search procedure is in progress the search is automatically aborted and has to be restarted. The Radiation Security System is described in detail in Appendix VI.

To make certain that personnel are aware of the status of the accelerator several beacons, strobes, lighted signs and postings are provided. When a search of the accelerator vault is initiated, five strobe lights begin flashing that are positioned next to signs stating "Warning, Search of Enclosure in Progress when Flashing". Four of these strobes are located inside the accelerator vault enclosure and one is located inside the gun hutch. When the search has been successfully completed the strobes turn off, and nine beacons located at the top of the shield wall inside the enclosure are illuminated. The signs next to the beacons state "Enclosure Secured when Flashing, Press Emergency Stop".

This notifies any individual inside the enclosure that they should break security by pressing any one of the fourteen emergency stop buttons (including 1 in the gun hutch) to stop potential accelerator operations.

On top of the wall next to each beacon, but not normally visible from the floor outside the enclosure are signs stating "Warning, Enclosure Secured When Flashing, Access Prohibited". These signs are placed as a last notification to a person trying to go over the enclosure wall when the enclosure is secured. This is unlikely since there are distributed along the outside wall fourteen readily visible security status signs with warnings. Each has a permanent sign stating "Warning, Do Not Climb on Wall when Sign is On", next to signs that illuminate when the enclosure is secured that state "Warning, High Radiation Area Above". In addition, at the two entry doors to the enclosure there are signs that illuminate when the area is secured stating "Interlocked".

This elaborate information and warning system was installed in recognition of the fact that the enclosure has no physical barrier to prevent entry from the top by climbing over the wall. The placement of the signs and beacons was done in a manner that would deter personnel from climbing the wall. If the signs outside the wall were missed or ignored, on climbing to the top of the wall an individual would see flashing beacons that are not normally visible next to signs telling them access is prohibited.

A security system is also in place for the Ti:Sapp laser system which is classified as a Class IV laser as per BNL ES&H Standard 2.3.1. All entry doors to laser equipment rooms are electrically interlocked so that unauthorized entry will cut power to the lasers. There are also manufacturer provided lock-outs for the laser power supplies. The procedure for securing the laser room is similar to that of the radiation security system for the linac. There is a timed prescribed search path and reset button as well as emergency off buttons. However, in order to provide the capability for tuning the laser, it is possible to secure the area with properly trained and protected personnel inside the laser room and gun hutch. The beam path between the laser room and the electron gun is enclosed by an opaque beam pipe. A detailed description of the Laser Security System is provided [A7] (Appendix VII).

3.5 SDL Safety Program

3.5.1 Introduction

Responsibility for safety of the SDL lies with the SDL Project Manager. The SDL project is administratively a part of the NSLS Department and, as such, is under the umbrella of the existing NSLS safety organization. The Department has a strong commitment to safety in the operation of its accelerators and beamlines as evidenced by the central position of the safety group in the NSLS organizational chart. The NSLS Environment, Safety and Health (ES&H) Coordinator, and the NSLS Safety Officer report directly to the Associate Department Chairman for ES&H/Q and are assisted by two full time safety engineers and three representatives of the Radiological Control Division. In addition, the Department maintains an Environment, Safety and Health Committee which acts in an advisory capacity to the NSLS Chairman.

The NSLS safety policies and procedures are detailed in the NSLS ES&H Policies and Requirements Manual (PRM) [2]. The Source Development Laboratory is included as part of the NSLS Emergency Plan. Any unreviewed safety issue (USI) which presents a significant safety consequence will be thoroughly analyzed and processed as described in the Accelerator Safety Subject Area. Operations affected by the USI will not be performed until a review process has been completed.

3.5.2 Internal Safety Review

The project safety committee is the NSLS ES&H Committee and as such, has reviewed this SAD for the Source Development Laboratory. In addition, the Department conducts quarterly Tier I safety inspections of the facility as outlined in the NSLS PRM 1.2.0. In ongoing or future reviews of the SAD, the standards of NSLS PRM 1.2.0 or its successor documents will be applied.

Within the SDL, the Project Manager will bear primary responsibility for the safe conduct of operations of the accelerator and the associated building support facilities. The NSLS ES&H staff will assist him in these duties. In addition to input from the project technical staff and advice from the NSLS ES&H Committee, the Project Manager will be informed and act upon safety concerns conveyed by the NSLS area safety representative for building 729 appointed by the Department ES&H Coordinator. The area representative has direct responsibility for bringing safety concerns to the attention of the Project Manager and the NSLS ES&H Coordinator.

The NSLS has a Beam Line Review Committee whose responsibility is to review new beam lines and ensure that NSLS and BNL ES&H standards have been properly applied to each beam line.

3.5.3 External Reviews

The Laboratory Environment, Safety and Health (ES&H) Committee is required by BNL policy to review this SAD and make a recommendation to the Deputy Director for Operations. Prior to commissioning and final operation, an accelerator readiness review (ARR) will be conducted to ensure that all technical, management, and training requirements have been met. The Deputy Director's approval and that of DOE is required before operation can begin.

The Accelerator Safety Subject Area also directs the ESH/Q Directorate to assist the Department in developing the SAD and in conducting an internal review of the document using ESH subject matter experts as appropriate, prior to its submission to the Laboratory ES&H Committee. In addition, ESH/Q personnel assist the Department in implementing the Laboratory safety program and in training NSLS personnel in safety matters.

3.5.4 Safety Training

The ESH/Q Directorate regularly schedules training programs in areas such as the use of respirators, crane operations, materials handling, personal dosimeter usage, etc. as may be requested by personnel to perform their job assignments. However, there are several topics related to the SDL facility which will require specialized training such as electrical, laser, radiation and radio frequency safety. Written procedures for securing radiation areas are provided [A6] (Appendix VI).

Written instructions on safe operation of high voltage power supplies are required for modulators, and vacuum pumps as well as potentially hazardous high current power supplies for the DC magnets in the linac. These will be provided to operations and maintenance personnel by line supervisors with the assistance of cognizant project engineers who will also provide training to carry out these procedures.

3.5.5 Experimental Operations Safety

Operation of the Linac will require a minimum of two trained personnel at least one of whom is a fully qualified operator. The other individual must be qualified as a minimum to shut the machine down and respond to emergency conditions within the facility. The training to become an operator is determined by the accelerator manager (or designee) who will qualify operators by on the job training and challenge examinations. The outline of the qualification process is as follows:

At a minimum, qualified operators will

1. Become proficient in the operation of the linac personnel interlock system - become certified to sweep and secure accelerator vault.
2. Learn where the crash buttons are - emergency power shut-down.
3. Learn layout and indicated levels of SDL ionizing radiation monitoring system.
4. Study and train on the operating system.
5. Become familiar with component and indicator layout in the control area
6. Be trained in laboratory and SDL emergency response procedures.

Before an operator is certified, on the job training will take place to learn:

1. Controlled turn-on and shutdown sequences of accelerator components.
2. Operating ranges of accelerator components and normal operating conditions.
3. Sequence of steps for resetting trips.

Basic SDL Operator Duties are:

1. Search and secure the accelerator vault.
2. Operate the accelerator and laser systems.
3. Maintain a log of machine status, trips, and special or unusual operating conditions.
4. Shut down any part of the facility within their area of control that may present a safety hazard

until that hazard has been removed.

As detailed operational procedures are developed they will be added to the SDL Conduct of Operations Manual for reference in training personnel at the SDL.

The experiments to be carried out at the SDL are either located in-line with the accelerator using the electron beam directly, or will extract optical radiation for analysis. Only one experiment may be carried out at any given time and the electron beam, after passing through the experimental apparatus, will be analyzed and/or dumped. The experimental region is secured as part of the linac security system and cannot be occupied while the linac is operating. Every experiment prior to its installation at the SDL will undergo an Experimental Review carried out by the NSLS Experimental Review Coordinator. The review requirements are given in [A5] NSLS PRM 1.3.5a and 1.3.5b. This assessment is made to assure that the operation of an experiment will not present any safety or environmental hazards that are not properly controlled.

3.5.6 Radiation Monitoring

The SDL is a radiologically controlled area, and all personnel working at the SDL are required to wear a personal radiation monitor. Radiological Control personnel assigned to NSLS provide routine radiation monitoring. In addition TLD's are located at appropriate locations around the facility, outside the shielded area. These are read and recorded periodically and NSLS safety personnel maintain a database that is regularly evaluated by the NSLS ALARA committee.

In addition a number of real-time radiation monitors are used where accidental or unusual operations conditions could give rise to some radiation. Although significantly elevated radiation levels are not anticipated during machine operation, real time radiation monitors (Chipmunks) have been provided in several areas to monitor ambient radiation levels in occupiable areas. The alarm levels for these monitors will be adjusted to insure prompt detection of radiation faults consistent with NSLS procedures.

SAFETY ANALYSIS 4

Risks associated with the various hazards identified in Section 3 are reviewed in this section. The following hazards are specifically addressed: environmental and hazardous waste issues; fire safety, natural phenomena, electrical safety; exposure to magnetic or electromagnetic radiation, and ionizing radiation. Summary risk assessments for the described hazards are given in Appendix VIII.

4.1 Environmental and Hazardous Waste Issues

The operation of the SDL will not create significant environmental releases or generate significant quantities of radioactive or hazardous wastes. The activities at the facility will utilize small amounts of chemicals and will generate minimal hazardous waste (<5 gallons/year). There are no routine discharges of liquids to the environment. Maintenance of the cooling systems is not expected to result in the generation of hazardous wastes.

Operations at SDL will also not generate any significant airborne releases; estimated emissions are far below the 0.1 mrem per year at which monitoring and formal reporting would be required. The electron beam will not traverse an air path anywhere in the system under normal operating conditions. Small quantities of airborne radioactivity may be created during fault conditions, but does not result in either significant building or environmental releases. A NESHAPS (National Emissions Standards for Hazardous Air Pollutants) evaluation for the 230 MeV linac has been conducted by the Environmental Services Division and is included here as part of Appendix IV.
A NEPA Environmental Assessment was prepared for the predecessor of the SDL: "*Construction and Operation of a Support Facility (Building 729) for Operation/Testing of a Prototype Accelerator/Storage Ring (XLS) and Machine Shop for the National Synchrotron Light Source at Brookhaven National Laboratory, Upton, NY; June 1992; DOE/EA-0602.*" DOE approved this Environmental Assessment and a Finding of No Significant Impact (FONSI) was issued on July

2,1992. The BNL NEPA Coordinator reviewed this EA and the current SDL configuration in June 1997. This review concluded that' … the proposed activities have been effectively evaluated in a current NEPA document and no additional documentation is required in accordance with 10 CFR 1021 and DOE Order 451.1" This documentation is found in Appendix IV.

4.2 Fire Safety

A detailed "Life Safety Code Analysis" and a Fire Assessment/Fire Analysis Report have been prepared by the BNL Fire Protection personnel and are included as Appendix I(Hyperlink to A1). The level of fire protection in the SDL is classified as an "improved risk", thereby meeting the objectives of DOE Order 420.1. While the SDL is considered a high value property, the noncombustible construction of the building and the accelerator is expected to keep the dollar loss expectancy from any credible fire to below $250,000.

4.3 Natural Phenomena

The SDL has been evaluated for Natural Phenomena Hazards (NPH), utilizing the criteria of DOE Order 6430.1A "General Design Criteria" for wind, flood, and earthquake design criteria. DOE Order 5470.28 "Natural Phenomena Hazards Mitigation" and its associated standards were used as guidance for this evaluation. Details of the site geography, seismology, meteorology, hydrology and demography are contained in "DOE Accelerator Order 5480.25 Implementation Plan for BNL Natural Phenomena Hazards Evaluation" April 25, 1994 by Steve Hoey (See Appendix X).

The probability of an earthquake sufficiently intense to damage buildings and reactor structures was thoroughly investigated for this site during the construction of the Brookhaven Graphite Research Reactor (BGRR) and revisited in 1999 as part of the Hazard Classification and

Auditable Safety Analysis for the BGRR Decommissioning Project. The most recent evaluation shows that BNL falls into an area where the acceleration velocity is slightly less that 0.10 g, and thus has been classified as a "low" seismicity zone. This classification has been agreed to by DOE during the course of the recent project of implementing Executive Order 12941, "Seismic Safety of Existing Federally Owned or Leased Buildings," as documented in a BNL memorandum, DeBobes to Helms dated May 28, 1998, "Phase 2,3, and 4 submittal for Executive Order 12941." As was the case in the original BGRR review and subsequent examinations of the High Flux Beam Reactor, it is the consensus of seismologists that no significant quakes are to be expected in the foreseeable future. No active earthquake-producing faults are known in the Long Island area.

The SDL has been designated as a Low Hazard Class (See Appendix IX) and Performance Class 2. It does not contain significant quantities of radioactive or chemical materials. Should an NPH event cause significant damage to the SDL, the impact would be mission related and not create a hazard to the public or the environment.

4.4 Electrical Hazards

The klystron/modulator system is used to provide the high power pulses of radio frequency energy to the electron gun and accelerating structures. The modulator consists of a high voltage DC power supply used to charge a pulse-forming network (PFN) to about 40 kilovolts. A thyratron tube is used to discharge this PFN into a high voltage step-up transformer to deliver a pulse of power to the klystron. The modulator, step-up transformer, and klystron are bolted together to form a single enclosure. Three identical klystron systems are used. All of the klystron/modulator assemblies are locked and interlocked to allow both administrative control and interlock protection. Only trained and qualified personnel will service these assemblies. Several electromagnets are powered by low voltage direct current power supplies that are interlocked because of the possible large short circuit currents, and because of the primary power distribution system in the power supply enclosures. Control of plant and accelerator security as well as operation control of the accelerator is performed at low voltage wherever feasible (<24 volts). No exposed voltage or hazards are present in this equipment. These systems all use conventional equipment and do not represent any unusual hazards. All SDL electrical equipment conforms to the existing codes and regulations.

4.5 Non-ionizing radiation

4.5.1 RF

The emission of non-ionizing radiation is controlled to prevent the radio frequency power generated by the klystrons from interfering with low level instrumentation or from providing a source of personnel hazard. Each klystron is capable of producing a peak power of 45 Megawatts at a frequency of 2856 MHz. Normally the requirements for preventing interference with sensitive monitoring equipment are much more restrictive than those required for personnel protection. The radio frequency output power is confined to the vacuum enclosure of the klystrons, feed waveguides, and accelerator structures which provides a redundant safety protection system. A break in the vacuum integrity of any of these systems would immediately trip the system interlock. Further, the loss of vacuum would also remove the insulation the system requires to continue generating this power. Thus, the high power radio frequency fields are contained within the system's waveguide or accelerating cavities and should not present a significant exposure potential. Surveys as described in ESH Standard 2.3.2 "RF and Mircowaves" have been made which confirm that RF fields are well within the limits defined by the American Conference of Governmental Industrial Hygienists (ACGIH) and OSHA.

4.5.2 **Magnetic Fields**

The ACGIH recommendation for people with cardiac pacemakers is that they not be exposed to magnetic fields exceeding 5 Gauss (0.5 milliTesla). Magnetic fields in excess of that limit are not accessible to personnel in normal work areas. Magnetic fields are surveyed as described in the SBMS Subject Area 'Static Magnetic Fields'.

4.5.3 Lasers

Conventional Helium - Neon laser systems (up to Class IIIb) may be used for alignment purposes. The titanium sapphire (Ti:Sapp) laser system used to excite the electron gun cathode is comprised of three Class IV laser sources. A 5W CW Nd:YVO_4 laser pumps a Ti:Sapp oscillator that feeds a Ti:Sapp regenerative amplifier. The pump energy for the amplifier is provided by two pulsed Nd:YAG lasers operating at 10 Hz and producing 650 and 850 mJ in the green. The regen output is frequency amplified into the UV which is relayed to the gun enclosure. A second beam for the purpose of seeding the High Gain Harmonic Generation FEL will also be derived from the Ti:Sapp laser and transported to the gun hutch. From there it will be relayed along side of the linac to an optical table just downstream of the linac.

Stability and timing requirements necessitate the laser light be relayed though controlled environments. The transport line between the laser room and gun hutch is a stainless steel vacuum pipe. Similar enclosed beam paths will be utilized for transporting Class IV laser light. In normal operation the laser components are themselves covered on their tables to improve stability. However, there may be times during setup when the light will not be enclosed on the tables, and at these times only trained laser users wearing protective eyewear may be inside the special interlocked enclosures used to contain the laser light. The integrated system is effectively a Class IV laser as defined in BNL ES&H Standard 2.3.1, and is operated as required by that document and the NSLS PRM 2.3.1. The FEL laser beam created by the NISUS undulator is expected to operate in the Class IV power level and will also be subject to the requirements and controls specified in BNL and NSLS standards.

4.6 Ionizing Radiation Safety Hazards

Ionizing radiation hazards associated with a 300MeV, 20 nA electron beam are significant and must be carefully considered. During normal operation, electron losses can occur in the electron gun region, during acceleration and transport, and at the beam dump. Analyses are also necessary for higher intensity beam losses that can occur during abnormal operation as the result of miss-steering or other equipment malfunction. Calculations to characterize radiations hazards and to permit specification of shielding thickness have been performed using analytic approximations developed by W. P. Swanson [4] and described in his IAEA publication Technical Report Series #188. In addition, in many situations Monte Carlo calculations utilizing MCNP 4c [20] were performed. Specialized Monte Carlo calculations were also performed by a shielding physicist (P. Degtyarenko) from Thomas Jefferson National Accelerator Laboratory using DINREG (a nuclear fragmentation model) [21] and a Monte Carlo transport code "GEANT" [22]. A summary of the analysis is provided in a table at the end of this section.

4.6.1 Prompt Radiation Hazards Under Normal Operating Condition

High energy electrons stopping in any material will produce x-rays. During normal operation, several sources of electron losses in vacuum pipe or other beam line equipment are present:

- "Dark current" electrons accelerated by the high electric fields in the RF gun (>100MV/m) are a source of x-rays. This is particularly true for dark current electrons which may be produced at all phases of the RF in the electron gun, some of which are accelerated along the axis of the gun and thence through the accelerator.
- Those particles near or outside the edge of the acceptance region during transport will be accelerated non-synchronously and will be lost either along the accelerator itself or

in transport elements after the accelerator or in the magnetic pulse compressor situated after the first two accelerating sections.

- Beam profile monitors are placed at many locations within the accelerator and transport lines to assist in the set-up and monitoring of beam transport parameters. These monitors are "thick" and essentially produce a full beam loss during operation.
- The beam is terminated in a dump at one of the two locations described in Section 3.4. Much of the energy of the beam will be converted into prompt radiation which must be shielded.
- Both the radio frequency photocathode electron gun and the linac accelerating sections are potential producers of significant Bremsstrahlung radiation from field emission electrons released from the metal surfaces.

At energies above 10-20 MeV electron losses also give rise to neutrons, generated by the photons produced by electrons stopping in lead shielding, beam pipe or bending magnet yokes. The magnitude of these electron losses and the associated radiation fields are estimated below for the linac and gun operating at their full capability.

4.6.1.1 Electron Gun Operational Losses

Up to 100μA peak current of electrons [1 nA average] can be produced as "dark current" by field emission from all surfaces of the electron gun where high electric field gradients are present. Some fraction of these electrons can be accelerated axially, in the forward direction up to the maximum energy of the electron gun (~ 8 MeV) for a fraction of each RF cycle during the 1.5 μsec RF pulse.

These electrons can also be accelerated in the reverse direction, to lower than maximum energy (~ 3 MeV) during the reverse part of each RF cycle. There could be as many as 6.2×10^9

electrons/sec lost in this way with energies from less than 1 MeV up to a maximum of 8 MeV. Dose rates produced by this source will be highly dependent on the final energies of the electrons. Experience has shown that levels of the order of several 10's of R/hr can be generated from this source. Together with the concrete shielding, the 8 inches of lead at the end of the beam line and the 2 inches transverse will reduce this source to non-detectable levels in occupiable areas.

In addition to the dark current, losses (assuming 2 micro bunch operation at 1nC per micro bunch from the photocathode) can occur at the following locations prior to accleration:

(a) At an intercepting beam monitor situated before the linear accelerator sections $\approx 2\times 10^{11}$ electrons per second of up to 8 MeV energy. This is essentially a point source, and creates radiation fields at 90^{o} equal to about 2 Rad/hr at one meter. The Pb shielding in this area is 2 inches thick and will reduce this level by a factor of 10. The four foot thick concrete shielding in this region will reduce this source to non-detectable levels in occupiable areas.

(b) Losses can also occur due to missetting of the transport line solenoid magnets or trim dipoles. The latter would give rise to a loss of beam over a line source downstream of the mis-set device which could give rise to an estimated electron loss of up to 1.2×10^{11} electrons per second over a length of $\approx$50 cm at an energy of up to 8 MeV. These levels will be less than those described in (a) above.

4.6.1.2 Linear Accelerator Area

When the linear accelerator is correctly tuned with correct intersection phasing and correct amplitude in each of the accelerating sections and with proper beam steering, our operating experience with the machine shows that the losses in the accelerator itself are negligible. However, for the purpose of analyzing the potential hazards, we make the appropriately conservative assumption that beam losses averaging 1% - 2 % of the accelerated beam could occur during normal operating conditions. With maximum linac operation, this would produce a normal operating loss during acceleration and transport of 2.5×10^9 e/s at an energy up to 300 MeV. These losses could occur in the following locations:

(a) During the capture process of electrons in the first accelerating section, electrons could be lost along the length of the entire accelerator, at the first bend magnet of the pulse compression, or the first bend magnet of the high energy beam analysis system;

(b) In the high energy beam transport momentum analysis system (the dipole before the linac beam dump) electrons of 300 MeV energy could be lost due to wide energy spread in the beam caused by non-synchronous acceleration;

(c) In the pulse compressor, electrons outside of the acceptance region could be lost;

(d) Under normal conditions, electrons generated at any point within the linac accelerating sections by the primary beam in such processes as secondary emission, residual gas ionization, etc. or by non-beam related phenomena such as arcing. Radiation from these electrons has been observed and measured at the NSLS 120 MeV linac, although the energy spectrum and intensity have not been measured and are likely variable, dependent on the amount of primary beam loss and the position of origin of the secondaries. Consequently we are unable to estimate a source function for the resultant Bremsstrahlung: however, the radiation shielding necessary to reduce X-ray dose rates to BNL Standards has been empirically established. It is important to note that the SDL linac uses the same electron gun and accelerating sections as the Accelerator Test Facility where no radiation of this type has been observed, even at the highest accelerating gradients attainable in the accelerating sections. This is consistent with experience for baked copper surfaces operating in high voltages at or above the accelerating gradients anticipated for the SDL under comparable vacuum conditions. It should be noted that during the first year of commissioning of the SDL that this effect has not been observed.

In these regions there is a minimum of 2 inches of lead shielding horizontal to the beam and three inches of lead shielding vertically. Attenuation in the lead will limit maximum x-ray levels from the loss of 2.4×10^9 e/s at a thick target within the enclosed area from normal losses to about 13 mrem/hr horizontally at one meter from the loss point, and about 2.5 mrem/hr vertically. The concrete shielding will reduce these x-ray levels in accessible areas to 7.2×10^{-3} mrem/hr. Neutron dose rates at one meter from a 2% loss have been calculated using Swanson's approximation to be about 133 mrem/hr. Using Figure 10, the concrete shielding around the accelerator will reduce radiation levels from penetrating neutron radiation to levels less than 5×10^{-3} mrem/hr backgrounds. MCNP calculations for neutron penetration through 4 foot of concrete provide similar results (6×10^{-3} mrem/hr).

However, scattered radiation over the concrete shielding (skyshine) will require on-going monitoring and potential attention as electron beam intensities are increased up to the maximum of 20 nA. MCNP calculations for skyshine neutrons estimate the radiation levels in the building from a 2% loss to be on the order of 0.1 mrem/hr. Chronic loss points will require additional concrete or 5% borated polyethylene shielding to ensure that the 100 mrem/year administrative control level is maintained.

4.6.1.3 **Beam Dumps**

During routine operation, the full beam will be targeted on the aluminum Faraday cup within the lead beam dump at the end of the amplifier. During linac tuning, the beam will be directed to the linac beam dump. The dumps themselves are identical and have lead shielding that extends 14 inches in the direction of the beam and are 24 inches wide and 16 inches high centered on the beam. The aluminum faraday cups are 9.8 inches long and are shielded vertically by 5 inches of lead and horizontally by 4 inches of lead. To reduce neutron skyshine, a minimum of 12 inches of 5% borated polyethylene is provided above the stops. In addition, four precast concrete shield blocks (16"x30"x96") are placed alongside each dump (two on each side), which provide additional concrete shielding horizontally for the beam dump and reduce the skyshine solid angle.

X-ray Production

X-ray production in the faraday cups has been calculated adjusting for aluminum from figure 8. From figure 16 the attenuation factor through 5 inches of lead can be shown to be 3×10^{-3} and through 4 inches of lead to be 1×10^{-2}. Applying these factors, the x-ray dose at 90 degrees created by the electron beam interacting in the faraday cup is:

$$H_x = 12 \text{ mrem/hr vertically and } 40 \text{ mrem/hr horizontally at 1 meter.}$$

The bremsstrahlung beam at 0 degrees will be intercepted by the lead stop and will be attenuated by the 14 inches of lead. From figure 16, the attenuation factor can be found to be $B_x \approx 5x10^{-8}$, leading to the dose rate of:

$$H_x = 1 \text{ mrem/hr at one meter through the stop at 0 degrees.}$$

In addition to the lead, the faraday cup is contained within 16" of concrete on 2 sides, providing additional attenuation of about 1/2 for x-ray bremmstrahlung penetrating through the lead at 90°.

Neutron production

Neutron production from the bremsstrahlung beam must also be calculated. W. P. Swanson [4] provides an empirical formulation which conservatively estimates the neutron dose rates produced by electrons in this energy range interacting in a thick target as:

$$H_n = 2 \text{ x Power (in watts) rem/hr at one meter.}$$

This formula assumes no self-shielding from the lead and an average neutron energy of 2 MeV. Since the bremsstrahlung is produced by electron interaction in the aluminum cup rather than in a high Z material, we reduce the yield by a factor of 4 as indicated in Table XV from Swanson.. In addition to the lead shielding, 12" inches of 5% borated polyethyelene shielding have been provided above the faraday cup for neutron attenuation. Based on the tenth value layer for concrete shown in Figure 15, and the fact that 1 inch of polyethylene is equivalent to the shielding of 1.85 inches of concrete for 2 MeV neutrons (NCRP Report # 38 p. 118), an attenuation factor of about 2.4×10^{-2} is expected. Therefore the neutron dose rate above the beam dump is calculated to be:

$$H_n = 2 \times 6 \text{ (watts)} \times .25 \times 2.4 \times 10^{-2} = 72 \text{ mrem/hr at one meter above the dump}$$

MCNP calculations estimate the dose equivalent one meter above the faraday cup through the borated poly to be 90 mrem/hr.

In the horizontal plane, 16 inches of concrete will provide an attenuation factor of 6.8×10^{-2} (from fig 15), thereby giving a dose of ~200 mrem/hr from neutrons.

Effectiveness of Enclosure Concrete Shielding

With the values that have been calculated for x-ray and neutron dose rates at one meter, we can now calculate the dose rate penetrating through the 4 foot concrete walls. The X-ray dose-equivalent index rate exterior to the concrete wall can be evaluated from the expression of NCRP-51, Sect. 4.3.2, p. 50, Eq. (2):

$$\dot{H}_{1d,x} = \frac{\dot{D}_{10} B_x T}{d^2} \tag{1}$$

For this situation we use d= 3 meters as the distance from the source point to the exterior surface of the concrete shield wall. T is the occupancy factor which we set conservatively to unity here. The transmission factor B_x for photons through the 120 cm thick concrete wall is obtained from NCRP-51, App. E.8, reproduced here as Figure 9, as $B_x \approx 5 \times 10^{-3}$.

Therefore: $\dot{H}_{1d,x} = 22 \times 10^{-3}\, mrem/hr$

Finally, we can calculate the neutron dose rate outside the shield wall using the following equation from NCRP 51 (eqn 10 p 55).

$$\dot{H}_{1d,x} = \frac{\phi_0 B_n T}{(2.8x10^{-7}) d^2}$$

At 1 meter ϕ_0 can be shown to be 2.4x 10^{-4} n/cm^2-s and from figure 10 (assuming an average energy of 2 MeV) B_n=2x10^{-12} rem-cm^2. Therefore,

$$\dot{H}_{1d,n} = 19 \times 10^{-3}\, mrem/hr$$

Skyshine from Beam Dump

In addition to the dose rate from radiation penetrating the shield wall, radiation scattering over the shield wall should be considered. NCRP-51 gives an expression [14] for calculating skyshine for x-rays where the absorbed x-ray dose index rate $\dot{D}_{1S,ds}$ (rad/min) is:

$$\dot{D}_{1S,d_s} = \frac{2.5\ 10^{-2}\ \dot{D}_{10}\ \Omega^{1.3}}{d_s^2} \qquad (2)$$

where Ω (sr) is the solid angle subtended at the source by the periphery of the shielding walls, is the source dose index rate previously defined (rad m^2/min) and d_s is the straight line distance (m) between the source and point where the dose rate is to be evaluated.

The solid angle Ω subtended at a point within an enclosure bounded by shielding in the form of a polygon of L lines at height H above the point has been evaluated [19] by numerical integration of the solid angle increment dΩ = sinθdθdϕ and is summarized below for several points of interest given in Figure 5.

Point	Ω(Sr)
Beam Dumps (Normal full beam loss point)	1.71
After 1st Bend Magnet (Dump for failure of bend magnet)	3.90
Diagnostic Flag (upstream of 1st Bend Magnet)	4.29
End of linac tank 4	3.88
Compressor Flag (Energy selection slit)	3.81
Electron Gun	3.57

Using the value of Ω at the beam dump and the distance d_s = 10 m to the control console, we obtain the X-Ray skyshine dose rate from the beam dump;

$$H_{ss,x} \text{ (linac beam dump)} = 6.5 \times 10^{-3} \text{ mrem/hr}$$

Assuming 2000 hours occupancy per year at the console, the annual dose from skyshine would be about 13 mrem/year. This number will be reduced by the additional attenuation provided by the 12" borated polyethylene added to the top of the beam dump.

For neutron skyshine from the dump, NCRP-51 [14] gives the neutron flux rate at any point S at distance d_s < 20 m from the source point as:

$$\phi_{s,d_s} = 5.4 \times 10^{-4}\, \phi_o \frac{\Omega}{2\pi}\, neutrons/cm^2 \text{ sec} \qquad (3)$$

which we can convert to dose equivalent:

$$H_{ss,n}(\text{dump}) = 5.4 \text{ x } 10^{-4}\, H_n\, \Omega/2\pi \qquad (4)$$

Inserting the previously determined values, we calculate the neutron skyshine from the beam dump at distances less than 20 meters to be:

$$H_{ss,n}(\text{dump}) = 1.1 \text{ x } 10^{-2} \text{ mrem/hr}$$

Assuming 2000 hours occupancy per year at the console, the annual dose from neutron skyshine would be about 21 mrem/year. This dose is well within the shielding policy. The annual dose equivalent at distances beyond 20 m will be lower and consistent with the 25 mrem/year shielding policy for non-facility personnel.

Labyrinth

Finally, we need to calculate the dose rates from radiation escaping through the nearby gate labyrinth. The formulation for the X-ray dose rate at the outside aperture of the maze is given in NCRP-51 [14] as:

$$\dot{H}_{I,rj} = \frac{\dot{D}_o \alpha_1 A_1 (\alpha_2 A_2)^{j-1}}{(d_i d_{r1} d_{r2} \ldots\ldots d_{rj})^2} \qquad (5)$$

where $\dot{D}_0$ is the previously defined source absorbed dose rate index at 1 meter (rad m^2/min), α_1 is the reflection coefficient of the material at the first reflection point, α_2 is the reflection coefficient at the 2nd and subsequent reflections, A_1 is the surface area irradiated by X-rays at the first reflection (m^2), A_2 is the cross-sectional area of the maze, i.e. H x W (m^2), d_i is the distance from the source to the first reflecting wall (m), d_{r1} the distance from the 1st to 2nd wall (m), etc. The reflection coefficient is given in NCRP-51, App. E.15, and reproduced here for convenience as Figure 11.

We previously estimated the X-ray source strength at 90° to the beam dump in the horizontal direction to be $\dot{D}_0$ = 40 mrem m^2/hour. To evaluate the reflection coefficient we need the incident gamma-ray energy, which we take here to be the average photon energy at 90° in the Bremsstrahlung spectrum from incident E_o = 230MeV electrons, which was obtained by Blumberg and Perlman [16] from integration of the Bremsstrahlung cross-section given by Bethe and Ashkin [17].

The photon energy spectrum is:

$$n(E_\gamma) = \frac{1}{E_\gamma}\left[\frac{4}{3} - \frac{4}{3}\left(\frac{E_\gamma}{E_o}\right) + \left(\frac{E_\gamma}{E_o}\right)^2\right] \qquad (6)$$

and the average photon energy in the spectrum is:

$$< E_\gamma > = \int_{E_{min}}^{E_o} E_\gamma\, n(E_\gamma)\, dE_\gamma \Big/ \int_{E_{min}}^{E_o} n(E_\gamma)\, dE_\gamma \qquad (7)$$

which is evaluated to give:

$$< E_\gamma > = E_o\left[\frac{4(1-y)-2(1-y^2) + (1-y^3)}{-4(\ln y)-4(1-y)+3/2(1-y^2)}\right] \qquad (8)$$

with $y = E_{min}/E_o$.

It is necessary to provide a low energy cut-off E_{min} in the integration The value of $<E_\gamma>$ is somewhat sensitive to the choice of E_{min}. For present purposes we look at the absorption coefficients μ_x at low photon energy given by Bethe and Ashkin [17] and reproduced here as Figure 12. For Cu the coefficient is rising rapidly below $E_\gamma \approx .5\ (mc^2)$ and it seems reasonable to take $E_{min} \approx 0.2\ (mc^2) \approx 0.1$ MeV where the photons will be appreciably attenuated in the 0.11 cm steel vacuum pipe wall. Evaluating Eq. 8 for this choice of E_{min} [18] and, for an effective electron energy of 100 MeV as given in Figure 13 for 90° Bremsstrahlung, results in an average photon energy of $\langle E\gamma \rangle \approx 12$ MeV. This energy is beyond the range of Figure 11 and we make an extrapolation to obtain $\alpha_1 \sim 2.3x10^{-3}$ for normal incidence on concrete.

The reflecting area A_1 of the south wall of the enclosure is approximately 9' wide by the 8' height of the wall so $A_1 \sim 6.6\ m^2$. The distance d_i from the source to the south maze wall from Figure 5 is $d_i = 8$ m and the average distance from the wall to the north wall inside the maze ~ 4.7 m. with an available area for reflection of approximately 4 x 8 feet ($A_2 = 2.97\ m^2$). Finally, the distance from this wall to the gate 1 door is approximately 3.9 m. Following this path, Eq. 5 then gives:

$$\dot{H}_{I,r1} = 40\frac{mrad - m^2}{hr}\frac{(2.3x10^{-3})(2.97)m^2(2.3x10^{-3})(6.6)m^2}{(8)^2(4.7)^2(3.9)^2} = 2x10^{-7}\frac{mrad}{hr}$$

This is a negligible x-ray dose rate for radiation workers in the controlled area outside gate 2. We do not expect this value to change for 300 MeV electrons.

Neutrons leaking through the maze can also pose a radiation hazard. In NCRP-51 the dose rate $\underline{H}_M$ (mrem/hr) is given in terms of the neutron flux ϕ_m (neutrons/cm^2 sec) incident on the entrance aperture of the maze as [14]:

$$\dot{H}_M = \frac{K\,\phi_m\,B_{nm}}{270} \qquad (9)$$

where K=8 for a two-legged maze, K = 4 for a 3-legged maze, etc. and the factor of 270 is the neutron fluence rate per unit dose - equivalent index rate for thermal neutrons.

The neutron flux ϕ_m can be recalculated by estimating the neutron dose rate at the entrance to the labyrinth and then use the flux to dose conversion coefficient for 2 MeV neutrons. Previously, we had calculated the neutron dose rate at one meter from the beam dump to be 2.3 rem/hr unshielded. A concrete block has been placed between the dump and the labyrinth entrance. This 16" thick block provides a slant thickness in the direction of the labyrinth door of 23 inches, which will reduce the neutron dose rate from the beam dump in this direction to about 57 mrem/hr. At a distance of d = 3 m from the source to the maze entrance, we have H= 6.3 mrem/hr or ϕ_m = 44 neutrons/cm^2 sec. The neutron transmission ratio B_{nm} through the maze is evaluated from NCRP-51, App. F.11, reproduced here as Figure 14. For a maze of width W = 4 feet, height H = 8 feet, the centerline distance through the maze in units of $\sqrt{HW}$ is 4.1 and Figure 11 gives $B_{nm} \sim 3.2 \times 10^{-2}$. Then, with K = 4, Eq. 9 gives $\dot{H}_M = 0.02$ mrem/hr.

MCNP calculations were performed for neutron transmission through the labyrinth. A maximum dose equivalent of 0.1 mrem/hr was obtained from these calculations.

4.6.1.4 **Beam Transport Through the NISUS Undulator**

This section addresses radiation issues associated with the transport of a 300 MeV electron beam from the linac into the NISUS wiggler and on to the final beam stop. The transport of the electron beam into NISUS does not introduce a different set of radiological source terms from those analyzed earlier. The concrete shielding around the NISUS and the final beam dump design are the same as those installed in upstream areas and the same calculations apply. Three new issues will be evaluated in this section: 1.) bremsstralung production from residual gas interactions during transport through NISUS, 2.) bremsstrahlung and neutron production associated with beam loss during transport in NISUS, and 3) and radiation leakage through the laser penetration in the downstream shield wall.

Gas Bremsstrahlung Production

The generation of bremsstrahlung x-rays produced by the interaction of the accelerated electron beam with residual gas in the beam line is a potential problem associated with long straight sections in high energy electron accelerators. As an example, extra shielding has been provided in certain beam lines at the NSLS X-ray ring for this source of radiation. The long straight transport of the electron beam from the acceleration cavities through the NISUS wiggler suggests that this source of radiation be evaluated.

Gas bremsstrahlung is produced by the interaction of the primary electron beam with residual gas molecules or ions in the beam transport vacuum chamber. It is produced in a narrow cone, the characteristic emission angle being given by $1/\gamma$, where $\gamma = E/m_0c^2$ (E= energy of the electron beam and m_0c^2 = the rest mass of the electron). The energies of the bremsstrahlung x-rays range up to the energy of the electron beam.

Ferrari et al [23] have developed an analytical expression to estimate the gas bremsstrahlung dose rate which has been successfully applied at APS and other synchrotron light sources.

$$\dot{D} = 2.5x10^{-27}\left(\frac{E_0}{m_0c^2}\right)^{2.67}\frac{L}{d(L+d)}I\frac{P}{P_0} \tag{10}$$

Where L is the length of straight section (m), d is the distance from the end of the straight section to the point of interest (m), I is the stored beam current (e^-/s); P is the pressure in straight section (Pa); and Po is 1.33×10^{-7} Pa. Application of this expression to SDL energy and current provides an estimate of dose rate at the downstream wall during normal operation of 0.07 μR/hr. Dose rate created by a major vacuum failure (0.1 atmosphere) during machine operation would produce a maximum dose rate of ~ 5 mR/hr at the end of the shielding at the end of the beam line (12" lead and 4 feet concrete). A vacuum failure of this magnitude would result in shutdown of the machine in very short periods of time. Therefore, gas bremsstrahlung is not an important issue at the beam current and energies that SDL will operate at.

Beam losses in NISUS

Normal beam losses in NISUS will produce radiation levels similar to those discussed in Section 4.6.1.2. The set-up of the NISUS wiggler for the experimental program will require periodic use of a beam profile monitors (i.e. "pop-in" monitor) to ensure proper positioning of the beam. This beam monitor will result in essentially a full beam loss while the monitor is in use. This periodic "normal" loss condition, coupled with operational needs to minimize the total amount of shielding when possible, led to a more detailed set of calculations for the NISUS magnet for multiple-scattered "skyshine" radiation produced outside the shielded enclosure.

Skyshine calculations conducted by a shielding physicist (P. Degtyarenko) from Thomas Jefferson National Accelerator Laboratory were performed using DINREG (a nuclear fragmentation model) and a Monte Carlo transport code "GEANT". This code is used at Thomas Jefferson and has been demonstrated to provide a useful tool for determining shielding requirements for electron accelerators operating in this energy range or higher.

Four sets of analyses were performed by Degtyrarenko in an effort to evaluate several shielding configurations:

Set-up one modeled the NISUS for full beam loss, coupled with no additional close-in horizontal or vertical shielding. The second included shielding by two inches of lead mounted in close proximity to the vacuum pipe. A third configuration evaluated NISUS for full beam loss, shielded by two inches of aluminum in close proximity to the vacuum pipe. And finally, the fourth configuration included shielding by two inches of lead horizontally and 12" of 5% borated polyethylene in the vertical plane as shown in figure 17.

Summary of NISUS Calculations

All four configurations were evaluated and the results are summarized in the following table. In each case a 300 MeV electron beam with 20 nA current was assumed to strike a thick target. The addition of lead shielding was found to be necessary to reduce the level of x-ray radiation, and the borated polyethylene was included to attenuate the neutrons produced by the beam loss.

20 nA 300 MeV Electron Beam, Full beam loss in NISUS, Units are mRem/hr

Model	Dose at Inside wall (floor level)	Dose at Outside wall (floor level)	Dose 5 meters from inside wall (floor level)	Dose 5 meters from outside wall (floor level)
Model 1 No shielding	Peak - 125 General - 75	Peak - 20 General - 15		
Model 2 2" lead	Peak - 10 - 12 General - 8	Peak 9 - 10 General - 6		
Model 3 2" Aluminum	Peak 25 - 30 General - 20	Peak - 20 General - 15	Peak 25 General - 20	Peak - 10 General - 10
Model 4 2" lead + 12" 5% borated polyethylene	Peak - 4 General - 2	Peak 3- 4 General - 2	Peak ~ 2 General ~ 2	Peak ~ 2 General ~ 2

The radiation levels associated with Model 4 are acceptable, but will required careful evaluation as beam currents are increased in the future. Operating restrictions may be needed to meet the dose limits established in the ASE.

Forward directed bremsstrahlung levels produced by pop-in monitor use

In addition to the multiple scattered "skyshine" radiation, the use of the pop-in monitor will produce an intense, highly collimated forward directed x-ray beam. Using figure 8 and approximations to higher energy recommended by Swanson, the dose rate in this beam is estimated to be 5.4×10^4 Rad/hr at one meter from the loss point. The opening angle of the bremsstrahlung beam is about 1.7 milli-radians. The last pop-in monitor at the end of NISUS is about 12 feet from the wall or about 16 feet from the unshielded area in the forward direction. The shielding in this direction is a 12" lead stop and the four feet of concrete, which in examining Figures 9 & 16, provides a total attenuation factor of approximately 5×10^{-9}. Maximum dose rate through the shield for a 20 nA, 300 MeV electron beam during pop-in monitor use will be approximately 6 μRad/hr.

Radiation Levels through the Laser Penetration

As described in section 3.4, a small penetration of the down-stream shield wall must be provided to permit transport of the FEL beam out of the accelerator vault. This penetration has a dimension of 16 cm^2. This small penetration is located 15" below the height of the beam line to ensure that there is no line of sight between this penetration and the primary electron beam. The only source of radiation potentially incident upon this opening would be multiply scattered radiation occurring during normal or abnormal operating conditions. The very small size of the opening coupled with the orientation relative to the electron beam results in a minimal leakage path for scattered radiation. Monte Carlo calculations indicated maximum dose rates at the outside end of this opening of less than 1 mR/hr, which can be readily addressed during operations.

Radiation Exposure from NISUS Operation

The most significant radiological source associated with NISUS will be radiation levels produced when the "pop-in" monitors are used. Radiation levels within the building are predicted at ~ 2 mRem/hr for a 20nA beam loss. This is an important issue that will require ongoing evaluation during commissioning or special operations. Operational restrictions may be necessary for full beam currents in these situations. These issues will be resolved through fault studies and other measurements during commissioning.

4.6.2 **Activation Hazards**

Induction of radioactivity in machine components (e.g. vacuum chamber, magnets, accelerating sections, pop-in monitors and beam dumps) as well as the surrounding lead and concrete shielding and air, is normally not a significant source of radiation exposure to operational or maintenance staff.

Beam dump

As described earlier, electrons can strike structural components at a number of locations during operation. The maximum beam loss location is the aluminum faraday cup used to stop the beam. Activation of this aluminum beam stop may be calculated from data in the previously cited report of W. P. Swanson [4].

The principal radionuclides produced in the aluminum stop will be Al-26m, Na-22 and Na-24. For the 300 MeV electron beam with a maximum power of 6 watts, the saturation activities for Al-26m, Na-22 and Na-24 are 52.8, 1.4, and 1.7 mCi can be calculated. This will give rise to a radiation field of about 20 mR/hr at 1m from the target immediately on beam turn-off without shielding and assuming no self-shielding in the target. Because of the short-half life of Al-26m (6.37 s), this quickly decays to a level of about 4 mR/hr. The lead shielding around the Faraday cup will reduce these levels to non-measurable values. Beam losses in other areas will be a small fraction of the beam loss in the faraday cup.

Air

Since the SDL beam is contained within a vacuum pipe, air activation during normal operation will be insignificant. Air activation can be produced during a fault condition, but its production is limited by the relatively low beam power of this machine and the close-in shielding which restricts full beam travel through air. Using the formulation of W. P. Swanson (4), activation in air can be calculated using the following set of very conservative assumptions: full beam loss on a thick target for 1 hour, and an unshielded bremsstrahlung flight path in air of one foot.

The principal radionuclides produced in air are: ^{13}N ($T_{1/2}$ = 10 min., β^+) and ^{15}O ($T_{1/2}$ = 2 min. β^+). Using Swanson's table XXXb, the saturation activities of these nuclides are calculated to 28.6 μCi and 3.1 μCi respectively for the SDL operating at a beam power of 6 watts. This activity will be produced along the path of the bremsstrahlung beam before its strikes the lead shielding, and will disburse away from the path as a result of room air movement. If we assume that the activity is distributed uniformly in a small volume close to the point of production (a cube 3 meters on a side), the saturation activity concentration is 10.6×10^{-7} μCi/cc for ^{13}N and 11.6×10^{-8} μCi/cc for ^{15}O. These values can be compared to the Derived Air Concentration for these radionuclides of 2×10^{-6} μCi/cc. Clearly, even with the conservative assumptions, the air activation does not produce significant radiological issues either within the building or in the environment.

Water

All of the accelerator sections and beam line components are water cooled by closed loop, low conductivity water systems. In no case will the electron beam strike the water pipe directly, so water activation can only occur due to bremsstrahlung produced when electrons strike the copper discs of the accelerating structure or the stainless steel or aluminum beam pipe. This is a similar configuration to the 120 MeV electron linac at NSLS which operates at about the same average beam current as the SDL linac. No induced activity has been observed in the cooling water systems at NSLS.

4.6.3 Accidental Beam Losses

This section describes the various fault conditions anticipated, and the dose levels to be expected. Radiation area monitors are provided to monitor area radiation levels so that operator actions can be taken to correct fault conditions within a short time period. These calculations will be checked and the adequacy of the shielding will be confirmed by conducting fault studies during the commissioning of the machine.

Full beam loss in accelerator or transport area

The first scenario that we examine is a loss of the full beam at maximum energy on a thick copper or steel object such as a flange or momentum slits. From figure 8, we can calculate that this loss on a thick target creates a dose rate at 90 degrees (using a correction factor of 0.7 for a copper target) of $\dot{D}_{10}(\mathrm{Cu},90°) \sim 0.1$ rad m^2/min. The horizontal Pb shielding in all locations along the beam line is a minimum of 2 inches which will provide a shielding factor of 1×10^{-1} using figure 13 and 16 (assuming no self-shielding from the target). The X-ray dose rate outside the 4-ft. north wall from Eq. (1) at d = 2.88 m and with $B_x = 5 \times 10^{-3}$ (using figure 9) is;

$$\dot{H}_{1d,x} = 0.4 mrem/hr.$$

Similar losses in other portions of the transport line have longer distances to the shield wall, but have only three feet of concrete shielding. If we recalculate the x-ray doses assuming 3 meters to the exterior of the concrete and use $B_x = 1x10^{-2}$ for 32 inchesof concrete (using figure 9), we obtain

$$\dot{H}_{1d,x} = 4 mrem/hr.$$

The walls of the accelerator enclosure are posted as restricted areas, and occupancy in that location would be a flagrant act. However radiation levels created by the beam striking a thick target can also be calculated as an additional fault scenario. The x-ray transmission path from the loss point to the top of the shield wall will encounter considerably more shielding because of the slant angle in traversing the side and vertical lead shielding. The average lead thickness protecting the top of the north shield wall is 4 inches, which provides a $B_x = 1x10^{-2}$. The distance from the beam line to the top of the wall at waist height is 2.4 meters. Therefore, the dose rate on top of the north (exterior) shield wall during a full beam loss in the linac would be about 12 mrem/hr from x-rays. Neutron production from full beam loss in a thick pipe or flange has been calculated to be on the order of several rem/hr at one meter, and ranging up to 12 rem/hr for stopping in lead. Neutron dose rates on top of the north shield wall from this fault would be up to a maximum of 2.1 rem/hr. Dose rates on the top of other shielding surrounding the enclosure will be similar in magnitude.

Losses of this type can be easily detected by normal beam diagnostics and quickly corrected in the control room. Operators are required to take corrective action within five minutes. A person occupying this area would receive 175 mrem during the five minute period.
To mitigate this potential exposure, access to these areas is prohibited and posted to this effect.

A second failure mode that we examine is the full 300 MeV energy beam emerging through the vacuum chamber wall at point M, Figure 5 and impinging directly on the lead shielding wall. The resulting photons, after attenuation in the surrounding lead, will produce a forward beam towards point M7 of Figure 5. This situation could occur from a steering error in the external H-type bending magnet B1 and emerging through the 1/16" stainless steel (S.S.) vacuum pipe wall at the downstream end of B1 in the direction labeled "B" in Figure 5. A similar situation could occur at the downstream end of magnet B2 since B1 and B2 are powered by the same power supply.

The lead shielding provided in these regions is of sufficient thickness to stop the 300 MeV electrons so we need only to concern ourselves with photons generated in the lead shield impinging on the concrete shielding walls and with photo neutrons produced in the lead shield. We will calculate the dose outside the concrete shielding from photon and neutron penetration, as well as for skyshine over the top of the shield.

The beam emerging from the vacuum chamber at B1 would be 13.5 cm outside the normal beam axis of this 72.34° bending magnet, with normal radius of curvature ρ=792 mm, as shown in the magnet cross section view of Figure 7, and would therefore be making an angle of θ = 0.135 rad = 7.735° with respect to the chamber wall. The slant thickness through the 1/16" = 1.5875 mm stainless steel wall is then t_{ss} = 11.795 mm = 9.28 gm/cm^2, using a density ρ_{Fe} = 7.87 gm/cm^3 for iron. The slant thickness through 2 inches of lead at this angle is equal to about 15 inches. If we disregard the steel vacuum wall and assume that the entire beam strikes the lead, the beam emerging through the lead is 3.4x10^{-5} rem/min at one meter.

The X-ray dose-equivalent index rate exterior to the concrete wall is then evaluated from the expression of NCRP-51, Sect. 4.3.2, p. 50, Eq. (10):

$$\dot{H}_{1d,x} = \frac{\dot{D}_{10} B_x T}{1.67 \times 10^{-5} \ d^2} \qquad (10)$$

where d is the distance in meters from the source point to the inner surface of the concrete shield wall, B_x is the shielding transmission ratio, and the factor 1.67 x 10^{-5} converts the dose rate of Eq. (10) to mrem/hr. T is the occupancy factor which we set conservatively to unity here. The transmission factor B_x for γ's through the 120 cm thick concrete wall is obtained from NCRP-51, App. E.8, reproduced here as Figure 9, as $B_x \approx 5 \times 10^{-3}$. Therefore we arrive at;

$$\dot{H}_{1d,x} = 2.2 \times 10^{-4} \, mrem/hr$$

Finally, we can show that the neutron dose rate outside the shield wall due to this accident is also negligibly small. From Swanson (4), we have estimated the neutron dose rate at one meter from the beam interaction point to be about 12 rem/hr. From equation 10, and assuming a distance through the shield from the loss point of 4 meters, we can calculate the neutron dose rate to be 1.7 mrem/hr.

Using the methodology for skyshine that we previously applied, we can also calculate the skyshine radiation produced by this fault. Neutrons will contribute the greatest dose rate and will produce floor radiation levels of about 5 mrem/hr within 20 m of the loss point. This condition will be short-lived, not extending for more than five minutes due to operator intervention.

Summary of Ionizing Radiation Calculations

The following table summarizes the calculations made in evaluation of the potential ionizing radiation hazards associated with operation of the SDL accelerator. All dose rates are in mRem/hr and represent 'normal' operating conditions.

Radiation Levels in Accessible Area - Location	**Dose Rate (300 MeV)**	**300 MeV (MCNP)**
2% loss in transport line x-rays through 4 foot concrete wall	7.2 x10^{-3} 72 x10^{-3} (32" wall)	
2% loss in transport line neutrons through 4 foot concrete wall	4.7 x10^{-3} 67 x10^{-3} (32" wall)	6 x10^{-3}
2% in transport line x-ray skyshine at console	10 x10^{-3}	
2% in transport line Neutron skyshine	45 x10^{-3}	140 x10^{-3}
Beam dump Neutrons through wall	19 x10^{-3}	
Beam dump x-rays through wall	22 x10^{-3}	
Beam dump x-ray Skyshine at console	6.5 x10^{-3}	
Beam dump Neutron skyshine within 20 m	11 x10^{-3}	200 x10^{-3} (poor statistics)
Beam dump mouth of labyrinth (x-ray)	1.9 x10^{-7}	
Beam dump mouth of labyrinth (neutron)	0.023	0.1 (poor statistics)
Nisus Pop-in monitor inserted skyshine dose rate inside building (full beam loss)	6-8 (Pavel's calculation)	7
Nisus Pop-in monitor inserted (12" poly)-skyshine dose rate inside building (full beam loss)	2 (Pavel's calculation)	
Nisus Pop-in monitor inserted Forward directed bremmstrahlung	6.5 x10^{-3}	1.3 x10^{-3}
Nisus Laser Penetration		0.5 mr/hr x-ray

QUALITY ASSURANCE 5

The SDL project is part of the National Synchrotron Light Source (NSLS). The NSLS Quality Assurance Program applies to the work performed on the project. The SDL project management is responsible for the quality of construction, the operation of the equipment and the work processes in the facility. SDL accelerator components are evaluated for ESH&Q Risk Levels A-1 through A-4 as per SBMS Subject Area "Graded Approach for Quality Requirements." The SDL will comply with the QA Elements of the NSLS QA Manual which meets the requirements of the BNL Quality Assurance Program.

DECOMMISSIONING AND DECONTAMINATION PLAN 6

Operation of the Source Development Laboratory does not, in general, generate large quantities of radioactive or other hazardous material. There is no contamination of accelerator components and there is relatively little radioactive activation, the exceptions being the aluminum beam stops and molybdenum pop-in monitor mirrors where the electron beams are absorbed. These would receive the appropriate treatment at the decommissioning time.

At the appropriate time a full decommissioning plan will be developed based on the requirements outlined in the "Checklist for a Decommissioning Plan" contained in NSLS PRM 1.3.0 "Facility Design and New Program Review."

SUPPORTING DOCUMENTATION 7

1. BNL Environment Safety & Health Standards Manual.
2. BNL Operations Manual
3. BNL Quality Assurance Manual
4. BNL Implementation Plan for DOE Accelerator Order 5480.25.
5. NSLS ESH Procedures and Requirements Manual
6. NSLS Quality Assurance Manual
7. DOE Order 420.2A "Safety of Accelerator Facilities"
8. Guidance document for implementation of DOE Order 420.2A
9. BNL Radiological Control Manual

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FIGURES

APPENDICES

These appendices are available at the SDL website. If you are viewing this document electronically, clicking on the appendix should take you to the relevant document. These are living documents, so, like the SAD, the current official version is the one posted on the website.

Appendix 1: Fire Hazard Analysis

Appendix 2: NSLS Safety Organization Chart

Appendix 3: NSLS PRM (LS-ESH-PRM 1.2.0) Environment, Safety and Health Inspections

Appendix 4 NEPA and NESHAPS

Appendix 5: NSLS PRM (LS-ESH-PRM 1.3.5a) Experimental Review Requirements

Appendix 6: Security/Interlock Systems

Appendix 7: Laser Interlock System

Appendix 8: SAD Risk Assessments