DIAMOND BEAM LOSSES: SHIELDING IMPLICATIONS IN A MODERN LIGHT SOURCE

M W Poole, R Ryder, V P Suller, N G Wyles, CLRC Daresbury Laboratory,
Warrington WA4 4AD, UK

Abstract

Radiation safety legislation has evolved to produce ever stricter restrictions on dose rates surrounding modern particle accelerators. The selection of the type and thickness of necessary radiation shielding is a critical task that is dependent on an assessment of the various beam loss scenarios, perhaps over a wide range of operating scenarios. In the case of a light source such as DIAMOND the shielding dimensions have a critical impact on the layout of its beam lines and consequently on the size of the building; there is a major cost implication arising from this design exercise. This paper discusses the assumed loss models, both for injection processes and stored beams, and presents the resulting DIAMOND shielding design.

1. ASSUMPTIONS FOR LOSS RATES

Radiation shielding calculations have been carried out at all points in DIAMOND using the local electron loss rates. These have been estimated from assumptions of electron transfer efficiencies through the accelerator systems. In addition estimates have been required of the amount of time that would be spent in any given operating condition.

The locations at which electrons are expected to be lost can be logically subdivided by accelerator section. The assumed transfer efficiencies for these locations under standard operating conditions are shown in Table 1. In fault conditions the transfer efficiency at the relevant point is assumed to be 100% loss.

Table 1: Transfer efficiencies under normal operating conditions by location.

Location of electron loss	**Transfer efficiency**
Gun to Linac	0.1
Linac	0.9
Linac to Booster Transfer	0.5
Booster Injection	0.5
Booster Acceleration	0.9
Booster Extraction	0.5
Booster to Storage Ring Transfer	1
Storage Ring Injection	0.5

The stored beam current for the DIAMOND design [1] is specified as 300 mA, and with an assumed stack rate of 1 mA/s, this gives a fill time of 300 s. It is also assumed that the beam will be stored for 12 hours (two refills per day) with an exponential lifetime of 10 hours.

In the storage ring the losses at the septum from injection and the losses elsewhere need to be assessed separately. Under normal operating conditions, 80% of the losses due to injection are assumed to take place at the septum, with the remaining 20% lost elsewhere around the ring. Injection is assumed to take place for 2 periods each day on 240 days per year.

Abnormal conditions include periods of machine development study and optimisation of parameters. In these conditions - where it is assumed the whole beam is lost during injection - the losses at the septum are assumed to be quantitatively the same as under normal operating conditions i.e. 40% of the total loss; the remaining 60% is assumed to be lost elsewhere (and all at one location). The duration of injection and abnormal conditions per year is assumed to be 250 hours.

2. CALCULATION OF LOSS RATES

2.1 Overall Loss Rates

Overall loss rates need to be calculated for the three main modes of operation: stored beam, injection and abnormal conditions (optimisation and study).

For the purposes of radiation shielding calculations the peak loss rate of the stored beam due to lifetime processes (giving the maximum dose rate) is the appropriate value to use, since occupancy can occur at any time. The peak loss rate from a stored beam is 9.72×10^7 electrons per second.

The loss rate during injection is the sum of the losses at all the different points in the system; it is also the difference between the rate of injection from the gun and the rate of injection into the storage ring. This gives a value of 2.30×10^{12} electrons per second during a refill. The loss rate of low energy (100 MeV) electrons is the loss rate of all the electrons that are not accelerated by the booster; this is 2.26×10^{12} electrons per second during a refill. All other losses during a refill are assumed to be at 3 GeV, i.e. electrons lost during or after the booster acceleration process. This gives a loss rate for electrons at 3 GeV of 4.03×10^{10} electrons per second during a refill.

The loss rate when studies or optimisation is being carried out is assumed to be equal to the rate of injection from the gun: this is because all the beam that is emitted from the gun is assumed to be dumped somewhere. This loss rate is 2.31×10^{12} electrons per second; again however, it is the losses at 3 GeV which are important. The loss rate of 3 GeV electrons is taken to be all the electrons that make it to the booster: this gives a loss rate for electrons at 3 GeV of 5.20×10^{10} electrons per second.

It is assumed, importantly, that normal efficiencies are maintained in the accelerator chain before booster acceleration to 3GeV. Increased efficiency over the normal rates, or over-running of components (such as increased booster current) is assumed to be taken into account by the fact that total loss will not take place over the entire operating period of studies. It is assumed that occupancy outside shielded areas is such that an average rate of loss is seen, using radiation monitors and interlocks if necessary to control injection under these conditions.

2.1 Loss Rates at Individual Locations

The previous section details overall losses throughout the accelerator; however, losses at individual points within the system are also important. The loss rates at each location can be simply calculated from the rate of injection from the gun and the transfer efficiency at each point.

The loss rates for normal operating conditions are shown in Table 2. The loss rates for abnormal conditions (where all the electrons are assumed to be lost at one point) are shown in Table 3.

Table 2: Electron loss rates under normal operating conditions.

Location of electron loss	**Loss rate (electrons per second)**
Gun to Linac	2.08×10^{12}
Linac	2.31×10^{10}
Linac to Booster Transfer	1.04×10^{11}
Booster Injection	5.20×10^{10}
Booster Acceleration	5.20×10^{9}
Booster Extraction	2.34×10^{10}
Booster to Storage Ring Transfer	0
Storage Ring Injection Septum	9.35×10^{9}
Storage Ring Injection Elsewhere	2.34×10^{9}

Table 3: Electron loss rates under abnormal operating conditions.

Location of electron loss	**Loss rate (electrons per second)**
Booster Injection	1.04×10^{11}
Booster Extraction	4.68×10^{10}
Storage Ring Injection Septum	9.35×10^{9}
Storage Ring Injection Elsewhere	1.40×10^{10}

3. SHIELDING MODEL

A revised SHIELD11 [2] model has been used to calculate the required shielding, as shown in fig 1. This model has been revised to use only the direct gamma component, GAMD, resulting from the photons escaping from the electromagnetic cascade in the target and the HEN and GRN neutron components corresponding to the photo-pion and giant resonance reactions. The expressions used for the source terms and attenuation of the three radiation components considered have been taken directly from the original FORTRAN source code.

4. SHIELDING MATERIAL

Ordinary concrete was selected as the material for the linac and booster walls and roof, the inner wall and the

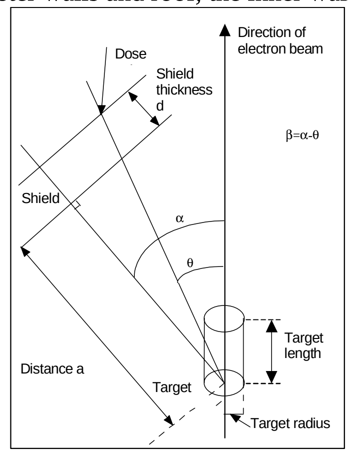

Figure 1. Loss point and shielding geometry

roof of the storage ring. It was decided to use a higher density concrete than ordinary with a larger atomic number for the outer wall of the storage ring, because of the advantage to the beamline area of a thinner wall. The types of concrete, their densities, the volumes of concrete and the associated costs for the storage ring outer wall are described in Table 4.

Table 4. Shielding materials.

Type of concrete	Density tonnes.m^{-3}	Volume used m^3	Cost* £ m^{-3}
Ordinary	2.3	3260	0.264
Barytes	3.5	2190	1.021
Haematite	3.5	2190	4.525
‘heavy iron’	4.5	1470	3.052

* At 2000 prices.

It was decided that barytes concrete was the best compromise of cost and minimum thickness of shield. The attenuation coefficients used are shown in Table 5.

Table 5. Attenuation coefficients of shielding materials.

	Attenuation Coefficients m^{-1}		
	Ordinary concrete	Barytes concrete	Lead
Bremsstrahlung	5.50	8.0	47.0
Giant Resonance Neutrons	5.90	7.50	4.00
High Energy Neutrons	2.60	3.20	5.70

5. DOSE LIMITS

The Ionising Radiations Regulations, 1999 [3] require exposure to ionising radiation to be restricted to be As Low As Reasonably Practicable (ALARP). The annual effective dose to employees and members of the public must not exceed 20 mSv and 1mSv respectively. Most statutory obligations are met and bureaucracy considerably reduced if an annual dose limit of 1 mSv is adopted. This annual dose limit of 1 mSv was interpreted to mean that a person working around the accelerator should not receive more than 1mSv per year. For a storage ring operating for around 6000 hours a year and assuming a person works 2000 hours a year, an occupancy factor of 3 has been agreed to be conservative. The annual dose immediately outside the shielding is therefore calculated to be less than 3mSv.

An annual dose of 1mSv is only 5% of the permitted dose limit for employees. This is an over-estimate because it is highly unlikely that a person would spend 100% of their time around the accelerators and geographically the dose rate will be less further away from the shielding. It is considered to be ALARP. To decrease the dose further would considerably increase the cost and place constraints on the width of the fan of synchrotron radiation that is designed to pass into the experimental areas.

Using a shielding design limit of 3mSv for 6000 hours operation a year will ensure that the annual dose to the public offsite will be less than 1mSv, even for 8760 hours occupation a year.

6. SHIELD DESIGN

A scheme has been drawn up (Table 6) which uses a combination of barytes concrete and lead for the outer shield wall of the storage ring. For a 24 cell storage ring, the beamlines initially diverge away from the electron beam at only 7.5 degrees. The position and thickness of the end and side walls of the ratchet constrain the width of the fan of synchrotron radiation which can pass through the shielding. The proposed scheme allows radiation fans of 25 mrad and 10 mrad from the dipole and insertion device beamlines respectively to pass through the shield wall without the use of optical elements located inside the shield. It would be possible to reduce the thickness of the concrete and avoid the use of costly lead by using iron loaded concrete with a density greater than 3.5 tonnes/m^3. However, this alternative would be much more expensive than barytes concrete.

Cast concrete will be used for the shielding except for the storage ring roof, which will be made from removable blocks to allow access to the ring for large items of plant. These blocks will be designed in at least two layers with overlapping joints to avoid gaps through which x-rays can penetrate.

7. CONCLUSIONS

It has been shown that even with the demanding requirements of today's current radiation safety legislation it is possible to design a light source radiation shield which meets the ALARP principle, is reasonably cost effective and permits good access to the photon beams.

Table 6. DIAMOND shielding details

Location			Material thickness[1] (m)	
			Ordinary concrete	Barytes concrete (+ lead)
Storage ring	Injection region[2]	Ratchet side wall (Dipole)		1.30
		Ratchet side wall (ID)		1.18
		Ratchet end wall (Dipole)		1.78
		Ratchet side wall (ID)		1.68
		Roof	1.60	
		Inner wall[3]	1.43	
	Elsewhere	Ratchet side wall (Dipole)		1.15
		Ratchet side wall (ID)		0.95 (+0.03)[4]
		Ratchet end wall (Dipole)		1.65
		Ratchet side wall (ID)		1.55
		Roof	1.43	
		Inner wall[3]	1.25	
Booster		Outer wall	1.90	
		Inner wall	2.10	
		Roof	2.05	
Linac		Walls	1.20	
		Roof	1.25	

Notes:
1. The thicknesses quoted result directly from the calculations. No contingency has been added.
2. The injection region is considered to be 1 cell before the septum to 2 cells after.
3. The inner wall excludes the wall common to the booster, which will be the same thickness as the booster outer wall.
4. This lead should be +/- 0.65m high centred on the beam height and sufficiently long to end 2.5m from the orbit.

8. REFERENCES

[1]V.P. Suller, 'Status of the DIAMOND project', these proceedings
[2]W.R. Nelson and T. Jenkins, *SHIELD11 Shielding Code* (Stanford Linear Accelerator Center, Stanford, CA94087) SLAC-265 (1985)
[3]*Ionising Radiation Regulations 1999* SI 1999/3232 Stationery Office 1999 ISBN 0 11 085614 7