THE SHIELDING OF ELECTRON ACCELERATORS: A MONTECARLO EVALUATION OF GAMMA SOURCE TERMS

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Abstract

One of the main goals of health physics at high energy accelerators is to define some realistic semiempirical formulae to calculate dose propagation behind shielding in case of accidental losses of the beam. Using the EGS Montecarlo code one can evaluate the gamma component of the cascade produced in an electron storage ring and verify that it is possible to assume to have a point source inside the shielding (source term) followed by an exponential attenuation at the interaction region. We present the results of a preliminary evaluation of the behaviour of the source terms and the attenuation coefficients as a function of primary electron energy.

Introduction

The calculation of the shielding around high energy electron accelerators may be approached in several ways.

Montecarlo programs can be used directly to propagate the electromagnetic cascade generated by electrons through any material of any shape in any direction. However, it is rather difficult and time consuming to be realistic in the simulation of the beam losses at an accelerator (possible target position, shape and thickness, shielding configuration and shape, etc) such that these programs are more often used as a check for other types of evaluations.

Another approach consists in scaling and adapting experimental measurements; however, there are very few experimental data available and rather seldom they are not general enough to allow their use to practical shielding situations.

The more used, for radiation protection purposes, is the semiempirical method. This method is an extension and a simplification of the phenomenological model introduced by B. Moyer [1]. One assumes that the primary particle beam hits upon a target: the first aim is the determination of the shape of the target (or of the targets) and its (or their) possible location around the ring. Secondary particles are emitted from the target as a result of electromagnetic and nuclear interactions: the second goal is to estimate the type, the number and the energy spectrum of these particles that shall be attenuated in the accelerator shielding i.e. defining the "source terms".

The grouping of the type and energy of the particles in each source term is generally done in such a way as to require a unique dose attenuation factor for each source.

Montecarlo programs become very useful to verify, specify and extend the energy range of the source terms and of the corresponding radiation attenuation coefficients.

In the present work, we have used the Montecarlo code EGS4[7] to study the source terms in copper for gamma-ray bremstrahlung at 0° and 90° and the relative attenuation factors in concrete for accelerators of energy between some 100 MeV and 10 GeV, which are today rather popular for synchrotron radiation production.

Considerations about the Source Term

Generally, the source term is assimilated to a pointlike source such that it follows also the inverse-square attenuation law. It will be located at particular points along the ring and its intensity and spectral shape may vary with its location in the ring.

It is generally expressed in terms of dose-rate af a given type of radiation per unit beam power emitted at a given angle from the direction of the primary electron beam at one meter from the source point.

Several authors have studied the source term approach: we cite just the more recent [2],[3]. The late W.P. Swanson had summarized various results in a very elegant and useful booklet [4].

These authors base their considerations mainly upon two experimental measurements reported by H. Dinter and K. Tesch [5] and by T. Jenkins [6]. From these experimental data, Dinter et al [2] and Hirayama et al [3] try to extrapolate general source terms and attenuation factors and to confirm their validity by using the Montecarlo Code EGS [7]. They suggest some expressions for the ST and for the attenuation factors that have been summarized by Swanson [4].

However, we feel that some of the expressions they find are rather peculiar to the experiments they have been derived from and do not grant the generality that is required for the source term.

In our opinion, to define the source term in the most general and useful way to allow direct shielding evaluation, one shall keep in mind the following requirements.

1) The source singled out and specified by the source term must be a point source: it must be propagated in the given directions by an inverse square law. This does not imply that the source must also be isotropic.
2) The attenuation of the selected radiation in the shielding must follow a simple exponential law, without any build-up due to further development of the electromagnetic cascade inside the shielding. This implies that the gamma cascade is fully developed in the target.

Requirements 1) and 2) force to locate the source in a "thick" target.

3) The source intensity shall be maximized in order to avoid dangerous underestimation of the required shielding thickness. The maximization of the source term is obtained by the optimization of the target, i.e. by finding the target shape and thickness that assure the maximum gamma emission in a solid angle large enough to grant conditions 1) and 2). This optimization of the target must be performed for all the propagation directions (often just at 0° and 90°).

If one adopts the "thin" target geometry, as some authors suggest, one finds higher doses at 0° but the propagation of the gamma radiation in the shielding may become much more complicated than a simple inverse-square and, in addition, a build-up factor inside the shielding due to incomplete development of the cascade shall be introduced.

The fulfilling of these requirements introduces some practical requirements to be realized in the ring. For instance, at the possible loss points for the primary electron beam inside the accelerator where the "real" target is not thick enough, it is advisable to introduce additional material (e.g. some lead blocks) to provide for enough thickness for the cascade to develop.

The Method of Calculation

The primary electron pencil beam hits a copper target: the secondary gammas produced at 0° and 90° are attenuated in layers of ordinary concrete (density 2.3 g/cm^3) 10 and 5 cm thick respectively.

Simulations have been performed in two separate steps:

a) The optimization of the dimensions of the target that, for simplifying the geometry, is assumed to be cylindrical.
b) The calculations of the source terms and the dose attenuations.

The Source Term and the Dose Attenuation Factors at 0°

i) The Target Optimization

For each electron energy we have determined the target thickness which gives the maximum of gamma production and plotted it as a function of electron energies.

We have checked that the transversal size of the target is not relevant provided that it is large in comparison with the incident beam section. In all the simulations of the source term at 0° we have considered cylindrical targets of different thicknesses with 1 cm radius.

ii) The Source Terms and the Absorption Coefficients

The gammas generated by the interactions of electrons with the target cover a wide energy spectrum. Most of gammas are emitted at low energies but a higher energy component of spectra can not be ignored. The gamma rays are also spread over wide angular distributions.

To calculate the source term at 0°, we must consider a very small portion of solid angle and score the gammas emitted within it. The choice of this angle is not trivial: it must be neither too small, to avoid stochastic effects (poor statistic), nor to large, to average correctly.

The figure 1 shows the geometry used for the evaluation of the source term and the dose attenuation at 0° in concrete.

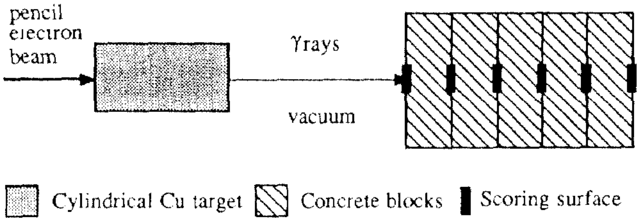

Figure 1. The geometry used for the simulation of the source term at 0°.

The gammas generated in the target are scored and converted into dose, using the flux-to-dose conversion factors [8], at the crossing of a small surface (having an area of about 1 cm^2), positioned at 0°, 1 m far from the target. Scoring surfaces of the same dimensions are used to calculate the gamma beam attenuation in some concrete layers each one 10 cm thick.

The source term S_0 (expressed in terms of Sv/h $(kW/m^2)^{-1}$), can be plotted as a function of beam energy (figure 2). The fit of these points let us obtain a semiempirical formula which relates the doserate due to the gamma component of the cascade produced at small angles, calculated in units of beam power (kW), at 1 m from the source, to the electron energy E_0(GeV):

$$S_0\left(\frac{Sv/h}{KW\ m^2}\right) = A\left(1 - e^{-B\sqrt{E_0}}\right)$$

where A = $1.06*10^6$ and B= 0.88.

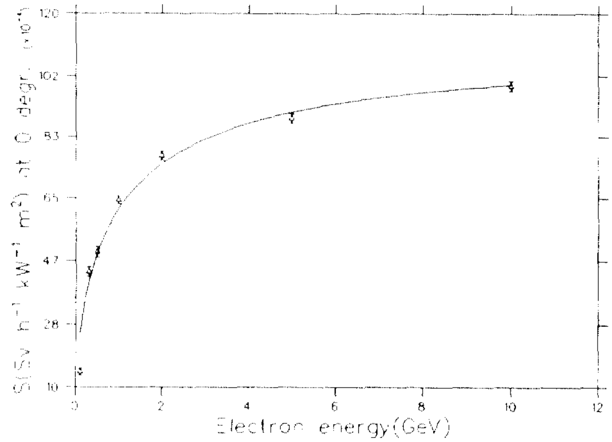

Figure 2. Source term at 0° versus electron energy.

In figure 2 the fit is superimposed over the calculated points: in the considered energy range the agreement is rather good.

The mean dose attenuation coefficients in ordinary concrete have been evaluated with the same procedure: by scoring the dose from gammas crossing the same surface positioned at different concrete depths. Since the gammas are not monoenergietic, the absorption curves do not present uniform slopes.

The numerical values of the mean attenuation factors $\mu_0(m^{-1})$ for different electron energies E_0 are listed in table 1.

Table 1. Dose attenuation coefficients in concrete at 0° for various electron energies.

E_0 (GeV)	μ_0 (m^{-1})
0.1	4.2 ± 0.2
0.3	4.3 ± 0.2
0.5	4.1 ± 0.2
1	4.5 ± 0.2
2	4.1 ± 0.2
5	3.3 ± 0.1
10	3.5 ± 0.1

Although a slight decrease with E_0 can be distinguished, as a "rule of thumb", we would suggest to consider only two ranges of energies and to assume the mean value of absorption coefficients as follows:

$$\bar{\mu}_0 \approx 4.1\ m^{-1} \quad \text{for } E_0 \le 2\ GeV$$

and:

$$\bar{\mu}_0 \approx 3.3\ m^{-1} \quad \text{for } 2\ GeV < E_0 \le 10\ GeV$$

The Source Terms and the dose attenuation factors at 90°

i) The Target Optimization

We have considered the same geometry adopted for the 0° optimization and scored gammas emitted out of the lateral walls of the target. The gamma efficiency calculated per incident electron and normalized over the lateral wall has been evaluated as a function of target lenght and radius for each electron energy.

ii) The Source Term at 90° and the Absorption Coefficients

In the evaluation of the source term at 90° the gammas crossing the wall of the target are scored and converted into dose when they hit a large scoring surface surrounding the Cu target at 1 m from it (see figure 3). Therefore the doses are averaged over a large cylindrical area.

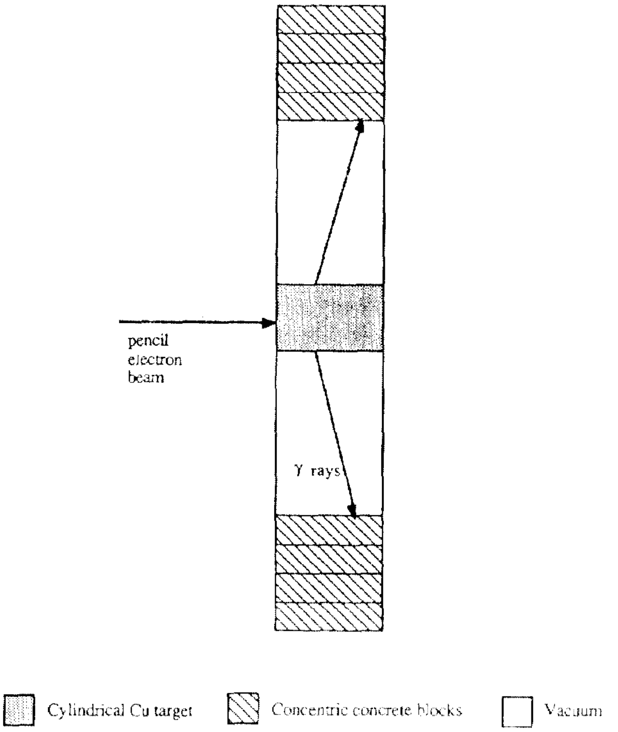

Figure 3. The geometry used for the simulation of the source term at 90°.

The value of the source term at 90° (expressed in terms of Sv/h $(KW/m^2)^{-1}$), as a function of the electron energy is shown in figure 4.

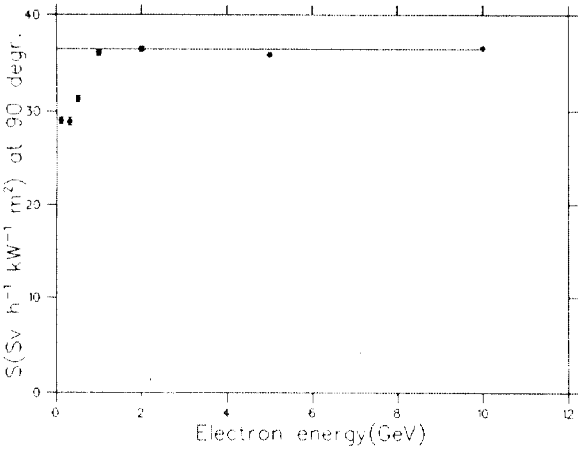

Figure 4. Source term at 90° versus electron energy.

For $E_0 > 1$ GeV the source term is practically constant. To be conservative, we suggest to assume:

$$S_{90}\ (Sv/h\ (KW/m^2)^{-1}) \approx 40$$

for the whole considered energy range.

The dose attenuation factors have been evaluated by scoring the dose from gammas which cross some concentric cylinders of concrete surrounding the target.

As it was expected, the attenuation coefficients are higher than in the 0° geometry, since the energy of the gammas is lower.

The numerical values of the attenuation factors are listed in table 2. They do not depend on E_0. We suggest to adopt the conservative value:

$$\overline{\mu_{90}} \approx 9.4\ m^{-1} \qquad \text{for } 100\ MeV \le E_0 \le 10\ GeV$$

Table 2. Dose attenuation coefficients in concrete at 90° for various electron energies.

E_0 (GeV)	μ_{90} (m^{-1})
0.1	10.2 ± 0.6
0.3	10.5 ± 0.2
0.5	10.4 ± 0.3
1	9.8 ± 0.3
2	9.4 ± 0.4
5	9.6 ± 0.3
10	9.4 ± 0.4

The Comparison with Swanson Semiempirical Formulae

The table 3 reports the values of the semiempirical formulae suggested by Swanson for the gamma source terms as a function of electron energy at 0° and 90°and the results of our Montecarlo simulations.

Table 3. Comparison between Swanson and EGS source terms semiempirical formulae. Here E_0 are expressed in MeV.

Source terms (Sv h^{-1} KW^{-1} m^2)	Energy range	0°	90°
SWANSON	$E_0 < 20$ MeV	$20\ E_0^2$	50
	$E_0 \ge 20$ MeV	$3.10^2\ E_0$	50
EGS	$100\ MeV \le E_0 \le 10\ GeV$	$A\,(1-e^{-B\sqrt{E_0}})$ where: $A = 1.06\ 10^6$ $B = 2.77\ 10^{-2}$	40

The Swanson source term at 0° as a function of beam energy is plotted over the EGS4 results in figure 5. In the simulation we cover the "suggested" portion of the Swanson formula. Both expressions represent a source term which increases with the energy of the primary beam: for E_0>20 MeV a linear trend is suggested by Swanson while a curve with something similar to a saturation value for higher values of E_0 has been obtained in the simulations.

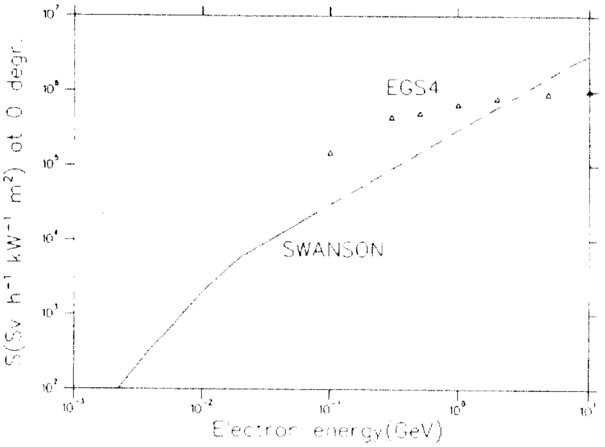

Figure 5. Comparison of Swanson and EGS4 semiempirical formulae for the source term at 0°.

According to Swanson formula the source term at 90° is given by 50 Sv h^{-1} kW^{-1} m^2 for all the electron energies. In our simulations we obtain a constant value which approachs 40 Sv h^{-1} kW^{-1} m^2 for E_0> 1 GeV and a rough linear trend at lower energies.

Concerning the dose attenuation coefficients (table 4), Swanson suggests to adopt the same mean value of 5.3 m^{-1} for both 0° and 90° direction at all the energies.

For the 0° direction we found that the attenuation coefficients veries between 3.3 m^{-1} and 4.5 m^{-1}. At 90° the attenuation factors are practically independent on E_0 and can be assumed equal to 9 m^{-1}.

Table 4. Comparison between Swanson and EGS mean attenuation coefficients.

Attenuation coeff.(m^{-1})	Energy range	0°	90°
SWANSON	All the energies	5.3	5.3
EGS	$100\ MeV \le E_0 \le 2\ GeV$	4.1	9.4
	$2\ GeV < E_0 \le 10\ GeV$	3.3	9.4

References

[1] H.W. Patterson, R.H. Thomas, "Accelerator Health Physics", p. 381, Academic Press, New York, 1973.

[2] H. Dinter, J. Pang, K. Tesch, "Calculations of doses due to electron-photon stray radiation from a high-energy electron beam behind lateral shielding", Internal Report DESY 88-117 (1988) and Radiat. Prot. Dosim. 25, 107 (1988).

[3] H. Hirayama, S. Ban, M. Sakano, "Calculation of dose equivalent due to stray radiation from a high energy electron beam in the forward direction", private communication, to be submitted to Radiation Protection and Dosimetry.

[4] W.P. Swanson, "Radiological safety aspects of the operation of electron linear accelerators", Technical Reports Series N. 188, IAEA, 1979.

[5] H. Dinter and K. Tesch; Nucl. Instr. Meth. 143, 349 (1977).

[6] T.M. Jenkins, Nucl. Instr. Meth., 159, 265 (1979).

[7] W.R. Nelson, H. Hirayama, D.W. Rodgers, "The EGS4 Code System", SLAC Report 265 (1985).

[8] D.W.O. Rogers, "Fluence to dose equivalent conversion factors calculated with EGS3 for electrons from 100 keV to 20 GeV and photons from 11 keV to 20 GeV", Health Ph., 46, 4, 891 (1984).