Radiation estimations for SESAME storage ring tunnel

A. Hamad

Synchrotron-light for Experimental Science and Application in the Middle East (SESAME), ALLAN, Jordan
Adli.hamad@sesame.org.jo

Abstract

SESAME, Synchrotron-light for Experimental Science and Applications in the Middle East, under construction in Allan- Jordan will offer 2.5GeV, 400mA by the beginning of 2016, at SESAME the ALARA principle is applied by guaranteeing the radiation limits for non-exposed workers to be 1mSv/y which corresponds to 0.5µSv/h, for 2000 working hours per year, normal operation and accidental total losses radiation leakage were estimated using some well known empirical formulas across SESAME storage ring tunnel, includes Mazes, utility openings, skyshine and straight sections gas bremsstrahlung in addition to air activation.

1. Introduction

This document describes the shielding calculations only for storage ring of SESAME (Synchrotron-light for Experimental Science and Application in the Middle East) project using a set of empirical formulas for different locations. The SESAME accelerator facility Fig.1, currently under construction at Allan-Jordan and comprises:

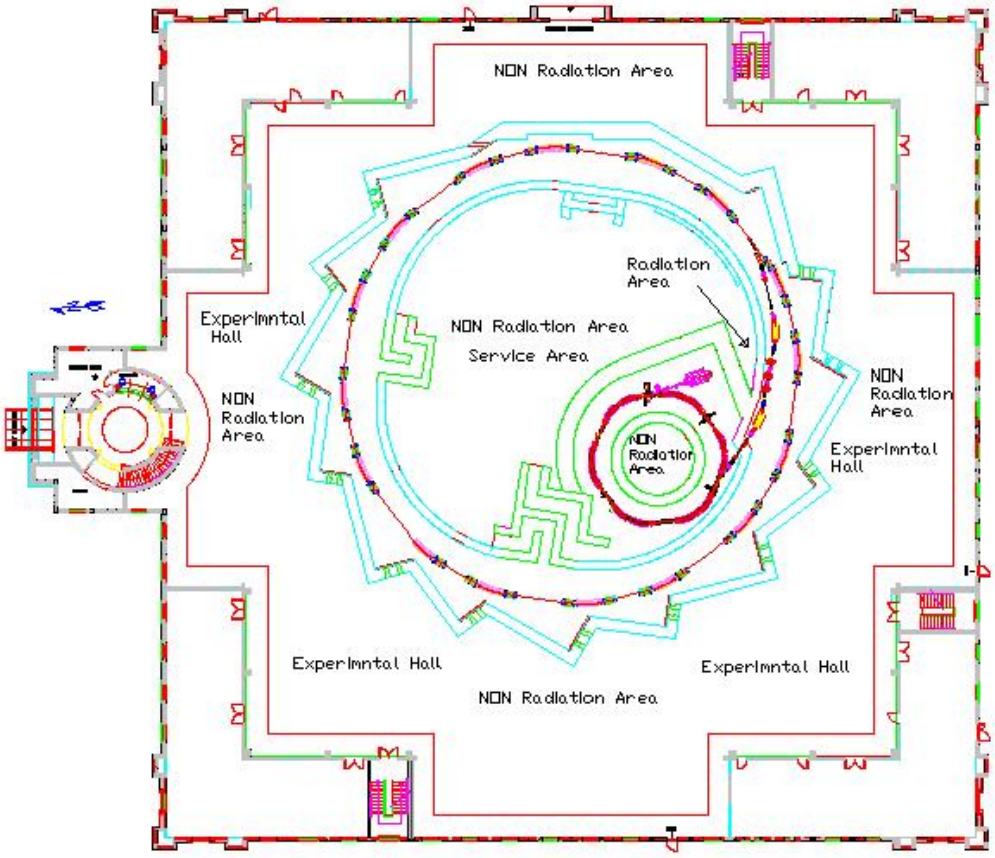

Fig: 1.a SESAME, Microtron, booster and Storage ring tunnels layout

1- A 22.5MeV circular microtron.
2- The transport line from microtron to booster (TL1)
3- A 800 MeV booster synchrotron.
4- The transport line from booster to storage ring (TL2).
5- A 2.5GeV storage ring.

Fig.1b: SESAME synchrotron

2. Shielding objectives

The basic principle of radiation protection is the ALARA (As Low As Reasonably Achievable) principle, which states that exposure to any person should be kept as low as reasonably achievable. At SESAME the ALARA principle is applied by guaranteeing the radiation limits for non-exposed workers (1mSv/y, corresponding to 0.5µSv/h, for 2000 working hours per year), except in controlled areas where access will not be possible during operation.

3. Shielding Calculation Methodology

The standard analytical shield models [1, 2, 3] (see appendixes 1 and 2) have been used for the SESAME shielding calculations. These standard models give an expression for the effective dose rate in a point behind a shield wall due to a local beam loss of a given power or number of electrons losses per unit of time:

4. Beam loss assumptions

The shielding estimates are based on conservation 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 experience and assumptions used at existing accelerator and synchrotron radiation facilities [5, 6]. The number of electrons per year stored in the storage ring is estimated as (a 400mA stored beam current in the 132.2 m long storage ring corresponds to 1.1 10^{12} electrons stored):

1. Normal operation:	
3 injections per day, 250 days operation per year	8.62 10^{14} electrons/year
2. Unwanted beam trips:	
Mean time between failure = 24 hours	2.75 10^{14} electrons/year
3. Accelerator R&D program:	
1 day per week, 10 injections per day	3.93 10^{14} electrons/year
Total number of electrons injected per year:	**1.5 10^{15} electrons/year**

Figure 2 shows the distribution of the corresponding beam losses throughout the accelerator facility.

Combining the loss scenarios of figure 1 with the total number of electrons stored per year, we obtain the average beam loss powers throughout the accelerator facility shown in figure 2.

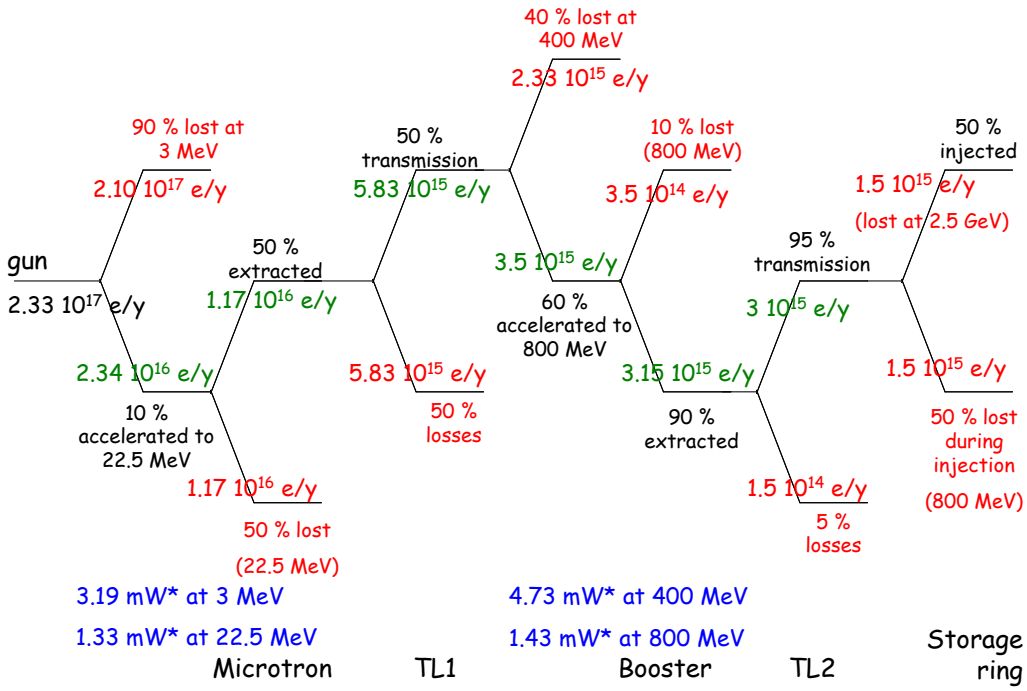

Figure 2 – Beam loss inventory used for shielding calculations

.

Note: the beam loss scenario given in figure 2 corresponds to the normal operation of the storage ring and do not include the commissioning phases of the different accelerators. Special attention will be given in the report to these commissioning phases.

5. Shielding Calculations for the Storage Ring

As a conservative assumption, we consider that all losses in the storage ring take place at 2.5GeV. The average total loss power in the storage ring then corresponds to 37.9mW (electron loss rate = 3 10^{15} electrons/ year, see figure 3).

The following beam loss distributions have been assumed for the shielding calculations of the storage ring:

80 % (30.3mW) of the total losses in any single point in the injection area.

10 % (3.79mW) of the total losses in any single point in any other point along the storage ring.

We use this local loss distribution pattern to calculate both average dose rates over one year **(total loss power 37.9mW)** and to calculate the integrated dose in case of a total beam loss **(total energy 441 J)**.

Storage ring area has been divided into 3 different shielding walls:

1- Outer S.R Shielding Wall (100 cm in thickness except 1.3m to 1.5m in the injection area and varies from 1.25m to 1.6m in the straight wall part in the direction of main service entrance).
2- Inner S.R Shielding Wall (80 cm in thickness except 1.25m in the injection area).
3- The Roof of the S.R tunnel, 100 cm (double overlapped ordinary concrete layers), except 1.5m (three overlapped concrete layers) in the injection area.

The same empirical formulas have been taken to anticipate the effective dose rates outside the storage ring shielding walls (bear in mind the background has been discarded for all expected values).

Table 1 shows the contact total dose rates (gamma and neutrons) just outside the outer S.R shielding walls forwardly in the direction of the experimental hall using analytical[1] and Swanson[2] formulas, taken in to account source to measure points are 9.5m and 11.35m for Short Straight Sections (SSS) and Long Straight Section (LSS) respectively.

Table: 1: Total dose rate in the forward direction at different locations for normal operation losses.

Radiation normal loss source in the direction of experimental hall	Total dose rate (μSv/h) in the forward directions using	
	Analytical [1]	Swanson[2]
SSS	202.08	302.3
LSS	288.44	431.4
LSS-Injection area	151.95	150.9

Table 2 shows the contact total dose rates (gamma and neutrons) just outside the outer S.R shielding walls laterally in the directions of the roof, experimental hall and service area using analytical [1] and Jenkins [3] formulas, taken in to account source to measure point distances are 2.3 m, 3m and 2m for the roof, experimental hall and service area respectively.

Table: 2: Total dose rate in the perpendicular directions for normal operation losses.

Normal radiation loss source (except injection area) in the direction of:	Total dose rates perpendicular to losses directions in (μSv/h)	
	Analytical [1]	Jenkins[3]
Exp. hall	0.44	0.42
Service area	0.77	1.4
Roof	0.44	0.94
Normal radiation loss source of the injection area in the direction of:	Total dose rates (μSv/h) perpendicular to losses directions	
Injection area normal loss (roof)	0.24	0.93
Injection area, normal loss (exp. hall)	0.24	0.65
Injection area normal loss (service area)	0.72	1.9

Table 1 and 2 give the following indications:

1. **Forward directions:**

Analytical formula [1] gives total dose rates, 202.08μSv/h for SSS, 288.44μSv/h for LSS case and 151.95μSv/h from the injection area towards service area.
Swanson formula [2] gives total higher dose rates 302.3μSv/h and 431.4μSv/h through SSS and LSS respectively and similar 150.9μSv/h from the injection area.

From above values we can see the needs of an extra 10 cm thickness of lead must be attached to the ratchet front ends ordinary concrete shielding walls to minimize the dose rates outside the front end concrete ratchet walls (see table.3) to be less than the pre designed value (0.5μSv/h).

2. **Perpendicular directions:**

Analytical formula [1] gives total dose rates less than 0.5μSv/h in the direction of roof, experimental hall and injection area (toward the service area) and less than 0.8μSv/h in the direction of service area.
Jenkins[3] gives less than 0.5μSv/h in the direction of experimental hall and less than 2μSv/h in the direction of service area and less than 1μSv/h from the injection area towards service area.

Table: 3: Total effective dose rate in the forward directions towards the Experimental hall at different locations with using 10 cm thickness of lead (±20cm around electron beam height) attached to front end concrete ratchet walls for normal operation losses.

Normal Radiation loss source	Total dose rate in forward directions with 10 cm in thickness of lead in (μSv/h)	
	Analytical (1)	Swanson(2)
Short straight Section	0.23	0.25
Long straight section	0.32	0.35
LSS-Injection area	0.17	0.14

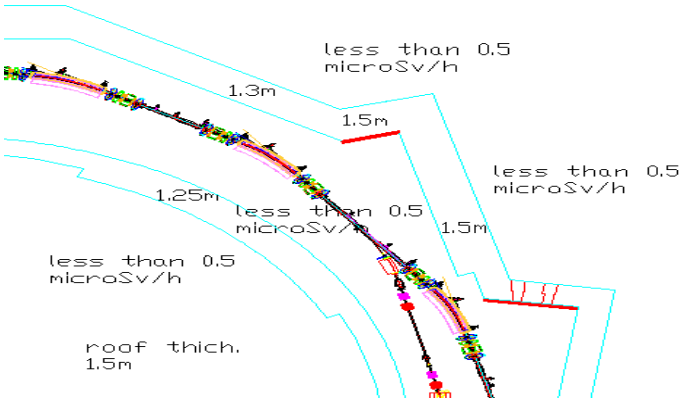

Fig.3: Total dose Rates around Injection Area.

6. Storage Ring Tunnel shielding walls Recommendations for normal operation:

- ✓ 1m O.C plus 10 cm of lead in thickness (±20cm around electron beam height) attached to the front end concrete ratchet walls will fulfil our needs (Table.3).
- ✓ 1m O.C for the ratchet side walls and 0.8 m thickness of ordinary concrete for inner storage ring shielding wall is enough.
- ✓ 1.25m, 1.5m and 1.5 m for inner, outer and front end OC ratchet walls of the injection area respectively.
- ✓ 1m O.C (double overlapped layers) for the roof all over the storage ring tunnel except 1.5m (triple overlapped layers) for the injection area is fulfil.

Finally SESAME general strategy during commissioning or normal work:

1- Start with mentioned (Initial) thicknesses for both concrete and the lead
2- Monitor, measuring instantaneous effective dose rates, passive area monitors will also be used to integrate doses in various areas and evaluate during commissioning via complete controlled system.
3- Extra thicknesses will be added if needed to get non radiation areas (≤ 0.5μSv/h coming only from radiation losses, however, keeping in mind there is, any way, the background which is not included in our estimations) looks like:
   a- Service area.
   b- Storage Ring Roof.
   c- Injection area (Fig.3).
   d- Experimental Hall.
4- Keeping some areas as controlled areas (> 0.5μSv/h).
5- Single losses must be taken into account in the future works.

7. Bremsstrahlung Source Estimates in the ID Beamlines

Gas bremsstrahlung is produced by interaction of the storage ring electron beam with residual gas molecules in the ring vacuum chamber. Such interactions are sources of stored beam loss, which results in beam decay and occurs continuously during storage ring operation. Gas bremsstrahlung interactions take place all around the storage ring, but are a particular problem in the straight sections for the insertion devices. Gas bremsstrahlung is produced in a very narrow beam in the straight path and sums up for the entire straight path in the line of sight of the beamlines. SESAME straight sections have two cases, see sesame parameters; table (4), the first case is using LSS with 6.7m short distance and SSS with 9.25m long distance.
To have both conservative conditions (LSS with short distance is another option)

Table.4: SESAME front ends parameters

Energy	2500 MeV
Current	400mA, 2.5E18e/s
Long straight section (LSS)	7.1m
Short straight section (SSS)	5.05m
ID vacuum chamber pressure	2e-7 Pa
Distance to Safety shutter	9.25m for SSS
	7.35 m for LSS
Real distance to ratchet wall	10.35m for SSS 8.5m for LSS

The first expression developed in this regard is by Rindi and Tromba [8]. This simple expression provides the dose rate in Sv/h at 10 meters (like our case ~9.25m) from the straight path as

$$\dot{D}_0 @10\text{m} = 1.7\times10^{-16}\cdot E^{2.43}\cdot L\cdot I\cdot\frac{p}{p_{atm}} \qquad (1)$$

Where L = effective length of the straight path, I = beam current in e/s (2.5×10^{18} electrons/s for 400mA), E = electron beam energy (2500MeV), P = operating pressure in the vacuum chamber (1.97E-12*atm*) and *Patm*= atmospheric pressure. This expression yields a primary bremsstrahlung dose rate of 1.074Sv/h and 0.764 for LSS and SSS respectively.
Another analysis developed by Ferrari[9] et al., gives the following expression for dose rate produced by the primary bremsstrahlung in the ID beamlines at a distance of L from the straight path (for photon energies ranging from 100MeV to 1GeV):

$$\dot{D}_0(\text{Sv/h}) = 2.5\times10^{-27}\cdot\left(\frac{E}{mc^2}\right)^{2.67}\cdot\frac{L}{d(L+d)}\cdot I\cdot\frac{p}{p_0} \qquad (2)$$

Where l = effective length of the straight path, I = beam current in e/s (2.5×10^{18} electrons/s, E = electron beam energy (2500) MeV, P = operating pressure in the vacuum chamber 2e-7Pa, and *P0*= 1.33e-7Pa. This equation yields a primary bremsstrahlung dose rate of 4.5Sv/h and 2.5Sv/h for LSS and SSS respectively.

The semi-empirical equation proposed by Frank [10] had been successfully utilized at the Advanced Photon Source and other similar facilities. Using the equation developed by Frank, the dose rate due to primary bremsstrahlung is described as at a distance L from the end of the straight path is

$$\dot{D}_0(\text{Sv/h}) = 3\times10^{-6}\cdot\left(\frac{E}{mc^2}\right)^2\cdot\frac{L}{d(L+d)}\cdot\frac{I}{\pi X_0} \tag{3}$$

Where X_0 = radiation length of air at 10^{-9} Torr equal to $2.34e^{16}$ cm, L = effective length of the straight path, I = beam current in e/s, and E = electron beam energy in MeV. This equation yields a primary bremsstrahlung dose rate of 1.6Sv/h and 0.9Sv/h for LSS and SSS respectively.

Table 5 shows three results using the mentioned formula for two cases, we can see the matching between Randi, Tromba and Frank and to be conservative we will go the worst estimated number which is Ferrari and this assumption will be used for bending magnets beamline as well.

Table: 5 Total dose rates just before Safety shutter

Empirical formula used	**Bremsstrahlung Dose Rate (Sv/h) LSS**	**Bremsstrahlung Dose Rate (Sv/h) SSS**
Rindi and Tromba	**1.074**	**0.764**
Ferrari	**4.5**	**2.5**
Frank	**1.6**	**0.9**

To see how much tungsten will be used as a safety shutter to have below than 0.5µS/h just next to the safety shutter, simple attenuation formula can be used,

$$\dot{D}_A = \dot{D}_0 \times \exp\left(-\mu\cdot\rho\cdot t\right) \tag{4}$$

Where:
D_0: is the dose rate just before the shatter in Sv/h.
D_A: is the dose rate just after the shatter in µSv/h.
ρ: tungsten density ~ 19 g/cm^3 (depends on used W alloy)
µ: Minimum photons attenuation coefficient, 0.0402cm^2/g.
t: Tungsten length in cm.

Table (6) shows the difference in the estimated values using three different empirical formulas

Used formula	Dose rates After 20 cm safety shutter LSS in µSv/h	Dose rates After 20cm safety shutter SSS in µSv/h
Rindi and Tromba	**0.25**	**0.177**
Ferrari	**1.04**	**0.58**
Frank	**0.37**	**0.21**

We think 20 cm tungsten block (alloy) thickness is enough to stop gas bremsstrahlung radiation from being entering in to FOE's of both bending magnets and ID beamlines taken in consideration low rate of occupancy close to the ratchet wall and decay mode of operation.

8. Radiation streaming from SESAME storage ring mazes

Storage ring tunnel has two mazes each, see Fig.(4) contains four clear legs with cross sections (1.2m×2.7m) the legs length in a series order is 3.4m, 2m, 2m and 3m. The calculations were taken in both single loss and normal losses scenarios.
Empirical formula [11] (see Fig.4) were taken in our calculations and all the expected values were within the predefined value which is 0.5 μS/h for normal losses and even for single beam lost the expected reading is very low value.
The leakage dose outside the maze can be calculated using an empirical formula given by [11].
For the first leg, gamma ray dose attenuation ratio, γ_1 is

$$\gamma_1 = 0.22 \times (\mathrm{d} + \mathrm{L}_1)^{-3} \tag{5}$$

And

$$\gamma_i = 0.26 \times (\mathrm{d} + \mathrm{L}_i)^{-3} \quad \text{(i=2, 3…) for other legs} \tag{6}$$

While for neutrons

$$N_i = 2 \times \exp(-\mathrm{L}_i / 0.45) + 0.022 A_i^{1.8} \times \exp(-L_i / 2.35) / 1 + 0.022 A_i^{1.8} \tag{7}$$

Where i=1, 2,…
And
Li : the length of the **i**th leg in m.
d : the half width of the maze leg in m.
A_i : the cross section of maze leg in m^2.
For the last leg, the factor 2 in formula is removed.

Table: 7. Total gamma and neutron dose rates and accumulated doses at exit doors

Losses scenario @Exist (door)	**Formula** [11]
Normal losses in μS/h	0.0026
Single losses in μS	0.088

From table 7 we can see that the dose rates just at the exit door of the storage ring maze is less than 0.5 μS/h for empirical which means that such deign of this maze is effective and we can see the difference at single loss scenario which still safe.

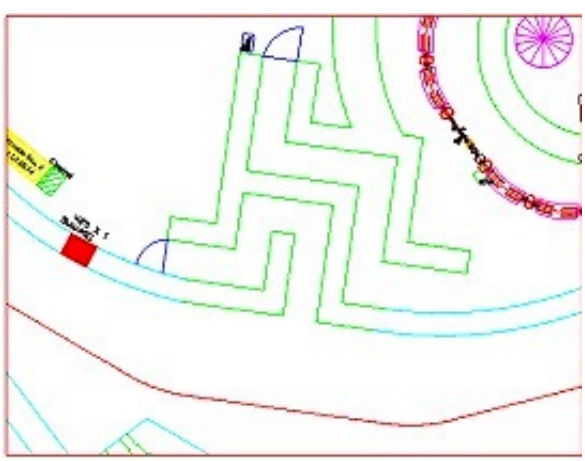

Fig. 4 shows storage ring maze.

9. Estimates of Skyshine

Neutron skyshine is, in most cases, the dominant source of radiation exposure to the general public from operation of well-shielded high-energy accelerators.
Some skyshine radiation will be produced at any point in the storage ring, where 1.1E12 electron beam will be lost as the worst case each time.
The skyshine dose rates due to neutron radiation are calculated using the method developed by Rindi and Thomas [12]. The unshielded neutron dose at the concrete roof is taken as the source term. The skyshine dose rate at a given distance is calculated by the following algorithm.

$$\dot{D}_0(\mu\text{Sv/h}) = a \times \left(\frac{D_0}{r^2}\right) \times e^{-r/\lambda} \tag{8}$$

Where **a** = 7 (constant), $\mathbf{D_0}$ = unshielded dose rate on the concrete roof (source term), **r** = distance of the dose point from the source in meters, and **λ** = 3300 meters, effective air attenuation factor.
For conservative case **1.5E+15** e/y (~1370 injections/y including normal operation, accidental beam losses and machine day losses) will be extracted to the storage ring and were lost at full 2.5GeV.
Table (8) gives the calculated skyshine estimates at 50 and 100 meters from common single storage ring lost point over one full year of operation and we can see all values are under tolerable absorbed dose level for public.

Table: 8. Skyshine dose along 1 year at 50m and 100m from SESAME roof.

Neutron source Component	Dose rate on the concrete roof mSv/y	Skyshine Dose at 50 m mSv/y	Skyshine Dose at 100 m mSv/y
Giant resonance neutrons	**2.518**	**0.00694**	**0.00171**
High-energy neutrons	**2.555**	**0.00704**	**0.00173**
Total skyshine dose	**5.073**	**0.01398**	**0.00344**

10. Cabling and cooling duct radiation streaming

Simon-Clifford formula [12] has been used to estimate the leakage dose rates just outside the cabling ducts (Fig.5) coming from losses just opposite the loss point and the rectangular ducts have been taken as circular ducts.
All SESAME cabling ducts are at floor level with different Width (10 to 100cm) and height varies from 10 to 20 cm and different lengths (80-120cm) the dose rates at the duct surface centers are calculated based on some well known formula[1,3].

Fig.5a: Real SESAME duct

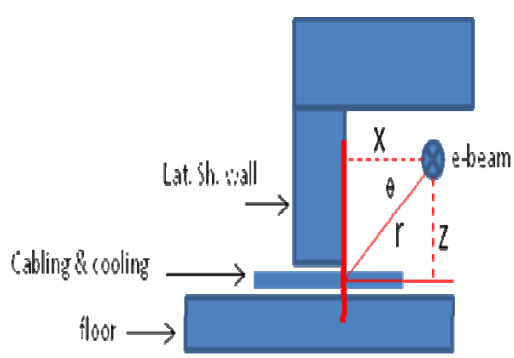

Fig.5b. Cross section @ duct center

$$\dot{D}_N(\mu Sv/h) = \dot{D}_{N_0}(\mu Sv/h) \times F_1 \times \alpha_N \times F_{2N} \times \left(\frac{1}{4}\right) \cdot \left(\frac{d}{L^2}\right)^2 \quad (9)$$

$$\dot{D}_\gamma(\mu Sv/h) = \dot{D}_{\gamma_0}(\mu Sv/h) \times F_1 \times \alpha_\gamma \times F_{2\gamma} \times \left(\frac{1}{4}\right) \cdot \left(\frac{d}{L^2}\right)^2 \quad (10)$$

Where:
D_N^0, D_γ^0: Neutron and gamma dose rates at duct entrance center surface respectively.
D_N, D_γ: Neutron and gamma dose rate at duct exit center surface respectively.
d: duct diameter in cm.
L: duct length (depth) across shielding in cm.

$$F_1 = \cos\theta = x/r = x/(x^2 + z^2)^{1/2} \quad (11a)$$

θ: angle between the radiation source to duct surface center line and the plane which contains the entrance surface of air duct.

$$F_{2\gamma} = 1 + \left\{\left(\frac{d}{2}\right)/(\mu_\gamma / \cos\theta)\right\}^{-1} \quad (11b)$$

$$F_{2N} = 1 + \left\{\left(\frac{d}{2}\right)/(\mu_N / \cos\theta)\right\}^{-1} \quad (11c)$$

μ_N, μ_γ = linear attenuation coefficient, 13.7cm and 18.9 cm for neutron and gamma respectively.
α_N, α_γ: Albedo coefficients (0.1) for neutron and (1.0) for gamma respectively.
Table (9) shows the leakage dose rates using an empirical formula only for steel bremsstrahlung radiation loses and using Simon-Clifford empirical formula for some cable and cooling ducts only for storage ring, for normal work operation (10% losses) and single loss dose (100% losses) and one point in the injection area (80% losses), we can notice that there are some high levels of radiation in the service area and very close to radiation, so some irregular shielding material must be added among cables and cooling pipes and some shadow shielding from inside storage ring tunnel in worst cases must be effective and tested experimentally during commissioning periods.

Table: 9. Dose rates at duct entrance and exit for some cabling and cooling ducts

Duct dimensions W×H×L	Total dose rate normal operation @ inside duct surface center in µSv/h	Total dose Single loss @inside duct surface center in µSv	Total dose rate/ normal loss operation @ outside duct surface center in µSv/h	Total dose Single loss @outside duct surface center in µSv
	Anal. (1)	**Anal. (1)**	**Si-Cl (12)**	**Si-Cl (12)**
100,20, 80	53.12	1711.67	2.86	92.23
60,20,80	53.12	1711.67	1.917	61.727
80,20,80	53.12	1711.67	2.399	77.241
50,20,80	53.12	1711.67	1.668	53.7
20,20,80	53.12	1711.67	0.854	27.5
10,15,120 [a]	424.93	1711.67	1.567	6.31
R=5cm[b]	74.71	2407.35	0.193	6.2
R=5cm[c]	90.30	2909.96	0.233	7.5

a: injection area,
b: Visible beam line opening centered at 30 cm above floor, 10cm diameter.
c: IR beamline opening centered at 70 cm above electron beam height, 10 cm diameter.

11. Air Induced Activity

High energy electron accelerators are considered as a source of radioactive materials including equipment, concrete, water and air.

Estimates of induced activity in any of such material can be made from data available in literature expressed in terms of saturated activity As per unit electron beam power and per electron power and per electron power and path length for air.

Extensive listing As values for different materials has been compiled by Swanson (2), in table (10) saturation activity for air nuclides for sesame case where the losses power during normal work is 3.79E-06 Kwatt and the largest path length of radiation in air is about 11 m. in practice mixing of air will occur due to the forced ventilation provided, reducing the activity significantly and use of local shielding close to known loss points will minimize path length of radiation in air and hence reduce the activation yield.

Table: 10. Saturation activity in Bq through SESAME storage ring enclosure.

Produced nuclide	$T_{1/2}$	As (Saturation activity) ($Bq.m^{-1}kw^{-1}$)	Saturation activity in SESAME (Bq)
H-3	**12.262y**	**5×10^6**	**208.45**
Be-7	**53.6 d**	**1×10^6**	**41.69**
C-ll	**20.34 m**	**19×10^3**	**0.792**
N-13	**9.96 m**	**520×10^6**	**21678.8**
O-l 5	**123 s**	**56×10^6**	**2334.64**
N-16	**7.14 s**	**20×10^3**	**0.8338**
Cl-38	**37.29 m**	**220×10^3**	**9.1718**
Cl-39	**55.5 m**	**1.5×10^6**	**62.535**

References:

1- Berkvens P., 14/02/2000, Shielding requirements for the Singapore Synchrotron Light Source, internal report.

2- Swanson W.P., Radiological Safety Aspects of the operation of Electron Linear accelerators. IAEA, Technical report Series No. 188, 1979.

3- Jenkins T.M., Neutron &photon measurements through concrete from a 15GeV electron beam on target; Comparison with models and calculations, Nucle. Instr. &Methods 159(265) 1979.

4- Special contact (Dr. Paul Berkvens, head of the Safety group at ESRF, Grenoble, e.mail: Berkvens@esrf.fr)

5- G.V. Egan- Krieger, D. Einfeld. W.-D. klotz, H. Lehr, R. Maier, G. Mulhaupt, R. Retcher and E. Weihreter. IEEE Transaction on nuclear science. Vol. NS-30, No. 4, August 1983.

6- Hubble,J.H., Photon Cross Sections and Attenuation Coefficients from 10 KeV to 100GeV,NSRDS-NBS 20 (1969).

7- Tromba, G. and A.Rindi, "Gas bremsstrahlung from Electron Storage Ring," Nucl.Instr. & Meth,. A292 (1990).

8- Ferrari, et.al., Estimation of Gas bremsstrahlung, Health Physics, 68 (1995).

9- Frank, J.C., LURE EP 88-01 (1988).

10- K.Tesch, "Attenuation of the PHOTON Dose in Labyrinths and Duct Accelerators", Radiation Protection Dosimetry 20 169 (1987

11- Rindi, A. and R.H. Thomas, "Skyshine - A Paper Tiger," *Particle Accelerators* **7** (1975).

12- Y.Asano & N.Sasamoto., Radiation Shielding and safety analysis for SPring-8", JAERI-Tech 98-009

APPENDICES

Appendix-1

The standard analytical shield model has been used for the SESAME shielding calculations. This standard model gives an expression for the effective dose rate in a point behind a shield wall due to a local beam loss of a given power:

$$\dot{E} = \sum_r \frac{C_r \times P \times \prod_i e^{-\frac{d_i}{\lambda_{i,r}}}}{R^2} \qquad (1)$$

With:

$\dot{E}$: Effective dose rate, in $Sv \cdot h^{-1}$
C_r: the conversion factor for the rth type of radiation, in $Sv \cdot h^{-1} \cdot kW^{-1} \cdot m^2$
P: the electron loss power, in kW
R: the distance between the loss point and the point of observation, in m
d_i: the effective thickness of the ith wall, in cm
$\lambda_{i,r}$: the attenuation length of the material of the ith wall for the radiation of type r, in cm

The following conversion factors are used ($Sv \cdot h^{-1} \cdot kW^{-1} \cdot m^2$):

Gamma dose rate at 0 degrees: $C_{g,0} = 300 \times E_0$, with E_0 the electron energy in MeV
Gamma dose rate at 90 degrees: $C_{g,90} = 50$
Giant resonance neutrons: $C_{GRN} = 10$
High energy neutrons: $C_{HEN} = 1.55$

The radiation attenuation lengths λ_r used for the materials in the current shielding calculations are given in Table 11. These data have been obtained from various references[1'6].

Table:1. Attenuation lengths and densities for different shielding materials

Shielding material	Density (g/cm^3)	Attenuation length (cm) for Gamma	Attenuation length (cm) for (GRN)	Attenuation length(cm) for (HEN)
Ordinary Concrete	2.30	21.3	17.4	27.66
Pb	11.35	2.2	14.2	16.8
Steel	7.87	4.3	12.7	17.5

Appendix-2

Swanson [2] gives leakage dose rates of gamma ($E_e \geq 1GeV$) and neutrons ($E_e \geq 50MeV$) in forward direction as follows:

$$\dot{E}_{\gamma} = \sum_{r} \frac{10^{6} \times E_{e} \times P \times \prod_{i} e^{-\frac{d_i}{\lambda_{i,r}}}}{R^{2}} \tag{2}$$

$$\dot{E}_{HEN} = \sum_{r} \frac{4 \times P \times \prod_{i} e^{-\frac{d_i}{\lambda_{i,r}}}}{R^{2}} \tag{3}$$

$$\dot{E}_{GRN} = \sum_{r} \frac{22.7 \times P \times \prod_{i} e^{-\frac{d_i}{\lambda_{i,r}}}}{R^{2}} \tag{4}$$

Where:

$\dot{E}$: Effective dose rate, in $Sv \cdot h^{-1}$
P: the electron loss power, in kW
d_i: the effective thickness of the ith wall, in cm.
R: the distance between the loss point and the point of observation, in m.
$\lambda_{i,r}$: the attenuation length of the material of the ith wall for the radiation of type r, in cm.
Attenuation coefficients are summarized in table (2).

Table: 2. Attenuation length for different shielding materials in forward direction

Shield material	**Attenuation length (cm)**		
	λ□	**λ_{HEN}**	**λ_{GRN}**
Lead	**2.1**	**66.7**	**23.8**
Ordinary Concrete (2.3g/cm^3)	**18.2**	**40.0**	**16.9**
Iron	**4.5**	**58.8**	**18.5**

While Jenkins formula [3] gives lateral dose rates for both gamma and neutron at $E_e \geq 150MeV$ and $\leq 20GeV$ and angle $\theta \geq 30^0$ and $\leq 130^0$.

$$\dot{E}_{\gamma} = 3.6 \times 10^{-14} \times J \times E_{e} \times \frac{1}{R^{2}} \times \left(\frac{133 \times \prod_{i} \exp(-d \cos ec\phi / \lambda_{ir})}{(1 - 0.98 \cos\theta)^{1/2}} + \frac{f1 \times 0.267 \times \prod_{i} \exp(-d \cos\phi / \lambda_{ir})}{(1 - 0.72 \cos\theta)^{2}} \right) \tag{5}$$

Also,

$$\dot{E}_n = 3.6\times10^{-14}\times J\times E_e\times\frac{1}{R^2}\times\left(\begin{array}{l}\dfrac{f_1\times\prod_i \exp(-d\cos ec\phi/\lambda_{HEN})}{(1-0.72\cos\theta)^2}+\\ \dfrac{f_2\times10\times\prod_i \exp(-d\cos\phi/\lambda_{IEN})}{(1-0.75\cos\theta)}\\ +3.79\times Z^{0.73}\times\prod_i \exp(-d\cos ec\phi/\lambda_{GRN})\end{array}\right) \quad (6)$$

Where:
E_e: electron energy in GeV
Z: atomic number of the shielding material.
λ_{GRN}, λ_{IEN} and λ_{HEN} Attenuation lengths for giant resonance, intermediate energy and high energy neutrons respectively for different shielding materials, see table (3).

Table: 3.Attenuation length for different shielding materials in lateral direction

Shielding material	**Density g/cm^3**	**Attenuation Length (cm)**			
		$\lambda_{\square}$	**λ_{GRN}**	**λ_{IEN}**	**λ_{HEN}**
Lead	**11.3**	**2.1**	**10.0**	**18.3**	**22.7**
Iron	**7.8**	**4.3**	**6.8**	**12.4**	**21.3**
O.C	**2.3**	**18.1**	**13.1**	**23.9**	**52.2**

J: number of electron loss in second.
θ and φ are the inclined degrees from the electron beam axis to a measurement point and the shield material respectively.
f_1, f_1 : corrections factors of a source reduction for high and intermediate energies (<5GeV).