SHIELDING HIGH-ENERGY ACCELERATORS

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Running Title: SHIELDING HIGH-ENERGY ACCELERATORS
Abstract

After introducing the subject of shielding high-energy accelerators, point-source line-of-sight models, and in particular the Moyer Model, are discussed. Their use in the shielding of proton and electron accelerators is demonstrated and their limitations noted, especially in relation to shielding in the forward direction provided by large, flat walls. The limitations of reducing problems to those using a cylindrical geometry description are stressed. Finally the use of different estimators for predicting dose is discussed. It is suggested that dose calculated from track-length estimators will generally give the most satisfactory estimate.

Word count: 90 words
INTRODUCTION

The goal of an efficient accelerator shielding design is to attenuate the high radiation intensities produced by the accelerator and its associated equipment to levels that are acceptable to humans and other apparatus outside the shielding, at a reasonable cost and without compromising the utility of the particle accelerator for its designed purposes. This is achieved in three stages:

1. Specification of the source term(s).
2. Specification of the design levels for the radiological constraints.
3. Design of the actual shield on an optimum cost-effective basis and with readily available construction materials.

For the first stage, the maximum intensities and losses that form the basis of the shield design must be agreed upon by laboratory management before shield specification begins.

The second stage, which has to have the agreement of the appropriate regulatory authorities, is illustrated by considering the design constraints chosen for the CERN Large Hadron Collider (LHC). One constraint is that the loss of one circulating beam at 7 TeV and at full intensity should not give rise to an Ambient Dose Equivalent of more than 50 mSv at the outer surface of the shield leading to a Controlled Radiation Area. This should not then involve any declaration of a radiological incident or accident to a controlling authority and would not jeopardise the future work with radiation of any persons involved. Another constraint is that the dose rate from a continuous loss under the worst credible circumstances should never exceed 100 mSv h\(^{-1}\). In addition the design dose rate averaged over 24 hours for normal, expected situations is 10 µSv h\(^{-1}\). Design constraints for other classes of areas are summarised in Table 1. The dose-rate constraints are supplemented by designing systems to warn operators if levels exceed three times the design level during actual operation, and for the offending operation to be stopped if levels exceed ten times the design constraints. This allows the shielding to be improved or the area classification hardened.

The third stage is the principal subject of this paper. In the following section the Moyer Model will be described as an example of all point-source line-of-sight models, and the limitations of such models noted.

POINT-SOURCE/LINE-OF-SIGHT MODELS

Two assumptions are often made in shielding calculations. The first is that the source can be approximated by a point source. For this assumption to hold the source must be localised in a geometrical region which is small in size compared with the other dimensions of the shielding situation so that the inverse square law of geometrical dilution holds. The second is that the dose, \(D\), as a function of position can be described in terms of the relative co-ordinates of the point source, \(S\), and the point of interest, \(P\) (see
Figure 1) and that there are no contributions from any other secondary sources. It should be noted that in this paper the word *dose* is used as a generic word, replacing dose equivalent, equivalent dose, effective dose etc.

If the point S is assumed to be at the origin of the co-ordinate system then the dose $D(r,z)$ at the point P which is at a distance $r$ off-axis and at a longitudinal depth $z$ can be described:

$$D(r,z) = D(\zeta, \theta) = k Z(\zeta, \theta) \Theta(\theta)/R^2,$$

where $R = \sqrt{r^2 + z^2}$ is the distance from S to P, $\zeta$ is the line-of-sight distance in the shield of the vector joining S to P and $\theta = \arctan(r/z)$ is the polar angle of this vector with respect to the beam axis.

The above equation represents a pure point-source/line-of-sight model where the radiation field at P is affected only by particles travelling along the vector linking S to P and not those from any other point. The function $Z(\zeta, \theta)$ need not have *a priori* any particular functional form and could have a build-up as well as an attenuation component. $k \Theta(\theta)$ is a source term which is a function of polar angle.

Such a model is directly applicable to the shielding of low-energy proton accelerators (< 400 MeV). The source of radiation provided by the interacting protons is limited to a distance equal to the range of the protons, and this is small when compared with the usual dimensions of a shield. The effective source strength and the absorption length vary with the angle to the beam axis, but this variation can easily be described by analytic fits or tabular values.

Such a treatment was extended to proton energies in the GeV range by Moyer during the up-grade of the Bevatron shielding (1) and was named the “Moyer Model” by De Staebler during the design of the Stanford Linear Accelerator (SLAC) (2). In its present form, as summarised by Thomas and Stevenson (3), the function $Z(\zeta, \theta)$ does not depend on the polar angle $\theta$ and is a pure exponential absorption term of the form $Z(\zeta) = \exp(-\zeta/\lambda)$ where $\lambda$ is an absorption mean free path which is independent of particle type and energy. The angular dependence $\Theta(\theta)$ now includes any build-up effect in the shield and is approximated by a function of the form $\exp(-\beta \theta)$, where $\beta \equiv 2.3$ radians$^{-1}$. The dose equivalent at the point P is then:

$$D = \psi \exp(-\beta \theta) \exp(-\zeta/\lambda) /R^2 ,$$

where $\psi$ is a constant which depends on the energy of the incident protons as a simple power law with an exponent of 0.8. The exponent is less than unity because the fraction of the incident proton’s energy leading to hadron production decreases as the proton energy increases.
Since, as will be seen later, the model is only applicable to angles, $\theta$, close to 90°, in its simplest form, and the most appropriate for lateral shielding, the above equation reduces to

$$D = H_0 \left( \frac{E_p}{E_0} \right)^{0.8} \frac{\exp\left(-\frac{r-r_0}{\lambda}\right)}{r^2},$$

where $E_p$ is the proton energy, in GeV; $E_0$ is 1 GeV; $H_0$ is a dose-equivalent normalisation constant with the value $1.26 \times 10^{-14}$ Sv m$^2$ per proton and $\lambda$ is 118 g cm$^{-2}$ for concrete or earth and 164 g cm$^{-2}$ for iron.

This simple model is also used to determine the lateral shielding required around targets and dumps at electron accelerators. In this case each of the three components of the radiation field needs to be considered separately, but for each case there is a linear dependence of $D$ on primary electron energy. The parameters in the above formula are listed in Table 2.

**FLAT WALLS**

**A Surface Inspection**

Many important features of shielding design are hidden by the restriction of limiting one’s consideration to cylindrically symmetric geometrical situations. New insight can be gained by making use of the flexibility offered by modern radiation transport simulation programs and the speed and memory capacity of present-day computers. The spur to consider the shielding offered by large flat walls, 50 to 100 metres long and 10 to 30 metres high, was given in the design of the experimental areas of the LHC by Huhtinen and Stevenson (4), but the conclusions are applicable to all accelerators. The geometry used is illustrated in Figure 2. Protons are considered to be lost at the origin in a long solid iron cylinder of 20 cm radius whose axis is along the z-axis, 2 m laterally away from the concrete wall.

The dose contours in the flat wall at a depth of 1 cm into the wall can be determined using the point-source/line-of-sight model described in the previous section for a Moyer-type source ($\beta = 2.3$ radians$^{-1}$), taking account of the attenuation in the iron cylinder. The contours for this situation are illustrated in Figure 3 and are normalised to the dose at the same depth, 1 m downstream of the target in the $y = 0$ plane. The $\lambda$ in the wall is assumed here to be 50 cm which is approximately the value for high-energy proton induced cascades in concrete. The $\lambda$ for iron is assumed to be 20 cm.

The contours show that the dose increases with vertical distance from the beam axis at longitudinal distances greater than 10 m downstream of the beam-entry point,
which is contrary to a normal intuitive expectation. This, however, can be confirmed with a Monte-Carlo simulation using a program such as FLUKA (see references (5,6) and the references they contain). Protons at 7 TeV entered the geometry at the co-ordinate origin. Contour plots of the doses in pSv per proton averaged over the first 20 cm depth of the inner surface of the wall are given in Figure 4. The contours for the long target also show the same dose increase with vertical distance at longitudinal depths greater than 10 m.

The contours for a shorter target, however, show the expected variation of dose with vertical distance from the beam axis for all distances downstream of the point of entry of the beam into the target. Thus the increase in dose with vertical distance must be linked with attenuation in the long iron target. The unexpected shape of the contours is in fact due to attenuation in the long cylinder of iron that "shadows" the wall at small values of $\theta$. But this would not have been detected in a cylindrical simulation of the radiation transport: it needed a full three-dimensional simulation to make it evident. This anomaly could completely negate shield estimations in the elevated dose regions that are which might be based on cylindrical models.

Testing in Depth

The results of the FLUKA simulation at $E_p = 7$ TeV for the flat wall provided good data for a more detailed testing of the validity of line-of-sight models. A first analysis was made for the runs where the protons impinged on the infinitely long iron cylinder of 20 cm radius. For several values of the angle to the proton beam, $\theta$, it was possible to look at the value of the dose as a function of distance along the line-of-sight and as a function of the azimuth angle, $\phi$ (this is the angle which the line-of-sight vector when projected on to the $z = 0$ plane makes with the $x$-axis). The point source was assumed to be at a distance of 50 cm downstream of the point of impact of the protons. (This assumption is obviously not necessary for the FLUKA calculation, but only as a reference point for measuring $\zeta$.) In Figure 5 the values of dose equivalent multiplied by the square of the distance to the source are shown as a function of line-of-sight depth in the shield for values of $\theta$ from 20 to 80°.

It will be seen that the points taken from different lines corresponding to different azimuth angles all follow a simple exponential dependence on depth, suggesting that a Moyer-type model could be appropriate. However the effective mean free path increases as the polar angle decreases, and this contradicts one of the tenets of the Moyer model viz. that $\lambda$ should be independent of angle. The effective mean free path corresponds to the value expected, slightly less than 50 cm, only at $\theta = 80^\circ$.

The increase of $\lambda$ with decreasing $\theta$ is even more marked for a second series of runs made with a target cylinder of only 2 cm radius (see Figure 6). This suggests that the situation may correspond more closely to one where secondary interactions along the inner layer of the shield wall are acting as the effective source, rather than there being a single point-like source in the target. (Even for a long target, the source point is
somewhat spread out over the length of the target but the maximum of the cascade still acts as a point source).

Even though the studies described were directed towards shielding evaluations at proton energies of 7 TeV, simulations were also performed for the 35 m long target at proton energies of 10 GeV, 100 GeV and 1 TeV in order to determine whether the variations of the effective mean free path found were unique to the high-multiplicity cascades initiated by 7 TeV protons. Values of the effective mean free path for the various proton energies at the four values of polar angle investigated (averaged over all azimuth angles) are given in Table 3. The values for a given $\theta$ for the 20 cm radius target are essentially the same given the fitting error and the slight systematic spread of values for the different azimuth angles $\phi$, which can be seen in Figures 5 and 6. The increase of $\lambda$ with decreasing $\theta$ is not a function of proton energy and is therefore related to something more fundamentally connected with the assumptions made in the point-source/line-of-sight model.

A Wall-Source Model

For short or laterally thin targets the cascade generally does not fully develop in the target. Many of the high-energy secondaries can escape from the target and generate their cascades in the shield-walls. The situation is illustrated in Figure 7. In this Wall-Source model, the dose at the point $P$ comes principally from the distribution of secondary sources $S'$ in the initial layers of the shield-wall, i.e. in the case of strongly oblique incidence of the secondaries on the wall, sideways build-up/attenuation dominates over line-of-sight contributions. This has been known in shielding studies for low-energy neutrons and photons for some considerable time, however it is not evident that this model should be applicable to high-energy radiation. The secondary source strength is a function of $R$ and $\theta$, depending also on the initial target length and radius as well as the proton energy, but the attenuation in the wall is now a function of $d$ only. The dose at $P$ will be an area integral of the form $\exp(-s/\lambda)/s^2$, where $s$ is the distance of the elemental area of wall source from the point $P$.

It was shown in (7) that for a thin, short target in cylindrical geometry the propagation of the cascade in the shield behaved in a similar way to the radiation from a line source situated on the inner surface of the shield where the variation with depth, $d$, is given by the Moyer-Integral:

$$D = k \frac{1}{d} \int_0^\pi \exp(-\beta \theta) \exp(-d / \lambda \cos \theta) d \theta .$$

In the case of a flat wall it is to be expected that the source will approximate to a somewhat uniform plane source distributed over the shield wall rather than to a simple line source.

Figure 8 shows the attenuation of plane, line and point isotropic sources through a wall. For simplicity the attenuation length has again been chosen as 50 cm. The inverse square law dependence has been removed in each case by multiplying the dose at the
point of interest by the square of the perpendicular shield thickness. This dependence arises out of the fact that only the part of the line or surface source directly “below” the field point contributes to the field. The lower curve is for a plane source distributed over the wall surface, the middle curve for a line source and the upper line the simple attenuation for a point source. The curves are normalised to the uniform wall-source attenuation at a depth of 10 metres.

Figure 8 indicates that at large depths all source types behave as a simple point source. The reason for this is that the negative exponential of distance effectively removes all contributions other than those closest to the source, and at large distances, this small contributing surface resembles a point.

The same data from the FLUKA simulations which were used to test the point-source/line-of-sight model were also used to test the wall-source model. When the value of the dose at a given perpendicular depth in the shield, multiplied by the square of the depth, is plotted as a function of \( \theta \) and \( \phi \), where the angles now correspond to the vector linking the source \( S \) to \( S' \) instead of linking \( S \) to \( P \) as in Figure 2, the results shown in Figures 9 and 10 are obtained for the thick and thin radial targets respectively.

The points for all values of \( \phi \) at a given \( \theta \) scatter around unique curves, apart from effects due to poor statistics. Also shown in these figures are lines calculated using a wall-source model where the source strength required for the surface integral is given by the simulated star-density distribution underneath the point of interest in the first 20 cm bin of the shield. As before a value of 50 cm was used for the effective absorption mean free path. The dashed curves calculated using the wall-source model reproduce well the form of the FLUKA simulations. An almost exact agreement, shown by the solid curves, can be obtained on an absolute basis by normalising the 20 cm depth point of the model calculations to the 30 cm depth point of the FLUKA simulations. This normalisation uncertainty is to be expected since in reality the source for the model calculations is not in fact a surface source but is distributed in depth over the first few tens of centimetres of the shield. However the overall agreement of this simple wall-source model with the data from the FLUKA simulations suggests that, even for the thick radial target case, the dose at a given point is more affected by the radiation coming perpendicularly through the shield than that coming along the line-of-sight from the primary target to the point of interest.

This conclusion is confirmed by considering the results from a simulation where a “black hole” was inserted in the inner layers of the shield downstream of the proton entry point to absorb the component coming perpendicularly through the wall (see Figure 11). The comparison of the original attenuation taken from Figure 5 for \( \theta = 40^\circ \) and the simulation with the black hole in the wall shows that, with the black-hole, the line-of-sight model is again appropriate and one finds the expected value of \( \lambda \) (\( \approx 50 \text{ cm} \)).

**Comparison of Line-of-Sight and Wall-Source Models**
An attempt was made \(^{(4)}\) to predict the form of attenuation found in the point-source/line-of-sight comparisons from the wall-source model in order to investigate further the validity of this latter model. As before, consideration was restricted to the isotropic wall-source and the strength of the source was taken to be the star-distribution in the first layer of the shield, as in the comparisons of Figures 9 and 10. The doses along the appropriate lines-of-sight were calculated from the wall-source model and plotted against the data from the simulations illustrated in Figures 5 and 6. The resulting comparisons are given in Figures 12 and 13.

In these Figures no attempt has been made to improve the normalisation. The result is that the curves show the same discrepancy of a factor of about three as was found in Figures 9 and 10. However the increase in effective absorption length \(\lambda\) with decreasing polar angle \(\theta\) is evident and the values of the slope of the attenuation are clearly a good fit to the FLUKA simulations.

This study gives added conviction that the attenuation in the flat shield wall is better represented by a wall-source model for both the radially thick \((r = 20\,\text{cm})\) and radially thin \((r = 2\,\text{cm})\) iron targets.

**Some Conclusions on Simple Models**

The study of the attenuation of a cascade initiated by a proton beam striking a long magnet system in a flat shield wall has shown that the dose contours in the wall are severely affected by the attenuation of the magnets themselves. At very-forward angles, this leads to an increase of dose at the wall surface with increasing vertical distance from the beam axis. As a consequence, detailed magnet structures and realistic shields are de rigeur when estimating dose rates in the forward direction, in contrast to the simplifications which can be accepted when estimating lateral doses.

It has been suggested that the transmission of radiation in the shield is better represented by a wall-source model, where the effective source is the distribution of secondary interactions in the initial layers of the shield wall, rather than by a point-source/line-of-sight model where the point source is concentrated around the initial interaction point of the protons. The wall-source model is capable of predicting the apparent increase in effective mean free path with decreasing angle to the proton beam, found when using the line-of-sight model.

Great care must be taken in predicting lateral shielding requirements in the very-forward region, especially when the loss of protons occurs in thin or short objects.

**IMPORTANCE OF CORRECT GEOMETRICAL REPRESENTATION**

Because of the explosion in computer capability that has taken place over the last few years in both memory capacity and speed of execution, the way in which shielding problems can be tackled has significantly changed. There is now no reason to maintain
the simplification of a cylindrical geometrical representation of the problem. Details of the accelerator construction close to the beam-line may be important as secondary sources of radiation and require an azimuthally asymmetric representation. These cannot be represented correctly in cylindrical geometry. In a real shield, the thickness is nearly always a function of azimuth: a cylindrical representation using the minimum shield thickness as its radial thickness can seriously overestimate fluences outside the shield surface. Calculations made for the CERN Reference Field irradiation facility (CERF) demonstrate this further.

CERF was set up for the inter-comparison of detectors used in radiation protection around high-energy accelerators and for assessing instrumentation used for measuring the radiation exposure of air-crew. The facility consists of 48 exposure locations behind 40 cm thick iron or 80 and 160 cm thick concrete shields alongside copper targets bombarded by beams of hadrons of energies ranging from 100 to 200 GeV. A plan view of the facility is given in Figure 14 and a cross-section through the concrete shield in Figure 15. The facility is described in more detail in the article by Höfert and Stevenson (8).

Possible geometrical approximations to the “real” CERF geometry in the concrete shield position are indicated in Figure 16. Two rays, X and Y, through the geometry are chosen at the same azimuth angle. The distance through the shield in the Cartesian approximation is greater than that in the Cylindrical approximation, so the dose rate at A is less than the dose rate at B. Because of this the dose rate above the shield at point C should be lower than the dose rate above the shield at point D, even though the shield thicknesses are identical.

The measurement array above the target in the concrete shield is represented by the T1—T16 array in Table 4. The target was situated under the T8/T12 junction. Table 4 gives the ratio of dose in the Cartesian and Cylindrical approximations to the dose in the “real” geometry determined in FLUKA simulations. As expected the Cylindrical approximation overestimates in the side positions T1—T4 and T13—T16 but the reduction expected in this approximation for the axis positions T5—T8 and T9—T12 is not visible given the statistical accuracy of the simulation. It can be seen that the Cartesian is a good approximation, however it is interesting to note the effect of leakage around the thick shield in the “real” geometry for the T13—T16 positions.

### SCORING QUANTITIES

In a radiation transport simulation there are several ways of estimating the dose equivalent behind a shield e.g multiplying energy deposition by an appropriate quality factor, multiplying the density of inelastic interactions by primaries with energies greater than 50 MeV by the appropriate factor, or multiplying fluence as a function of energy by the appropriate conversion factors, where the fluence can be determined from boundary-crossing or track-length estimators. All of this may be correct for very specific situations but may give wrong estimates in others. For example in the above simulations for the
CERF facility, the dose estimated from the fluence leaving the concrete surface above the target is 40% higher that the dose estimated from track-length in a 50 \times 50 \times 50 \text{ cm}^3 volume just outside the shield. It was considered that the track-length estimator would give a better representation of practical measurements made above the shield with detectors of finite volume.

Other problems arise concerning doses determined from boundary-crossing estimators. When the dose outside the shield is required then scoring the outward directed fluence gives the correct estimate, but in a tunnel inside the shield where the shielding continues beyond the occupied area then the two-way fluence is more appropriate. This can give rise to a 25% increase in the estimated dose \(^{(9)}\). Both energy deposition and star-density estimators require that material of a significant density be present in the scoring region, and this may perturb the actual particle transport. Fluence determination from track-length estimators suffers none of these disadvantages and should be used wherever possible since it is correct both in solid materials and voids.

**IN CONCLUSION**

Dose contours in flat walls are severely affected by the attenuation in magnet strings. At very-forward angles, this leads to an increase of dose at the wall surface with increasing vertical distance from the beam axis. As a consequence, detailed magnet structures and realistic shields are *de rigeur* when estimating doses in the forward direction. This is in contrast to the drastic simplifications that can be accepted when estimating lateral doses.

The transmission of radiation in flat-wall shields is better represented by a wall-source model, where the effective source is the distribution of secondary interactions in the initial layers of the shield wall, rather than by a point-source/line-of-sight model where the source is concentrated around the initial interaction point of the protons.

Great care must be taken in predicting lateral shielding requirements in the very-forward region, especially when the loss of protons occurs in thin or short objects.

Cylindrical geometry is not the best approximation for most realistic shielding situations.

The dose at the shield wall boundary is not the dose to which a person will be exposed. One must make sure that the distance of a person from the shield wall is correctly taken into account.

Finally there can be a significant difference between the dose calculated from one-way and two-way fluence estimators. Energy and star density estimators need perturbing material in order to be scored. Dose calculated from track-length estimators will generally give the most satisfactory estimate.
ACKNOWLEDGEMENTS

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REFERENCES


Table 1

Design doses and dose-rates outside the shielding of the LHC.

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<th>Area Classification</th>
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<th>Dose rate µSv h⁻¹</th>
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Table 2
Parameters for use with the simple formula for shielding electron accelerators.

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<th>Radiation Component</th>
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Table 3
Effective mean free paths (cm) in the concrete wall for different values of $\theta$ at various proton energies.

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Table 4
Ratio of dose in the Cartesian and Cylindrical approximations to the dose in the “real” geometry.

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TABLE CAPTIONS

Table 1: Design doses and dose-rates outside the Shielding of the LHC.

Table 2: Parameters for use with the simple formula for shielding electron accelerators.

Table 3: Effective mean free paths (cm) in the concrete wall for different values of $\theta$ at various proton energies.

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FIGURE CAPTIONS

Figure 1: Sketch of the cylindrical geometry situation.

Figure 2: Sketch of the geometry used in the point-source/line-of-sight calculations for an iron cylinder close to a flat shield wall.

Figure 3: Isodose curves close to the inner surface of a flat wall at a depth of 1 cm for a Moyer-type source with $\beta = 2.3$ radians$^{-1}$ inside an infinitely long iron cylinder of radius 20 cm.

Figure 4: Doses in pSv/proton averaged over the first 20 cm depth of the inner surface of a flat wall for proton beam losses at 7 TeV in a magnet string. The upper figure is for the 35 m long magnet and the lower for a magnet 2 m in length. All dimensions are in cm.

Figure 5: Attenuation along the line of sight for various polar angles, $\theta$, for a 20 cm radial thickness target. 
Closed circles — $\varphi = 0^\circ$,
Open circles — $\varphi = 15^\circ$,
Closed triangles — $\varphi = 30^\circ$,
Open triangles — $\varphi = 45^\circ$.

Figure 6: Attenuation along the line of sight for various polar angles, $\theta$, for a 2 cm radial thickness target. 
Closed circles — $\varphi = 0^\circ$,
Open circles — $\varphi = 15^\circ$,
Closed triangles — $\varphi = 30^\circ$,
Open triangles — $\varphi = 45^\circ$.

Figure 7: Sketch of geometry used in the wall-source model calculations for an iron cylinder close to a flat shield-wall.

Figure 8: The attenuation of an isotropic source through a flat shield-wall. The upper line is a simple point source, the middle curve corresponds to a line source and the lower curve to a uniform plane source. All curves are normalised at a depth of 10 m.

Figure 9: Attenuation perpendicular to the wall for various polar angles, $\theta$, for a 20 cm radial thickness target. 
Closed circles — $\varphi = 0^\circ$,
Open circles — $\varphi = 15^\circ$,
Closed triangles — $\varphi = 30^\circ$,
Open triangles — $\varphi = 45^\circ$.
For an explanation of the curves see the text.
Figure 10: Attenuation perpendicular to the wall for various polar angles, $\theta$, for a 2 cm radial thickness target.
Closed circles — $\varphi = 0^\circ$,
Open circles — $\varphi = 15^\circ$,
Closed triangles — $\varphi = 30^\circ$,
Open triangles — $\varphi = 45^\circ$.
For an explanation of the curves see the text.

Figure 11: Attenuation along the line of sight for a polar angle $\theta = 40^\circ$, for a 20 cm radial thickness target, without and with a black-hole in the wall.
Closed circles — $\varphi = 0^\circ$,
Open circles — $\varphi = 15^\circ$,
Closed triangles — $\varphi = 30^\circ$,
Open triangles — $\varphi = 45^\circ$.

Figure 12: Comparison of attenuation along the line of sight for various polar angles, $\theta$, for a 20 cm radial thickness target as determined from the FLUKA simulations (point data) and as predicted from the wall-source model (lines).
Closed circles and solid line — $\varphi = 0^\circ$,
Open circles and dashed line — $\varphi = 15^\circ$,
Closed triangles and dotted line — $\varphi = 30^\circ$,
Open triangles and dashed/dotted line — $\varphi = 45^\circ$.

Figure 13: Comparison of attenuation along the line of sight for various polar angles, $\theta$, for a 2 cm radial thickness target as determined from the FLUKA simulations (point data) and as predicted from the wall-source model (lines).
Closed circles and solid line — $\varphi = 0^\circ$,
Open circles and dashed line — $\varphi = 15^\circ$,
Closed triangles and dotted line — $\varphi = 30^\circ$,
Open triangles and dashed/dotted line — $\varphi = 45^\circ$.

Figure 14: Plan view of the iron and concrete shields of the CERN Reference Field facility. The iron shield is shown diagonally shaded. The measurement positions are indicated by the dotted squares.

Figure 15: Vertical section through the shield at the concrete-target position.

Figure 16: Possible geometrical approximations for the real CERN geometry.
4-fold Cartesian

Cylindrical