Chapter 14

RADIATION SHIELDING

1. Introduction

A new SESAME storage ring is being designed, SESAME will be 2.5 GeV 3rd Generation light source, the ring will be injected at 800 MeV from a booster synchrotron with 22 MeV Microtron as pre-injector, [1].

In this report we intend to give a summery for the calculations of the shielding for SESAME accelerator system, These calculations have been carried out at all points in SESAME using various electron beam loss scenarios, these have been estimated from assumptions of electron loss through the accelerator system and also to outline the different types of radiation.

2. Safety and Dosage Limits.

SESAME accelerator system is a user-oriented facility with different types of ionising radiations of different energies and intensities. The emission of this ionising radiation will constitute a health risk; an optimised radiation shield surrounding the accelerators is needed to provide an appropriate protection against these sources.

The most important rule in ionising radiation protection is the ALARA principle, which says that any exposure to personnel should be kept *As Low As Reasonably Achievable*. This requires that the radiation shielding design has to be optimised so that the measured annual equivalent dose at any point in the facility even immediately outside the shield is below 5 mSv. Dose limits are expressed in terms of equivalent dose to compare the risk posed by different kinds of radiation where the relative biological effectiveness of these radiations is taken into account. [2]

3. Shielding Design.

3.1 Ionising Radiation

The interaction between radiation and matter will lead to energy transfer from the radiation field to the matter. The energy transferred to electrons may be sufficient to make the charge separation. An ionising radiation is the radiation that causes the ionisation of the interacting matter. There are two types of ionising radiation, one can cause immediate ionisation which consists of charged particles with enough kinetic energy for making ionisation while colliding with the atoms of the material, As examples of this can be α- and β- radiations of radio-nuclides, proton and electron radiations of the accelerators, etc. the other consists of neutral particles that produce the origination of charged particles enabling immediately the ionisation. Examples of that are neutron and photon radiations.

The processes involved in the types of ionising radiations generated by electron accelerator are complex and for practical shielding calculations it is often necessary to make simplifications and assumptions regarding beam loss patterns, distance from the source, etc. In each case, a conservative assumption has been accounted for.

Many measurements of the production rates and radiation length, see table (3.1) below, for common shielding materials have been made at accelerators facilities over a period of many years and these have been used to derive the empirical formulae used here.

The secondary radiation generated in the electromagnetic cascade that starts by the interaction of the primary high energy electron beam with matter can be divided into different groups, representing the radiation sources, which must be considered in the shielding calculations:

- Electromagnetic Radiation (Bremsstrahlung): high energy gamma rays are generated in the electromagnetic cascade initiated by the electrons interacting with matter. The Bremsstrahlung process in an electron accelerator is one of the basic interaction of electrons with matter which can convert a large fraction of the electron beam power into X-ray power, The gamma rays also help to propagate the cascade. The cascade at high energy propagates mainly in the forward direction, however a lateral spread up to 90^o has to be considered. The Bremsstrahlung in the forward direction is a strong function of the original electron energy E. At energies below about 20 MeV the output varies as E^2, while above 20 MeV it varies as E. [3, 4]
- Medium energy neutrons (energy up to 10 MeV): these are generated by giant resonance reactions of gamma rays with matter. These neutrons are emitted isotropically from the interaction region.
- High energy neutrons (up to a few hundred MeV): these are produced by gamma ray interactions with nuclear components (quasi deuteron interactions, photopion production). These neutrons are slightly forward peaked.
- Muons: when the primary energy beam is higher than about 1 GeV, high energy muons produced by direct interaction (muon pair production) or by decay of pions and kaons (produced in photonuclear reactions) have to be taken into account. However their production here is neglected because the cross section is negligible at the energies that the SESAME will run. [4]

3.2 Shielding Calculations.

To evaluate the thickness of the shielding it is necessary to consider the frequency of use of the accelerators and the frequency of "accidents". The definition of an accident as any situation which causes abnormal total or partial loss of the beam.

Under optimal circumstances we expect the SESAME facility to operate for a maximum of 24 hours/day for 250 days/year, i.e. 6000 h/y.

Assuming a beam lifetime of about 24 hours, one injection per day must be sufficient.

However to cover possible failures, we will assume 1000 injections per year. And 4 minutes needed for one injection which will give a use factor of 66.7 hour/year for the Microtron and the booster.

An operating energy of 2.5 GeV at 400 mA has been used for the calculation of the shielding, i.e. 1.04×10^{12} circulating electrons in the storage ring and 1.04×10^{15} stored electrons per year, each accelerator has been considered separately although the microtron and the booster will be housed inside the storage ring enclosure.

The assumed, worst case, conditions for accidents at any point other than injection during the normal operation phase can be listed as follows:

- Microtron: 50% of the beam is lost at 0^o and 90^o with respect to the beam axis.
- Booster: 50 % of the accelerating beam may be lost at an energy of 800 MeV at one point anywhere in the booster.
- Storage Ring: The losses from the stored beam will be averaged over one year will be spread evenly around the ring circumference, a conservative estimation of 10% will be lost at a single point.

The total equivalent dose outside the shielding wall is the sum of the doses from Bremsstrahlung, low energy giant resonance neutrons and high energy neutrons, However, this will be somewhat pessimistic estimation since for electromagnetic component we have assumed a thin target, while for the neutron components a thick target is assumed, The thickness of the shielding wall is calculated so that the equivalent dose is less than the dose limit, i.e. 5mSv/year.

3.2.1 Lateral Shielding

Different equivalent doses for each component of the ionising radiation have been calculated using an empirical formulae as below:

a. Equivalent Dose from the Electromagnetic Component [5]

$$H_\gamma(x,\theta,d) = D_T(\theta) A_T e^{-\lambda x} / d^2 \tag{3.1}$$

$$D_T(90^o) = \frac{E(GeV)}{5GeV} 10mSv \qquad \text{at } 10^{11} \text{ electrons and 1 m distance}$$

$$A_T = 0.01$$

Where H_γ is the equivalent dose, θ is the observation angle, λ is the radiation length (cm^{-1}) and d is the distance in meters just outside the shielding wall.

b. Equivalent Dose from Low and Intermediate Energy Neutrons. [6]

$$H_{ni}(x,d) = \frac{N_e N_n E(GeV) F_{ni}}{4\pi d^2} e^{-\lambda x} \tag{3.2}$$

Where N_e is the number of electrons and *E (GeV)* is their energy. N_n (1/GeV) is the neutrons yield per a 1 GeV electron. It is assumed that the neutron yield scales linearly with electron energy and F_{ni} is a conversion factor from neutron flux density to equivalent dose.

N_n= 0.3 / e^-.GeV
F_{ni} = 4 ×10^{-7} mSv.cm^2

c. Equivalent Dose from High Energy Neutrons.[7]

$$H_{nh}(x,d) = F_{nh} N_e \frac{E(GeV)}{d^2} e^{-\lambda x} \tag{3.3}$$

Where N_e is the number of electrons and *E (GeV)* is their energy. F_{nh} is a conversion factor from the number of 1 GeV electrons to equivalent dose at unit distance.

F_{nh} = 1×10^{-10}mSv.cm^2/e^-. GeV.

The materials used for the shielding calculations, both laterally and perpendicularly, are ordinary concrete and lead, table (3.1).

Table 3.1: Radiation length

Shielding Material	Density (g/cm^3)	for Brems (cm^{-1})	for Low Neut (cm^{-1})	for High Neut (cm^{-1})
Ordinary Concrete	2.3	0.055	0.058	0.0235
Led	11.3	0.7	0.04	--

For the lateral shield of the storage ring in the normal operation mode, an assumption of 10% loss of the stored electrons per year, i.e. 1.04 ×10^{14} electrons / year at a single point, with 80 cm ordinary concrete as a lateral shield and a minimum distance of 2 m from the source point just outside the shielding wall, a total equivalent dose of 1.15 mSv/year is obtained. To include the injection loses, an injection efficiency of 50% were assumed, this will mean that the number

of the lost electrons at injection with an energy of 0.8 GeV is the same as the number of electron eventually stored, assuming 50% of the loses at the septum and 10% could occur at some other single point, this will give a total dose for both the stored beam loses and the injection loses of 2.99 mSv/year after the lateral shield of the septum and 1.52 mSv/year elsewhere.
For the maximum stored beam loss if we define it as a loss of tenth of the stored beam at a single point [8], then the total dose of 10% of the beam, i.e. 1.04 $\times 10^{10}$ electrons is 1.16μSv.

For the booster synchrotron, with 0.8 GeV and 15 mA at 1 Hz, i.e. 1.21×10^{10} electrons per second, with conservative assumption of 50% loss at single point, A lateral shield of 80cm of ordinary concrete has been used, the total equivalent dose with minimum distance of 3m is 22.8 μSv/hour is obtained, that is 1.51 mSv/year for the 66.7 hours per year of operation.

An assumption of 50% beam loss in the microtron within the last turn or at the injection straight of the booster, i.e. 22 MeV electron energy, 15 mA current at repetition rate of 10 Hz and a pulse duration of 4 μsec. has been chosen, this gives a loss 1.875 $\times 10^{12}$ electron per second, or 4.5 $\times 10^{17}$ electrons per year, and since the microtron is installed in the same enclosure where the booster located, just the walls near the microtron are needed to be 1 m thickness of ordinary concrete, a total dose of 4.25 mSv/year has been obtained at a distance of 3.5m outside the shield.

3.2.2 Perpendicular Shielding

A significant part of the normal beam losses is inelastic scattering against nuclei in rest gas molecules. Bremsstrahlung radiation will be produced, and the main point where it has to be stopped is downstream the straight sections of the ring.

Since the mean current will be around 400 mA in the storage ring, the production rate for this current is 2.5 $\times 10^{18}$ electrons /second. We will also assume a pretty poor vacuum, 10^{-8} Torr. The constituent molecules will then be, for our case, comparable with air molecules. One radiation length in air is 308 m at atmospheric pressure. The long straight sections in the ring will be around 3.2 m, and the short straights around 3 m. Thus, the production rate of effective quanta is [8]

$$n_\gamma = \frac{3}{308}\frac{10^{-8}}{760}2.5\times 10^{18} = 3.2\times 10^{5}/s \quad \text{in the short straight sections.}$$

$$n_\gamma = \frac{3.2}{308}\frac{10^{-8}}{760}2.5\times 10^{18} = 3.425\times 10^{5}/s \quad \text{in the long straight sections.}$$

To include the eventual halo effect, we assume $n_\gamma=1\times 10^{6}$/s for both cases. With a perpendicular ordinary concrete wall of 1m thickness and 20 cm of lead (effective thickness) at the height of the beam, we get, [9]

$$H_\gamma = \frac{1\times 10^{6}}{5\times 10^{9}}\frac{2.5GeV}{6.3GeV}150mSv.e^{-10\times 0.7}.e^{-100\times 0.054}2.16\times 10^{7}/year = 1.06mSv/year \qquad (3.4)$$

For the calculation of the perpendicular shielding of the low and intermediate neutrons, equation (3.5) can be used.

$$H_{ni}(x,d) = \frac{N_e N_n E(GeV) F_{ni}}{4\pi d^2} e^{-\sum_i \lambda_i x_i} \qquad (3.5)$$

With 1 m thickness of ordinary concrete and 20 cm of lead, using the values for the λ's from table (3.1), an equivalent dose of 0.21 mSv/year is obtained at distance of 2 m from the source point outside the shield.

To calculate for the perpendicular shielding of the high energy neutrons, equation (3.3) can be used since these neutrons are essentially emitted with isotropic angular distribution, [3] which gives 0.39 mSv/year with 1 m thickness of ordinary concrete.

For the maximum beam loss which has been assumed to be 10% of the beam, or 1.04 $\times 10^{11}$ electrons will be lost at single point, 1% of this energy is converted to Bremsstrahlung radiation or $n\gamma = 1.04 \times 10^9$ /s, [3,6], From equation (3.4), this corresponds to 0.051 μSv or 17 minutes of rest gas induced Bremsstrahlung.

Losses at injection, with the same assumption for the lateral shielding case where the injection efficiency is 50%, that is each pulse from the booster of 15 mA at 1 Hz repetition rate, or 1.21×10^{10} electrons, 6×10^9 electrons will be lost in the injection straight at one point per pulse, 1% is converted to Bremsstrahlung at 0.8 GeV, a dose of .15 mSv/year by scaling to Equation.(3.4) and knowing that with 50% injection efficiency 160 pulses needed to store 400 mA per injection and 1000 injections needed per year.

Figure (3.1) shows a sketch for the geometry and thickness of the lateral and perpendicular shielding for a part of the storage ring.

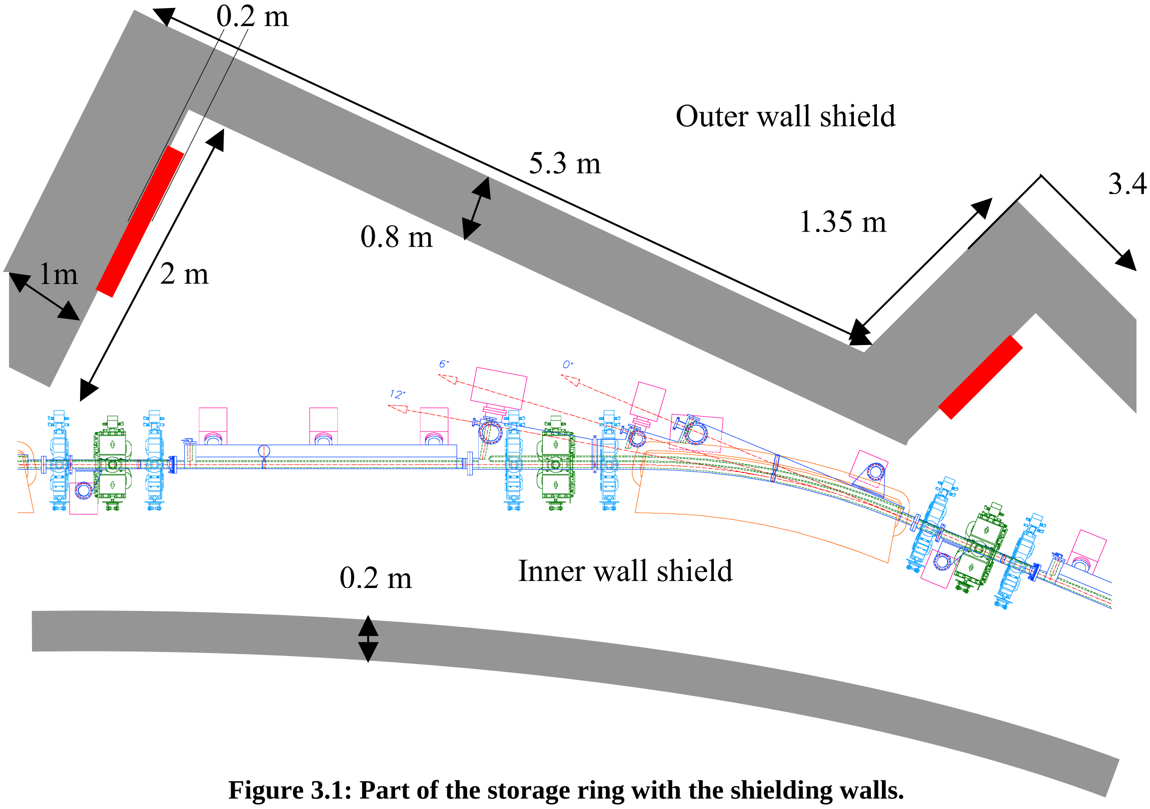

Figure 3.1: Part of the storage ring with the shielding walls.

3.2.3 Shielding for Sky-Shine

Radiation scattered through air or "sky-shine" (for example, due to a weaker shield on the accelerator roof) may cause radiation at remote occupied areas which are not in direct sight of the accelerator. Sky-shine may contribute to the dose to the public beyond the boundary of the accelerator site.

The long distance sky-shine propagation of neutrons (only neutrons are considered) that escape the shielded accelerator roof can be found from the expression, [10].

$$D(Sv/year) = 6.67 \times 10^{-17} N' \frac{E}{r^{1.5}} e^{-\lambda x} \tag{3.6}$$

Where *D(Sv/year)* is the equivalent dose per year, *N'* is the number of electrons lost per year at specific point along the ring and *r* is the distance, in meter, from the source.

An assumption of 10% loss of the stored electrons per year has been taken to evaluate the sky-shine of the storage ring after 0.4 meter of ordinary concrete as a roof, the same for the booster synchrotron also after assuming a 10% loss of the $2.9\text{x}10^{15}$ stored electrons per year, the annual doses are presented in table (3.2) for different distances from the source point with λ=0.058 cm^{-1} and x =40 cm.

Table 3.2: Annual equivalent dose from the sky-shine, with λ=0.058 cm^{-1} and x =40 cm

Distance (m)	Storage ring Equivalent dose (mSv/year)	Booster Equivalent does (mSv/year)
3	0.328	0.293
5	0.150	0.136
10	0.054	0.048
50	0.005	0.004

4. Considerations for BeamLines Shielding and Induced Activity

Synchrotron light and gas Bremsstrahlung are channelled into the beam lines which will generally be intercepted by the beam line components such as slits, mirrors, etc. A scattered photons, as well as photo neutrons will be induced which requires a consideration of that in the beam lines shielding design. The hutch walls and beampipes need to be thick enough to attenuate the scattered radiation from these components. Different schemes for shielding the beam lines depending on the characteristics of the individual beam lines as well as the photon source characteristics, that is the scattered radiation source.

An induced activity generated mostly in the highly irradiated electron beamline components, cooling water of these components, air, shielding materials and ground. Activation in the accelerator system enclosure usually requires waiting period after shutdown before access by personal is allowed. The air activation can also be minimized by using ventilation system.

5. Radiation Monitoring and Personnel Protection System

A proposed scheme for the radiation monitoring program which includes two distinct phases, the first consists of extensive radiation measurements during the initial startup period to ensure that the assumptions used in shielding calculations were appropriate by comparing the calculations with measurements of the radiation level so as to uncover any potential weak points in the shielding. The second phase will take place after the initial startup phase, during normal operation. Its purpose is to ascertain that the accumulated dose at the surface of the shielding does not exceed the design value of 5 mSv/ year. A radiation monitors around the storage ring and the booster enclosures will be used for accumulated dose measurements and dose rate over short intervals.

Furthermore, a personnel protection system which consists of electrical interlocks must be used. It prevents personnel from entering radiation safety enclosures of the accelerator system when an electron beam is operating in the rings. The interlocks also serve to shut off the radiation source if any of the gates into one of the enclosures are opened when the beams are on.

6. Conclusions

It can be seen for the different types of shielding above that with our assumptions on beam losses, the designed shielding, will give a sufficient radiation protection. In particular, the annual dose at any point in the facility, even immediately outside the shield, will be kept below 5 mSv.

Furthermore, the shielding calculations for the booster were made as a separate accelerator even though the access to the storage ring is not permitted while the booster or the microtron is running.

In table (3.2), the detailed shielding thickness of SESAME accelerator system.

Table 3.2: Details of SESAME shielding thickness

Accelerator	Wall	Shielding Material
Microtron & Booster	Outer wall at injection outer wall elsewhere	1 m Ordinary concrete 80 cm Ordinary concrete
Storage ring	Inner wall Outer wall • Side wall • End wall Roof	20 cm Ordinary concrete 80 cm Ordinary concrete 1 m Ordinary concrete + 20 cm lead 40 cm Ordinary concrete

References

[1] D. Einfeld, et. al., "*The new upgrade of SESAME*", Proceeding of EPAC 2002, Paris, France.

[2] Å. Andersson. "*Some notes on radiation protection at electron accelerator*", Internal Report, MAX-Lab, Lund.

[3] "*Shielding for high energy electron accelerator installations*", Handbook 97, US department of commerce, National Bureau of standards.

[4] LLS Detailed Design Report, December 1997.

[5] H. Dinter, K. Tesch., "*Dose and shielding parameters of electron-photon stray Radiation from high energy electron beams*", Nuclear Instruments and Methods, 143 (1977), pp 349-355.

[6] W. Steifler, "*Shielding considerations for MAX*", Internal Report, Nov.1981.

[7] K. Tesch, "*Data for simple estimates of shielding against neutrons at electron ccelerator*", Particle Accelerators, Vol. 9 (1979), pp201-206.

[8] Å. Andersson, et.al. "*esign Report for MAX-II Ring*", ISSN 0284-1258.

[9] G. Bathow, E. Freytag and K. Tesch. "*Measurements on 6.3 GeV electromagnetic cascades and cascade-produced neutrons*", Nuclear Physics, B2 (1967) pp 669-689.

[10] K. N. Sanosyan, et.al. "*Radiation safety considerations for CANDLE light source*" Proceedings of EPAC 2002, Paris, France.