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NSLS-II Project

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Shielding Requirements for NSLS-II

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Abstract

Keywords: Synchrotron Radiation Source, Shielding, Electron Storage Rings

Brookhaven National Laboratory is in the process of designing a new Electron Synchrotron for scientific research using synchrotron radiation. This facility, called the "National Synchrotron Light Source II" (NSLS-II), will provide x-ray radiation of ultra-high brightness and exceptional spatial and energy resolution. It will also provide advanced insertion devices, optics, detectors, and robotics, and a suite of scientific instruments designed to maximize the scientific output of the facility. The project scope includes the design, construction, installation, and commissioning of the following accelerators: a 200 MeV linac, a booster accelerator operating from 200 MeV to 3.0 GeV, and the storage ring which stores a maximum of 500 mA current of electrons at an energy of 3.0 GeV. It is planned to operate the facility primarily in a top-off mode, thereby maintaining the maximum variation in stored beam current to < 1%. Because of the very demanding requirements for beam emittance and synchrotron radiation brilliance, the beam life-time is expected to be low, on the order of 2 - 3 hours. Analysis of the bulk shielding for operating this facility and the input parameters used for this analysis are discussed in this paper. The characteristics of each of the accelerators and their operating modes are summarized with the input assumptions for the bulk shielding analysis.

Introduction

The bulk shielding calculations for the design and operation of National Synchrotron Light Source II (NSLS II) accelerator enclosures have been completed using the final design parameters. Calculations of the resulting radiation fields and required shielding have been made for normal stored beam loss and loss of beam during injection at the septum/extraction magnets. The shielding estimates are based on conservative assumptions, including several modes of operations that involve normal beam loss mechanisms as well as certain abnormal beam loss scenarios. These situations are drawn from experiences and assumptions used at existing accelerator and synchrotron radiation facilities. Shielding requirements for the linac, storage ring and booster synchrotron are based on maintaining exposure to personnel to less than 5 $\mu Sv\ h^{-1}$ during typical operation at the exterior surface of the shield wall.

Conservative assumptions are used in the shielding calculations methodology to provide additional margin of safety. These assumptions include radiation dose equivalent factors with thick target approximation, radiation attenuation factors, beam loss, storage ring beam life time, and the dose rates calculated on contact with the shield walls.

Components of Radiation Considered

For the radiological analysis of NSLS-II accelerator enclosures the following radiation components are considered;

- Bremsstrahlung radiation created during electron beam loss
- Neutron production by high energy bremsstrahlung
- Synchrotron radiation from the insertion devices and bending magnets

High energy electrons produce bremsstrahlung when intercepted by the accelerator components or residual gas molecules in the vacuum chamber. Bremsstrahlung or "breaking radiation" is emitted by the high energy electrons as they decelerate due to inelastic radiative interaction with the coulomb field of atomic nuclei of the medium they traverse through. Subsequent pair production and bremsstrahlung production can generate an electromagnetic shower (Perkins 1984). The radiation originating in the shower is highly forward peaked in the forward direction of the electron beam. However the transverse component is significant and cannot be ignored. The lateral shielding for the accelerator enclosures is designed to protect personnel from this transverse component of the electromagnetic shower. In addition to bremsstrahlung radiation, two other radiation components need to be considered. These are Giant Resonance Neutrons (GRN) and High Energy Neutrons (HEN) originating from the interaction of bremsstrahlung with the heavy metals (Levinger 1954). Giant Resonant Neutrons are produced by photonuclear interactions when photon energy is above the threshold energy of 7-20 MeV. This component has an average effective energy of about 2 MeV and is emitted isotropically. If the

photon energy is above 50 MeV, high energy neutrons (>25 MeV) are also emitted. The high energy neutron component is slightly anisotropic in the forward direction. These radiations have been considered under appropriate conditions to estimate the shielding and other requirements for the NSLS-II accelerator enclosures.

Shielding Design Criteria

NSLS-II, being a US Department of Energy (DOE) facility, is subject to DOE radiation protection standards. At NSLS-II, the accelerator enclosures will be shielded to reduce exposure at the exterior surface of the shield, during typical operation to < 5 $\mu Sv\ h^{-1}$ (0.5 $mrem\ h^{-1}$) in normally occupied areas. This limits the maximum exposure to < 10 $mSv\ y^{-1}$ (1000 $mrem\ y^{-1}$), assuming 2000 hours of occupancy. No full time occupancy is expected or will be permitted within one meter of the storage ring outer wall at the experimental floor side.

Dose Equivalent Factors Used for Shielding Calculations

Dose equivalent factors for the unshielded source terms at 1 m in the transverse direction from a 3 GeV electron beam interaction on a thick copper or iron target are provided by Swanson (1985) and later modified by Sullivan (1992) for higher energies. These dose equivalent factors are given in Table 1. It can be noted that the dose equivalent factors in the transverse direction (90 degrees) are independent of the electron beam energy, although dependent on the beam power.

In the absence of any shielding the bremsstrahlung component will include a low energy particle component (e^- and e^+), which is neglected since shielding for bremsstrahlung will ensure attenuation of the particle component. In the forward direction with respect to the electron beam (zero degrees) the dose equivalent factor for bremsstrahlung is $83 \times E\ \mu Sv\ m^2\ J^{-1}$ (Swanson 1985), where E is the electron energy in MeV. The bremsstrahlung dose rate at 1 m near zero degrees, but not within the forward spike, is taken as 8500 $\mu Sv\ m^2\ J^{-1}$ (Swanson 1985). The Giant Resonance Neutron component is assumed to be isotropic from the loss point. These forward

Dose Equivalent components are important for the design of ratchet wall shielding of the storage ring, where the forward component tangential to the storage ring will be incident on the ratchet wall at 90^0.

The bulk shielding for the NSLS-II accelerator enclosures has been calculated using the following methodology;

$$H = \sum\{(F_i\, J)\, R^{-2}\}\, e^{-(t/\lambda i)}\} \qquad (1)$$

Where H = Dose Equivalent Rate summed over all radiation components in $\mu Sv\ h^{-1}$

F_i = Radiation Dose Equivalent Factors for the corresponding radiation component (i^{th} component).

J = Electron energy dissipation in $J\ h^{-1}$

R= Total distance of the dose point from the source in meters

t = Thickness of bulk shielding in $g\ cm^{-2}$

λ_i = Attenuation length of the ith radiation component in $g\ cm^{-2}$

The equation (1) is solved using a parameter search for the thickness of the bulk shielding (concrete) such that $H < 5.0\ \mu Sv\ h^{-1}$. The shielding strategy employed is to use concrete as bulk shielding to provide global shielding for accelerator enclosures for distributed losses during normal operation. This shielding may need to be supplemented by additional local shielding, employing lead for bremsstrahlung or polyethylene for neutrons to reduce radiation fields from the probable high loss points to acceptable levels of $< 5.0\ \mu Sv\ h^{-1}$ at the occupied areas.

Radiation Attenuation Factors Used for the Calculations

The radiation attenuation factors used for the materials in the present shielding calculations are given in Table 2. This data has been obtained from the various sources in the literature, Hubbel 1969, Schaeffer 1973, Alsmiller 1973. A number of references which discuss

these attenuation factors have been reviewed. We have chosen conservative values of these attenuation factors to provide additional safety margin for the shielding calculations.

Beam Loss Assumptions in the Accelerator Structures

The beam loss assumptions used for the bulk shielding calculations of NSLS-II accelerator enclosures are summarized in Fig. 1 and also provided in Table 3.
The detailed beam loss assumptions for each of the accelerator structures are given below.

Linac and Booster Loss Assumptions

For the Linac system, the bulk shielding computations are based upon normal operation beam losses of a certain fraction of the beam power. Table 3 gives the estimated losses of beam energy in the Linac, Booster, Storage ring and transfer line components. In order to estimate the bulk shielding for the Linac tunnel, a distributed loss of 10 % of the beam energy is assumed along the length of the tunnel for 1 Hz operation. The shielding requirement for the lateral walls and the roof of the Linac tunnel is calculated based upon this beam loss scenario.

At the NSLS-II, the Booster Synchrotron will be housed in a separate enclosure. Injection from the Linac to the Booster Synchrotron takes place approximately once in every minute during the normal top-off mode of operation. The injected beam energy is 200 MeV and the injected charge is assumed 15 nC. These electrons are accelerated to 3 GeV and injected into the storage ring. During fill periods for the storage ring and during machine commissioning studies, a higher rate of injection may be used. Assuming the top-off as the prevailing mode, shielding calculations are performed for an average injection frequency of one in every minute. It can be safely assumed that the integrated beam loss over a period of one year for the top-off mode will be conservative compared to sum of losses combining all other modes of operations. Additional supplementary lead shielding is provided at probable high loss points for higher rates of injection. 2 % of the accelerated beam energy being dissipated at any single point in the booster synchrotron during acceleration and a 50 % injected beam loss are assumed at the injection region from linac to

booster. Beam loss assumptions used for the booster enclosure bulk shielding calculations are given in Table 3.

Storage Ring Beam Loss Assumptions

In the beam loss scenario used for these calculations, we assume four scrapers in the injection region of the storage ring (2 vertical and 2 horizontal) to intercept injected electrons which enter the storage ring at the wrong trajectory. These scrapers intercept incorrectly positioned electrons and prevent loss at other locations in the ring, e.g. at the insertion devices. It is believed that it will be possible to intercept essentially all electrons that might be lost during injection on the scrapers and septum. The scrapers are likely to intercept a significant fraction of stored beam losses as well. The bulk shielding calculations of the storage ring are performed with the following beam loss scenario. Assuming a conservative 2 hour life time and 80% injection efficiency, 18 nC of charge will be injected into the storage ring every minute to replenish the ~14 nC of stored beam lost the previous minute (assuming 2 hour life time). Of the 18 nC injected, 4 nC (~ 20%) is lost during injection. We assume that 50 % of the particles lost during injection (2 nC min^{-1}), will be lost at the injection septum and the remaining 50 % will be intercepted at 2 horizontal injection scrapers (1 nC min^{-1} each) in the storage ring.

It is further assumed that out of ~14 nC min^{-1} lost from the stored beam;

- 30 % is lost at the 2 horizontal scrapers (2.1 nC min^{-1} each)
- 15% is lost at the septum (2.8 nC min^{-1})
- The remaining 55% is lost at vertical apertures, assumed to be at 2 vertical scrapers and arbitrarily at five other limiting apertures (1.1 nC min^{-1} each).

Taking into account all the loss assumptions, in the present calculations a 13 nC min^{-1} loss is assumed at any point in the injection region of the booster to storage ring injection (combined loss at the septum and the scrapers) and 1.1 nC min^{-1} loss is assumed at any given location in the non-injection region of the storage ring. Fig. 2 summarizes the beam loss assumptions used for the storage ring bulk shielding calculations.

Linac Shielding Calculations

Linac Parameters

For NSLS-II, a Linac will be providing 200 MeV electrons into the booster synchrotron. In the present calculations the Linac tunnel is assumed to be approximately 40 meters long, 4 meters wide and 3 meters high. The salient features of the Linac system are the following;

Beam energy	200 MeV
Beam current	15 nA
Frequency	1 Hz
Position of beam from floor	1 m
Position of the beam from the Klystron gallery side	3 m
Linac power	2.96 watts

Bulk Shielding for the Linac Tunnel

The bulk shielding estimates of the concrete thickness for the Linac tunnel is given in Table 4. A 100 cm thick standard concrete with 2.35 g cm^{-3} of density at the lateral wall at the klystron gallery side and 110 cm thick standard concrete at the roof will limit the dose rate to < 5.0 $\mu Sv\ h^{-1}$ at the exterior of the bulk shielding on contact. The beam injection region from the linac to booster ring needs supplementary shielding due to higher injection loss and higher rate of injection. The bulk shielding in the forward direction injection transfer line is based on an assumed 50% loss at a momentum slit located downstream of the first dipole in the transfer line. The calculations are done based on the forward direction bremsstrahlung dose equivalent factors corresponding to a 50% beam loss. These bulk shielding estimates are also given in Table 4. The estimated concrete equivalent thickness for bulk shielding in the forward direction is > 220 cm. Local shielding in lead in the forward direction can be provided to save on the concrete bulk shielding. The equivalent thickness of lead and concrete combination required in the linac forward direction is also provided in Table 4. The momentum collimator slit and the beam dump

require supplementary shielding in lead and polyethylene in the transverse direction for probable higher losses and higher rates of injection.

Booster Shielding Calculations

Booster Parameters

The salient features of the booster synchrotron are given below.

Beam Energy	3 GeV
Maximum Repetition Rate	1 Hz
Repetition Rate during Top-off	1/min
Ring Circumference	158.4 meters
Accelerated Charge	15 nC
Number of Electrons per Fill	9.36×10^{10}
Total Energy in the Booster	43.75 Joules

Bulk Shielding Estimates for the Booster Enclosure

In the present calculations the lateral wall at the occupied region of the booster enclosure is assumed to be at a distance of 2 meters and the roof at 2 meters from the booster vacuum chamber center line. The results of the bulk shielding calculations based on the given beam loss assumptions are given in Table 5. The lateral walls at the occupied region require a thickness 70 cm of normal density concrete and the roof 70 cm of normal concrete. The injection region of booster to storage ring requires supplementary shielding for higher beam losses and possible 1 Hz operation during machine studies and storage ring fill up from zero current. The extraction magnet in the booster ring also requires supplementary shielding in lead and polyethylene for higher rates of injection.

Storage Ring Bulk Shielding Calculations

Storage Ring Parameters

The NSLS II storage ring will be storing 3 GeV electrons injected by the booster synchrotron. The estimated life time of the beam in the storage ring is 2 hours. It is assumed that the machine will be topped-off approximately every minute in order to maintain the variation in

the circulating stored beam to 1% or less. The storage ring tunnel is assumed to be 791 meters in circumference. The salient features of the storage ring system during normal top-off mode of operation are the following;

Beam Energy	3 GeV
Beam Current	500 mA
Beam Life Time	2 hours
Tunnel Circumference	791 meters
Stored Charge	~1.3 μC
Position of Beam from Expt. Floor Wall	1 meter
Position of Beam from Floor	1 meter
Stored Electrons	8.1×10^{12}
Stored Energy	3898 Joules

Bulk Shielding for the Storage Ring Enclosure

Table 6 summarizes the bulk shielding requirement for the storage ring enclosure based on the beam loss assumptions considered above. The lateral wall of the storage ring on the floor side is assumed to be at an average distance of 1 meter from the beam center line. The roof and the inboard walls are assumed to be at a distance of 2.0 meters from the beam center line. The ratchet wall shielding thickness at the first optics enclosure region is calculated using the forward peaking component of the Dose Equivalent Factors (Swanson 1985). The occupied regions on the experimental floor side of the storage ring are shielded for a dose limit of < 5 $\mu Sv\ h^{-1}$ on contact. No occupancy will be permitted within 1 m of the experimental floor wall. Roof and inboard wall are also shielded for < 5 $\mu Sv\ h^{-1}$ on contact. Shielding wall thickness of the storage ring enclosure in standard concrete equivalent (2.35 g cm^{-3}) is given in Table 6.

The ratchet wall shielding thickness at the first optics enclosure side of the beam lines perpendicular to the photon beam is also given in Table 6. These walls are assumed to be at a distance of 20 meters from the center of the straight section of the insertion devices. The ratchet walls are thicker in order to shield the bremsstrahlung forward peaking component, tangential to the vacuum chamber, resulting from the electromagnetic shower due to beam losses in the storage

ring. Supplementary shielding in lead is required as a collimator around the beam line penetrations at the ratchet wall.

The bulk shielding estimates in terms of concrete thickness for the storage ring enclosure at the booster-to-storage-ring injection region are also given in Table 6. 141cm thick standard concrete with a density of 2.35 g cm^{-3} will limit the dose rate to < 5 μSv h^{-1} at the exterior of the lateral wall of the storage ring. 116 cm of concrete on the roof will limit the dose rate to the same level at the exterior wall on contact. It may be possible to replace the additional concrete bulk shielding by lead supplementary shielding at the roof and inboard side of the injection region in the form of septum shielding. Supplementary shielding is also required for probable higher beam loss locations and for higher rates of injection (greater than 1 injection per minute).

Summary

This paper summarizes the results of the bulk shielding calculations for the National Synchrotron Light Source II accelerator enclosures and the basic parameters and beam loss assumptions used in these calculations. The ratchet walls and the injection regions are shielded for higher beam losses. The concrete bulk shielding thickness is given for the linac, booster and storage ring enclosures. In addition to the concrete bulk shielding, supplementary shielding in terms of lead and polyethylene is required at the probable higher beam loss locations and for higher rates of injection.

References

Alsmiller, R.G. and Barish, J. Shielding Against Neutrons Produced when 400 MeV Electrons are Incident on Thick Copper Target. Particle Accelerators, 5; 1973.

Hubbel, J.H. Photon Cross Sections and Attenuation Coefficients from 10 keV to 100 GeV. NSRDS-NBS 29; 1969.

Levinger, J.S. Theories of Photonuclear Reactions. Ann. Rev. of Nucl. Sci., 4; 1954.

Perkins, D.H. Introduction to High Energy Physics, Third Edition, Addison-Wesley Publishing; 1984.

Schaeffer, N.M. Reactor Shielding for Nuclear Engineers, NTIS, Springfield, VA. 1973

Sullivan, A.H. A Guide to Radiation near High Energy Particle Accelerators, Nucl. Tech. Publishing; 1992.

Swanson, W.P., DeLuca, P.M., Otte, R.A. and Schilthem, S.W. Aladdin Upgrade Design Study, University of Wisconsin Report, AUS14; 1985.

Fig. 1 Beam loss assumptions used for bulk shielding calculations

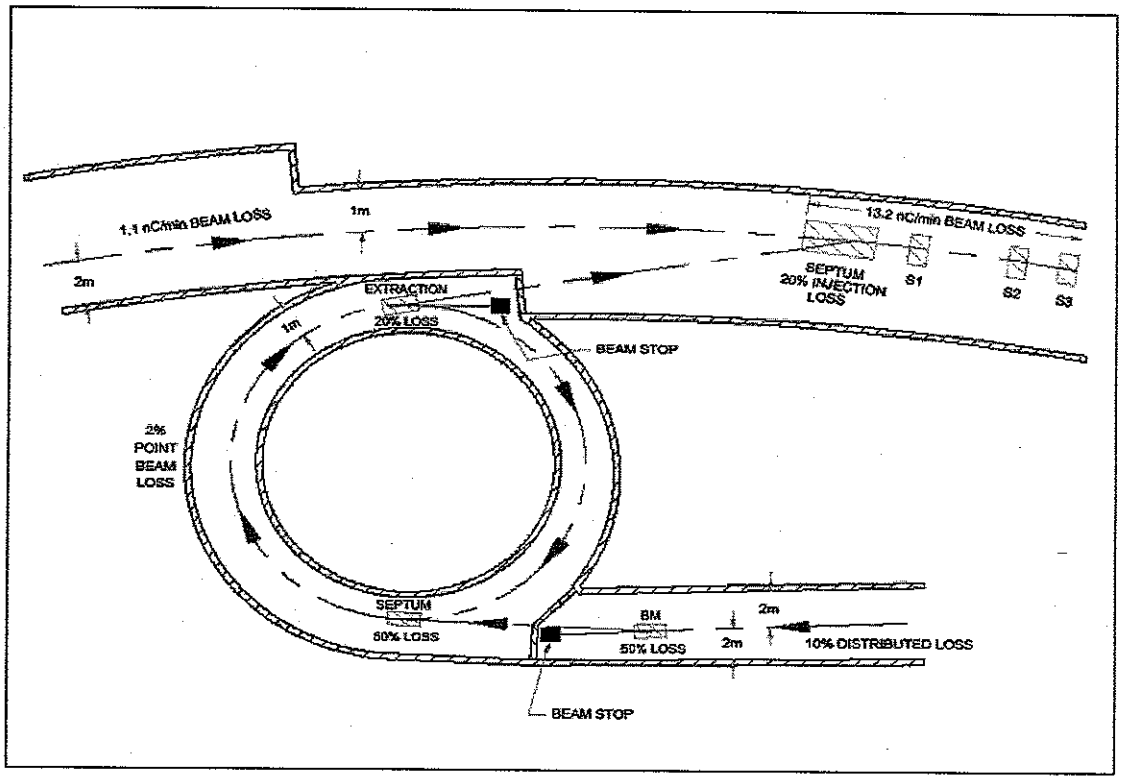

Fig. 2 Distribution of Storage Ring Beam Losses during Operations

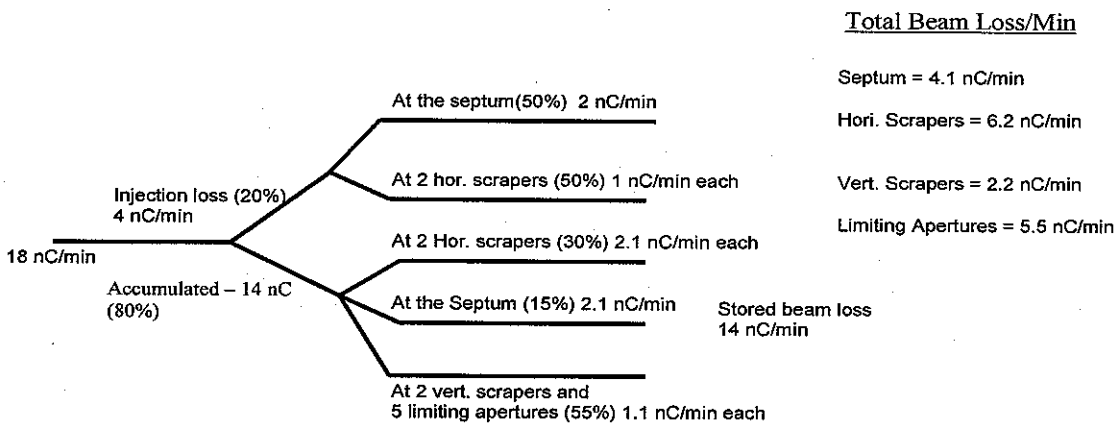

Table 1 - Dose Equivalent Factors at 90^0 from Beam Losses on a Thick target (F_i)

Radiation Component	Dose Equivalent Factor ($\mu Sv\ m^2\ J^{-1}$)
Bremsstrahlung	13.9
Giant Resonance Neutrons	2.7
High Energy Neutrons	0.43

Table 2 Radiation Attenuation Lengths of Shielding Materials

Radiation Component	Shielding Material	Density ($g\ cm^{-3}$)	Attenuation Length ($g\ cm^{-2}$)
Bremsstrahlung	Concrete	2.35	49
	Heavy Concrete	3.70	50
	Lead	11.34	25
	Iron	7.80	37
	Earth	1.60	70
	Polyethylene	1.01	70
Giant Resonance Neutrons (E < 25 MeV)	Concrete	2.35	40
	Heavy Concrete	3.70	45
	Lead	11.34	161
	Iron	7.80	100
	Earth	1.60	33
	Polyethylene	1.01	6.3
High Energy Neutrons	Concrete	2.35	65 (<100 MeV) 115(>100 MeV)
	Heavy Concrete	3.70	125(>100 MeV)
	Lead	11.34	191
	Iron	7.80	138
	Earth	1.60	90
	Polyethylene	1.01	62

Table 3 Beam Loss Assumptions used for Linac, Booster and Storage Ring Calculations

Accelerator system	Loss (%)	Energy (MeV)	Power Loss (W)	Charge Loss (nC)
Linac - general	10 % (distri.)	200	0.20[a]	1 nC/s[a]
- Momentum slit [b]	50%	200	1.5	7.5 nC/s
- Beam dumps [b]	100%	200	3	15 nC/s
Booster - general	2 %	3000	0.015	0.3 nC/min
- injection septum [b]	50%	200	0.025	7.5 nC/min
- extraction septum [b]	20%	3000	0.15	3 nC/min
- beam dump [b]	100%	3000	0.73	15 nC/min
Storage Ring – general	8 %	3000	0.053	1.1 nC/min
- injection region [b]	~ 70%[c]	3000	0.632	13.2 nC/min

a. Linac bulk shield is calculated for 1 Hz operation – Booster and Storage Ring bulk shield is calculated for 1 injection per minute.
b. Local lead shielding required to supplement bulk concrete shielding.
c. 20% lost during injection, the remaining fraction during stored beam operation

Table 4 Concrete Shielding Requirements for the Linac Enclosure

Location	Lateral wall Concrete Equivalent Thickness (cm)	Roof Concrete Equivalent Thickness (cm)
Klystron Gallery Side	100	110
Berm Side Wall	130	
Linac Downstream Wall	220 or 100 cm + 15 cm (Pb)	

Table 5 Bulk Shielding Estimates of Booster Enclosure

Location	Lateral Wall Concrete equivalent (cm)	Roof Concrete equivalent(cm)
Booster synchrotron	70	70
Booster Forward Wall	116	-

Table 6 Bulk Shielding Requirements for the Storage Ring

Location	Expt .Floor Wall Concrete Equivalent Thickness (cm)	Roof Concrete Equivalent Thickness (cm)	Inboard Wall Concrete Equivalent Thickness (cm)
Storage Ring Non-Injection region	101	81.5	81.5
Storage Ring Injection Region (~ 1 super-period)	141	116	116
Storage Ring Ratchet Wall (Forward Direction)	137	---	---