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Preliminary shielding calculations for a 2 GeV superconducting proton linac

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Abstract

This note provides a preliminary estimate of the lateral shielding required for the 2 GeV superconducting proton linac (SPL) and the high-energy transfer line to the accumulator and compressor. The calculations were performed first by a simple line-of-sight model and subsequently by Monte Carlo simulations in cylindrical geometry. Two situations were considered, namely normal linac operation with continuous particle losses equal to 1 W/m and an accidental scenario with a full loss of the 4 MW beam either at a single point or distributed over a length of several metres. A first assessment of the radiation streaming through the waveguide ducts, linking the accelerator tunnel to the klystron tunnel, was also performed using a simplified approach based on universal curves of neutron transmission through ducts and labyrinths.

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1. Introduction

The conceptual design of a superconducting H^- linear accelerator with beam energy of 2.2 GeV and a power of 4 MW has just been completed at CERN [1]. The accelerator will be about 800 m long, will operate at 352 MHz and will deliver 10^{16} protons per second, in 2.2 ms bursts with a repetition rate of 75 Hz. In conjunction with an accumulator and a compressor to be installed in the ISR tunnel, this linac will be the proton driver of a future CERN neutrino factory. Furthermore, it is designed to upgrade the performance of the PS complex by replacing Linac2 and the PS booster. The linac uses room-temperature RF cavities up to 120 MeV and superconducting structures above. The low-energy part of the accelerator, up to 390 MeV, is a new design, whereas above this energy the LEP superconducting cavities will be employed. In the present design the linac tunnel and a parallel service tunnel housing the klystrons (klystron gallery) follow the Route Gregory immediately outside the existing CERN fence, on Swiss territory. The linac tunnel is 800 m long, 4 m wide and 4.8 m high. The klystron gallery is also 800 m long, with cross-sectional dimensions of 4 m x 4 m. The 2.2 GeV transfer line from the linac to the ISR will be housed in a tunnel about 150 m long, with the same cross-sectional dimensions of the linac tunnel.

In this initial stage of the shielding design, a preliminary estimate of the lateral shielding required for the linac and the high-energy transfer line was performed first by a simple line-of-sight model and subsequently by Monte Carlo simulations in cylindrical geometry. A first assessment of the radiation streaming through the waveguide ducts linking the accelerator tunnel to the klystron tunnel was also performed using a simplified approach based on universal curves of neutron transmission through ducts and labyrinths. This note discusses the design assumptions, gives details of the calculations and provides the shielding requirements.

2. Design assumptions

Two situations were taken into account for the shielding calculations, namely normal linac operation and accidental beam loss. Beam losses for normal operation were assumed as 1 W/m, a somewhat generally accepted figure which should keep the induced radioactivity in the machine at a level sufficiently low to permit hands-on maintenance (see, for example, ref. [2]). This value corresponds to a proton beam loss of 6×10^{11}, 6×10^{10} and 6×10^{9} protons per metre and per second at 10 MeV, 100 MeV and 1 GeV, respectively. An accident scenario considers a full loss of the 4 MW beam either at a single point or distributed over a length of several metres (probably a more realistic scenario).

If the accelerator is installed underground on Swiss territory, i.e. in a non-designated area according to the CERN Radiation Safety Manual [3], the dose must be kept below the limit of public exposure. Outside the fenced areas of the Organisation, the dose equivalent at any point must not exceed 1.5 mSv per year and the dose equivalent actually received by a person must not exceed 0.3 mSv per year. The latter figure includes both external exposure due to stray radiation and the internal exposure due to radioactive releases from CERN. The klystron gallery is also underground but its access being restricted to CERN personnel, it will be classified as a controlled radiation area.

For the shielding design the dose equivalent rate limit was taken as 0.1 µSv/h for public areas and 10 µSv/h for controlled areas. With an operating time assumed to be 180 days per year, i.e. $1.6x10^7$ s per year, these figures assure that the annual dose equivalent for the public and for CERN staff under individual dosimetric control (15 mSv) will not be exceeded. In practice, due to the limited occupancy time of the klystron gallery, the dose to CERN personnel will stay well below the annual limit.

In addition to the above requirements, a full beam loss at a localised point must not give rise to a dose equivalent rate outside the shielding exceeding 100 mSv/h and the accelerator control system must be capable of aborting the beam in a time short enough that the integral dose caused by such an accidental condition remains negligible.

3. Line-of-sight model

Preliminary shielding calculations were performed using a simple point-source/line-of-site model. This model assumes a localised radiation source (i.e., a localised beam loss) and requires the knowledge of the source (i.e., the number and energy distribution of the neutrons generated by the interaction of the proton beam with accelerator components or a target) and of the attenuation length (which accounts for the shielding properties of the material). For lateral shielding (i.e., 90° to the proton beam) and pure cylindrical geometry, the model takes the simple form:

$$H = H_0 \frac{\exp(-d/\lambda)}{r^2} \qquad (1)$$

in which H is the dose equivalent past the shield, H_0 is the source term (the dose equivalent at unit distance from the unshielded source), d is the thickness of the shield, λ is the attenuation length of the shielding material and $r = r_0+d$, where r_0 is the distance from the radiation source to the inner wall of the shield. Below 1 GeV, H_0 and λ vary with neutron energy and depend on target material. At energies above about 1 GeV the Moyer model [4] can be employed, for which $H_0 = 1.26\text{x}10^{-14}\ E_p^{0.8}$ Sv·m^2 (with E_p the proton energy in GeV) and $\lambda = 118$ g/cm^2 for concrete or earth. H_0 is now a slowly varying function of incident proton energy and is essentially independent of target material. A discussion on source term and attenuation length is given in ref. [5] along with a list of references to neutron data.

There also exists a formulation of the Moyer model for an infinite line-source [6], valid for proton energy above about 1 GeV. For one proton per metre interacting uniformly over the whole length of an infinite source, the dose equivalent past the shield is given by:

$$H(r) = (\Upsilon/r)\int_0^{\pi} \exp(-\beta\theta)\exp[-(d\operatorname{cosec}\theta/\lambda)d\theta = (\Upsilon/r)M(\beta, d/\lambda) \qquad (2)$$

The parameter β has the value $\beta = 2.3$ for $\theta = 90°$. $\Upsilon = 2.84\text{x}10^{-13}\ E_p^{0.8}$ Sv·m^2 is the source term. The integral in this equation, $M(\beta,d/\lambda)$, is know as the Moyer integral. Values of the Moyer integral $M(2.3,d/\lambda)$ are given in table 2.25 of ref. [6] (1).

The line-source model was applied above 1 GeV and the results compared with the results of the calculations made for a point-source. Such a comparison has shown that the two calculations give similar results if one assumes a beam loss over a

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(1) The parameter β in expression (2) is not to be confused with the relativistic velocity $\beta = v/c$.

distance of about 7 m concentrated at a single point, in agreement with data in ref. [6]. Thus the shielding assessments were made using eq. (1) and assuming a 1 W/m loss over 7 m concentrated at one point.

3.1 Normal operation

The calculations were performed at a few selected energies, namely 25, 100, 400, 1000 and 2000 MeV. The most stringent shielding requirements are imposed at the high-energy end of the accelerator due to the more penetrating component of the secondary neutrons. Source terms and attenuation lengths from ref. [7] were used for energies from 25 MeV to 1 GeV, taking data for a thin copper target. The use of thin-target data is a reasonable assumption since a continuous loss during normal operation will most likely be produced by the beam halo grazing the vacuum chamber or interacting with aperture limitations at inter-cells gaps or at quadrupoles. This choice also represents a conservative assumption, as the neutron spectrum from a thick target would be softer, i.e, less penetrating through the shield. At 2 GeV use was made of source term and attenuation length of the Moyer model. The minimum shielding thicknesses required to reduce the ambient dose equivalent rate, H*(10), to below the public limit and to below the design value of a controlled radiation area are given in Table 1. The distance from the source to the outer surface of the shield (the parameter *r* in eq. (1)) was taken as 5 m for proton energies of 25 and 100 MeV and 10 m for higher energies. The earth thickness was assessed by simply scaling the shielding thickness for concrete by the ratio of the densities of the two materials (taken as 1.9 g/cm^3 for earth and 2.35 g/cm^3 for concrete). This approximation is sufficiently accurate for the present purpose. Actually the value of 1.9 g/cm^3 taken for the earth density should be regarded as conservative for local soil, a density of 2 g/cm^3 being probably a more realistic figure. A 5% reduction in the soil density translates into a 5% increase in the required shielding thickness (i.e., in the depth at which the linac has to be installed) thus introducing a small conservative factor (2).

Table 1. Minimum shielding thickness required to reduce the dose equivalent rate to below 0.1 µSv/h (the limit for public exposure) and 10 µSv/h (controlled radiation area) for a continuous loss of 1 W/m. It has been shown that this condition is equivalent to assuming a localised loss of 7 W. I_p is the intensity (protons per second) corresponding to a 7 W loss at a single point.

Energy (MeV)	I_p (p/s)	H_0 (Sv m^2 per proton)	λ (g/cm^2)	Required shielding (cm) for public occupancy			Required shielding (cm) for controlled area		
				d/λ	concrete	earth	d/λ	concrete	earth
25	1.7×10^{12}	5.8×10^{-15}	29	16.5	205	255	11.8	150	185
100	4.5×10^{11}	7.6×10^{-15}	46	15.5	305	380	10.8	210	260
400	1.1×10^{11}	9.8×10^{-15}	95	12.9	520	645	8.3	335	415
1000	4.5×10^{10}	1.2×10^{-14}	115	12.2	595	735	7.6	375	465
2000	2.2×10^{10}	2.2×10^{-14}	118	12.1	605	750	7.5	380	470

There is also the possibility that the piece of land under which the linac will be installed is acquired by CERN. In this case this land will be classified as supervised area and the dose equivalent rate limit taken as 1 µSv/h (2.5 µSv/h being the

(2) A value of 2.2 g/cm^3 was measured in 1966 for the soil on top of the PS, in the course of a joint CERN-LRL-RHEL shielding experiment [8].

maximum allowable under normal operation and 7.5 μSv/h the value under transient conditions [3]). The required shielding thickness will therefore be somewhere in-between the two values given in Table 1.

A beam loss monitoring system, interlocked with the accelerator control, will be needed to insure that during operation losses will stay below the specified value of 1 W/m.

3.2 Full beam loss

A loss of the entire beam (2 mA average current) corresponds to $1.25x10^{16}$ lost protons per second. If such loss is localised at one point, the source term for $E_p = 2$ GeV is approximately 10^6 Sv m^2/h, which would produce an instantaneous dose equivalent rate outside a shielding designed for public occupancy ($d/\lambda = 12$ and $r = 10$ m) of 60 mSv/h. If the beam is cut within 100 ms, the integrated dose equivalent would be less than 2 μSv, a perfectly acceptable figure. In case the beam is lost over a distance of several metres – say 10 m – which is probably a more realistic scenario, the line-source model yields a source term, for a 0.4 MW/m line-source at 2 GeV, of about $2.2x10^6$ Sv m^2/h. This radiation source would produce an instantaneous dose equivalent rate outside the shield of about 30 mSv/h and the integrated dose to an individual would be of the order of 1 μSv if the beam is again cut within 100 ms.

Therefore a shield designed for a continuous beam loss of 1 W/m during routine operation is also adequate for an accidental loss of the full beam at a localised point, provided that the linac can be stopped within 100 ms, which is well within the capabilities of the accelerator control system. The integral dose delivered to the public area in this time interval is of the order of 1 μSv, essentially independent of the fact that the loss is localised at one point or distributed over several metres.

4. Monte Carlo simulations

Monte Carlo simulations were performed with the FLUKA code [9-12] to calculate the attenuation curves in earth of secondary neutrons generated by beam losses. To this aim, a simplified cylindrical geometry was adopted, allowing a more efficient scoring in fictitious rings inside the shield. The actual geometry of the facility will be taken into account at a more advanced stage of the project.

A “multi-ring” source was set-up to simulate beam losses at aperture limitations at inter-cells gaps of the RF cavities. Twenty copper rings 4 cm thick (inner and outer diameter 12.5 and 13.0 cm, respectively) were centred on the beam axis, spaced by 50 cm, over a total length of 10 m. This scheme approximates the beam losses in a LEP superconducting RF module, which is made up of four 4-cell cavities with a total length of about 12 m. Twenty ring sources constituted by monoenergetic parallel beams of protons were made to impinge on each copper ring to simulate beam losses. Different calculations were performed to account for the energy increase of the beam inside the linac, namely at 50, 100, 200, 400, 800, 1000, 1500 and 2000 MeV.

The copper structure of the cavities was approximated with a cylindrical copper layer 4 mm thick and 35 cm radius, while the cryostat was simulated with an aluminium cylinder 1 cm thick and 60 cm radius, both 12 m long. A cylindrical concrete shell 30 cm thick was placed at 2 m distance from the beam axis to simulate the tunnel walls. Twenty cylindrical shells of earth of the same composition of the soil of the region (i.e., moraine with density $\rho = 1.9$ g/cm^3), each one 1 m thick, were placed concentrically outside the tunnel walls. The total length of the lateral shielding structure was 15 m. To refer to a situation comparable to an infinite line-source, the fluence of secondary neutrons was scored in cylindrical rings 1 m long at the boundary of each pair of moraine shells. Each scoring cylinder was placed in the middle of the shielding structure. Only particles directed outwards were taken into account for fluence scoring. The ambient dose equivalent H*(10) was estimated with the conversion coefficients of ref. [13]. The simulation geometry is sketched in Fig. 1.

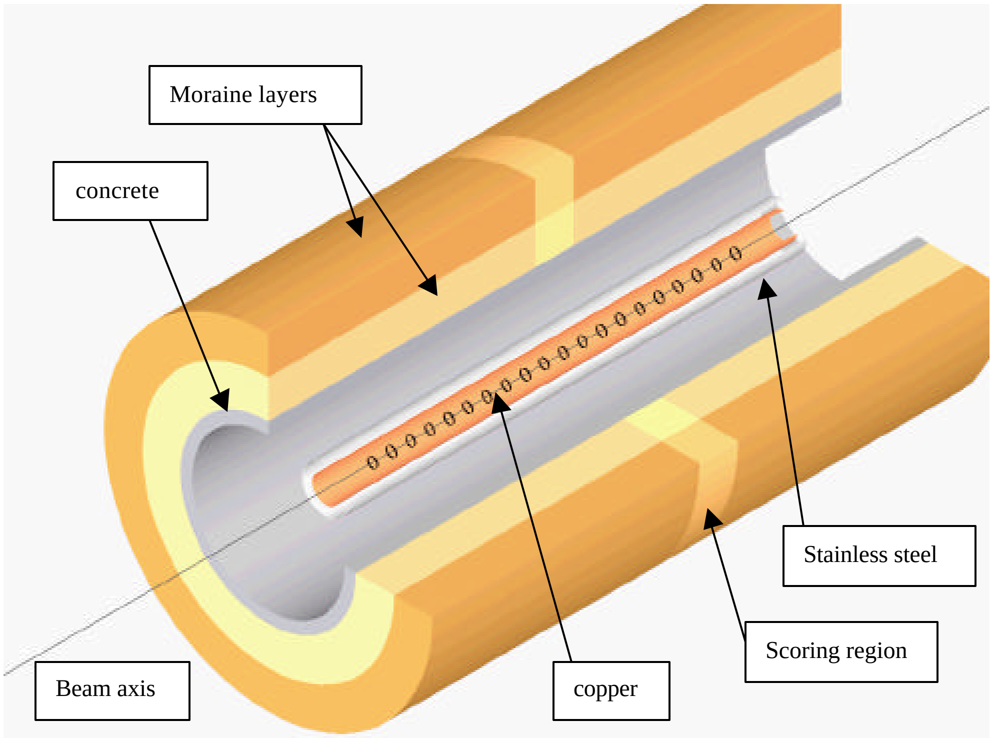

Fig. 1. Cut-off view of the geometry of the FLUKA simulations. The plot shows the twenty copper rings simulating the loss points, the inner copper cylinder simulating the cavity, the stainless steel cylinder representing the cryostat, the 30 cm thick concrete wall and the two, 1 m thick inner shells of the moraine shield (the complete shield is made up of 15 shells). Scoring is done in the central region shown in lighter colour.

The resulting attenuation curves for secondary neutrons are shown in the Appendix for the various proton beam energies, along with the fits to the data. The source terms H_0 and the attenuation lengths λ in moraine, extracted from the fits, are listed in Table 2. Table 3 gives the minimum shielding thickness required to reduce the ambient dose equivalent rate to below the public limit and to below the design value of a controlled radiation area, assuming a total loss of 10 W over 10 m distributed as explained above and using the parameters (H_0,λ) of Table 2. For consistency with the calculations of section 3.1, the distance from the source to the outer surface of the shield was taken $r = 5$ m for proton energies up to 200 MeV and $r = 10$ m above.

From Table 2 one sees that the values of H_0 and λ vary smoothly above 400 MeV; above this energy λ tends to the limit of 120 g/cm^2, as expected [6,7]. A comparison of the source terms and attenuation lengths in Tables 1 and 2 shows that the values of H_0 obtained from the Monte Carlo simulations are substantially lower than the figures calculated by the line-of-sight model, while the values of λ are slightly larger. This is essentially due to two reasons. First, in the FLUKA simulations the source is much different from the point-source assumed in the simplified approach adopted in section 3. Second, in the simulations the source neutrons interact with the copper of the cavity, the stainless steel of the cryostat and with 30 cm concrete of the tunnel wall, before actually impinging on the soil shield. The largest differences in H_0 and λ are indeed observed at the lowest energies, where the neutron spectrum is softer. These results indicate that the use of a simplified line-of-sight model is usually conservative, but can also lead to substantial overestimations of the required shielding, as in the present case.

Table 2. Source terms and attenuation lengths in earth (moraine) for primary protons of various energies resulting from the FLUKA simulations.

Proton energy (MeV)	Source term H_0 (Sv m^2 per source proton)	Attenuation length λ (g/cm^2)
50	$(8.10\pm0.44)\times10^{-18}$	30.22 ± 0.37
100	$(9.96\pm0.55)\times10^{-18}$	55.60 ± 0.31
200	$(5.57\pm0.13)\times10^{-17}$	80.97 ± 0.19
400	$(2.57\pm0.13)\times10^{-16}$	102.55 ± 1.16
800	$(5.46\pm0.32)\times10^{-16}$	113.12 ± 1.15
1000	$(6.15\pm0.38)\times10^{-16}$	116.25 ± 0.98
1500	$(8.97\pm0.46)\times10^{-16}$	119.02 ± 0.95
2000	$(1.16\pm0.04)\times10^{-15}$	119.20 ± 0.72

Table 3. Minimum shielding thickness (FLUKA simulations, Fig. 1) required to reduce the dose equivalent rate to below 0.1 µSv/h (the limit for public exposure) and 10 µSv/h (controlled radiation area) for a total loss of 10 W spread over a distance of 10 m. The beam losses are at inter-cells gaps evenly spaced by 50 cm.

Energy (MeV)	I_p (p/s)	H_0 (Sv m^2 per proton)	λ (g/cm^2)	Required shielding (cm) for public occupancy		Required shielding (cm) for controlled area	
				d/λ	moraine	d/λ	moraine
50	1.3×10^{12}	8.1×10^{-18}	30	9.6	155	5	80
100	6.3×10^{11}	1.0×10^{-17}	56	9.1	265	4.5	135
200	3.1×10^{11}	5.6×10^{-17}	81	10.1	430	5.5	235
400	1.6×10^{11}	2.6×10^{-16}	103	9.6	520	5.0	270
800	7.8×10^{10}	5.5×10^{-16}	113	9.6	570	5.0	300
1000	6.3×10^{10}	6.2×10^{-16}	116	9.5	580	4.9	300
1500	4.2×10^{10}	9.0×10^{-16}	119	9.5	595	4.9	310
2000	3.1×10^{10}	1.2×10^{-15}	119	9.5	600	4.9	310

The influence of other secondary particles (photons, pions, protons and electrons) produced in the interactions with the RF cavities and in the shielding materials was investigated for 2 GeV protons. The resulting source term and attenuation length are 20% higher (1.4×10^{-15} Sv m^2 per source proton) and 4% lower (115 g/cm^2), respectively, with respect to those referring only to secondary neutrons. Such differences are within the total uncertainties of the calculations (cross sections and fluence to dose equivalent conversion coefficients included). The ratio of the ambient dose equivalent induced by the different sources of secondary particles to the total is plotted in Fig. 2 for various depths in soil, showing that, as expected, neutrons rule the shielding estimate.

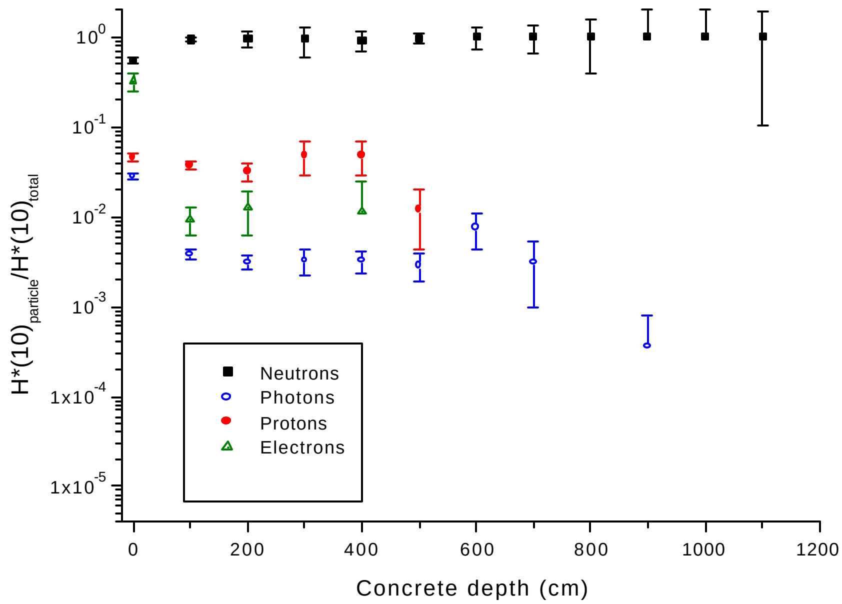

Fig. 2. Ratio of the ambient dose equivalent due to each secondary particle to total.

As mentioned above, fluence scoring in each fictitious cylinder inside the earth layer accounted only for outward-directed particles. This should minimise the effect of reflection (especially for neutrons) of the outer shells which lead to fluence (and consequently H*(10)) overestimation. Anyway, reflection is not eliminated completely in this way, because, as a second order effect, neutrons can be reflected more than once inside the shielding. Each time a multi-reflected neutron crosses a boundary outward, it is counted in this one-way fluence scoring. The exact estimate would have required a set of different simulations, each one with the correct shield thickness, and a much longer computing time. The effect of this approximation was investigated for 2 GeV protons with three separate simulations considering earth shields 2, 4 and 6 m thick. The ambient dose equivalent due to neutrons resulted about 30% lower than the present simulations with fictitious shells. Since the slopes of the attenuation curves are the same within the statistical uncertainties, this translates into a 30% overestimation of the source term when the shell approximation is adopted.

As mentioned above, a 20% underestimation of the source term was observed when considering the contribution of secondaries other than neutrons. Therefore, in the present case, the observed differences tend to compensate each other when the shell approximation is used and only the contribution of secondary neutrons is scored. This can be considered sufficiently accurate for the present purpose.

5. Neutron streaming through waveguide ducts

Several calculations and experimental measurements of the transmission of neutrons through ducts and labyrinths at high energy accelerator facilities are summarised in ref. [7]. This book provides universal transmission curves for the first leg of a labyrinth for a point-source, a line-source and a plane-source or a point-source off-axis, as well as universal transmission curves for the second and subsequent legs of a labyrinth. These curves are called universal because the depth d in the duct is measured in units of $z/\sqrt{S}$, where z is the physical depth in the duct and S is the cross-sectional area, and they may thus be applied to ducts of different radius.

In the present design [1] the linac tunnel is tilted by 1.4%, whilst the klystron gallery is at constant depth just below ground level. Several ducts of 0.5 m^2 cross section will connect the two tunnels and house the waveguides linking the klystrons to the RF cavities. At the low-energy end of the linac, the duct consists of two legs, the first 3.5 m long and the second 11 m long. At the high-energy end the duct is four-legged, with the first leg 3.2 m long, the second and the third 3 m long and the fourth 8 m long. Using the transmission curves of ref. [7] and assuming a line-source to calculate the attenuation provided by the first leg, the overall attenuation provided by the two extreme configurations are approximately $6\text{x}10^{-7}$ and $1\text{x}10^{-10}$, respectively. Estimates of the line-source term corresponding to 1 W/m yield a (possibly conservative) value of about 10 Sv/h. To reduce this figure to the required 10 µSv/h demands that the duct must provide an attenuation factor of 10^6. Whilst this requirement is largely met by the four-legged configuration, the design of the two-legged one seems barely sufficient and will have to be more carefully studied at a further stage in the project.

6. Transfer line and collimators

If beam losses in the transfer line from the linac to the accumulator ring can be controlled to the value of 1 W/m, the shielding requirements are the same as those of the high-energy end of the linac. However, there will be exceptions represented by the collimators, where beam losses will be higher. The present design foresees 5 or 6 collimators that will in total intercept about 1% of the beam intensity. The collimators are actually stripping foils designed to remove particles from the beam halo and direct them into small dumps. If the beam transfer line will not be at sufficient depth, some local shielding will have to be provided around these dumps. For example, if the fraction of the beam dumped at one location is 0.3% of the full intensity, the shielding requirement is, according to the line-of-sight model of section 3, 10 m of earth plus a local shielding made of 80 cm of iron, to meet the dose rate limit for the public. For the section of the transfer line running under CERN territory, which is supervised area, the dose equivalent rate limit can be taken as 1 µSv/h and the local shielding can be reduced to 40 cm of iron. According to the discussion in section 4, these figures are probably conservative. A detailed study will be needed once the design and the positioning of the transfer line is finalised.

7. Conclusions

This note has provided preliminary shielding estimates for the 2 GeV superconducting proton linac and transfer line. With the assumption than beam losses under normal operating conditions can be kept to below 1 W/m, the maximum required shielding thickness estimated by a simple model is 7.5 m of earth. With a more realistic beam loss pattern the maximum required thickness reduces to 6 m. This shield is also adequate in case of an accidental loss of the full beam at a localised point, provided that the accelerator can be stopped within 100 ms.

The present preliminary shielding and duct design will have to be confirmed by more detailed Monte Carlo simulations before the design of the facility is finalised. At present no design study has been undertaken for the beam dumps. There will be at least two types of dumps, one to stand about 100 kW, for beam set-up at comparatively low intensity, and one designed to absorb the full 4 MW beam. The 100 kW unit has a thermal power of the same order of the present SPS internal dump and a similar design can possibly be used as a guideline. The design of the latter will need a dedicated study to address both radiation and thermo-mechanical issues (cooling, mechanical stresses, etc). Further issues which will have to be considered in a more advanced design are ground water activation (although geological prospecting carried out in 1970 showed that at this depth there is no water table, this will have to be confirmed), as well as radioactive air and liquid releases. Radiation streaming through the access shafts (three are foreseen in the present layout) also need to be studied. An aspect which will have to be carefully addressed is the induced radioactivity in the linac and surrounding structures (shielding, support structures, cables and cable-trays, etc.), also in view of assessing the amount of radioactive waste to be handled at the time of the facility's decommissioning.

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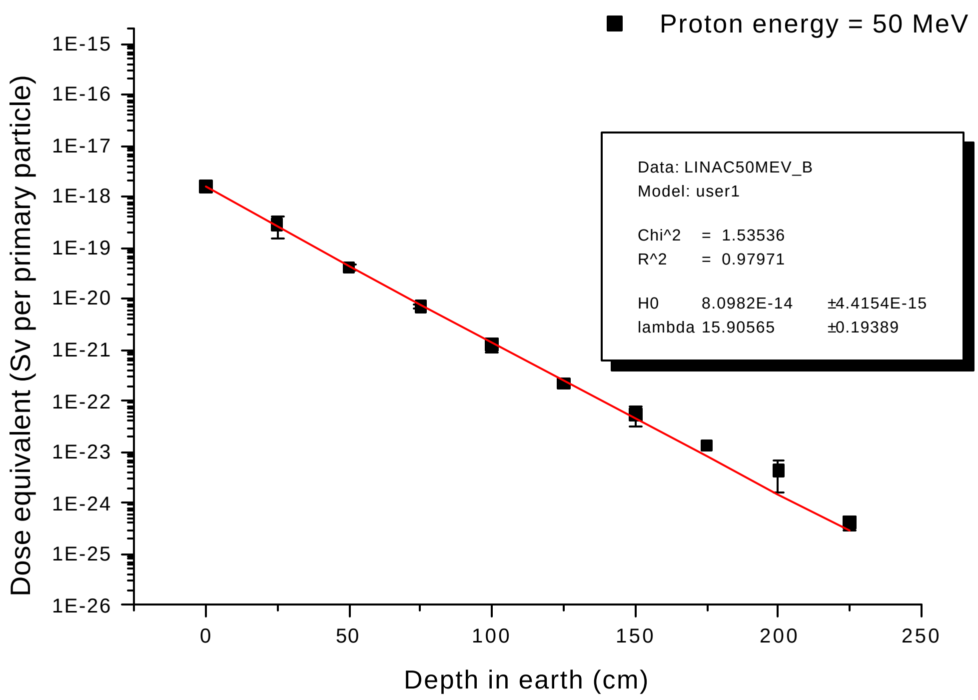
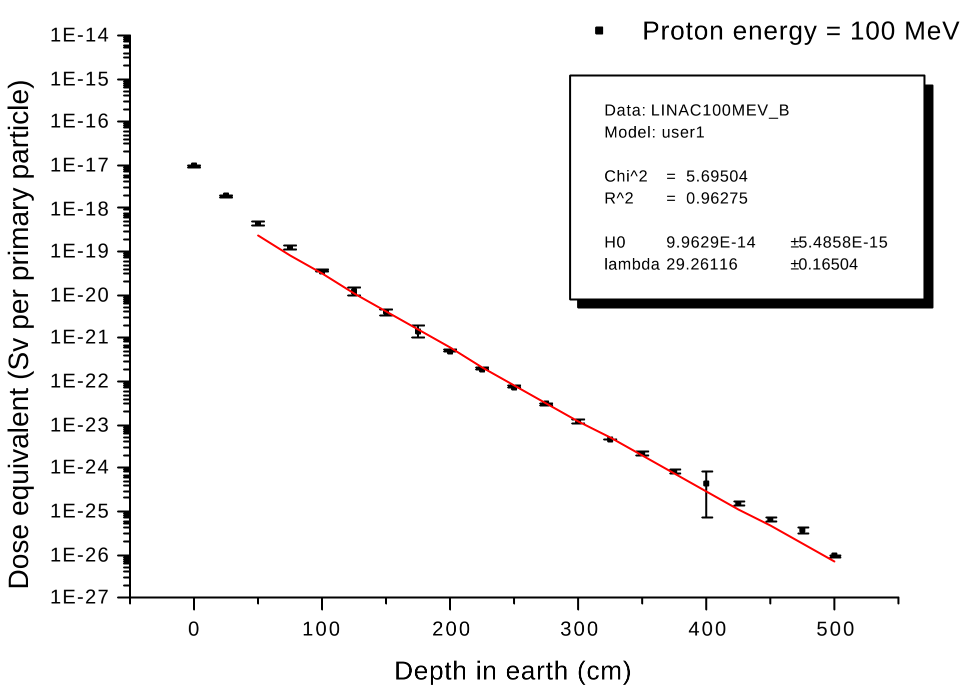
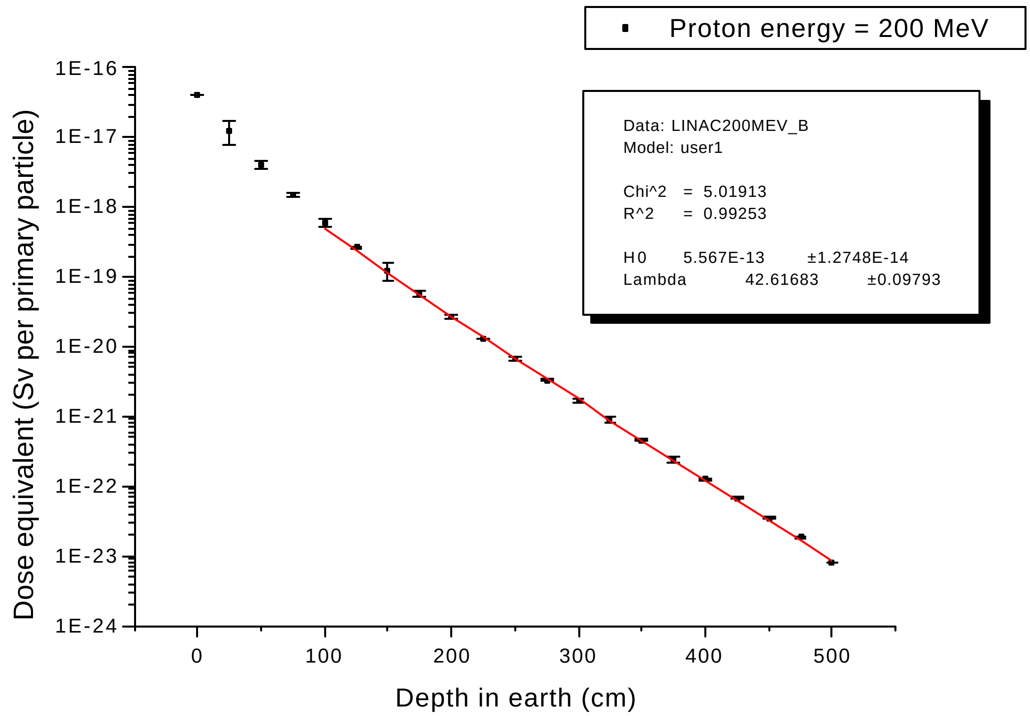
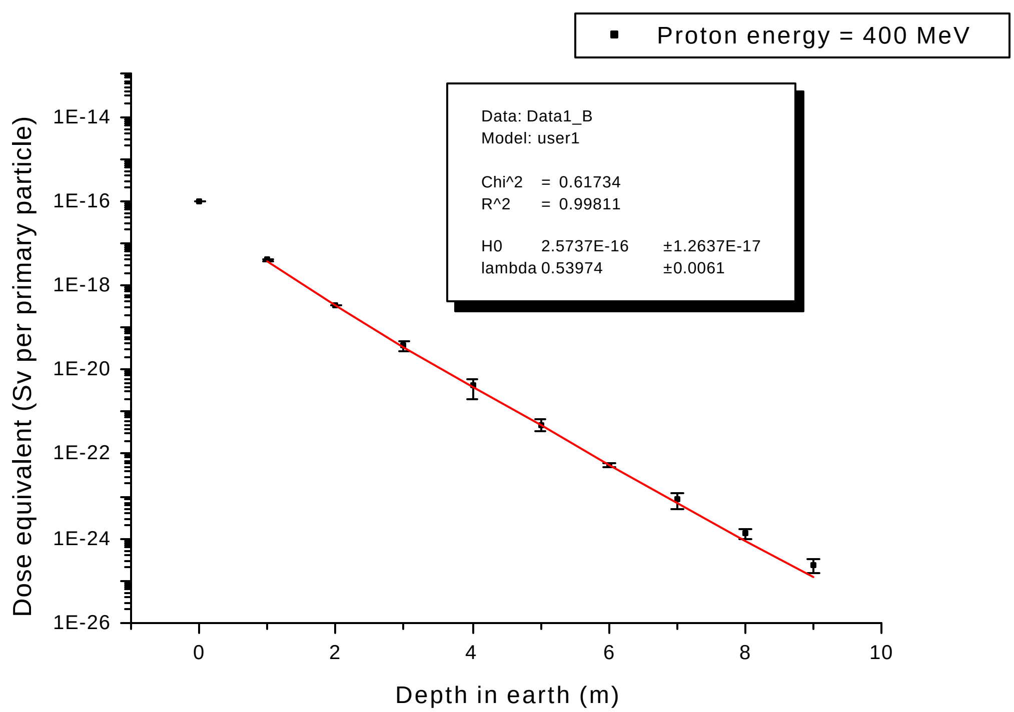
Appendix

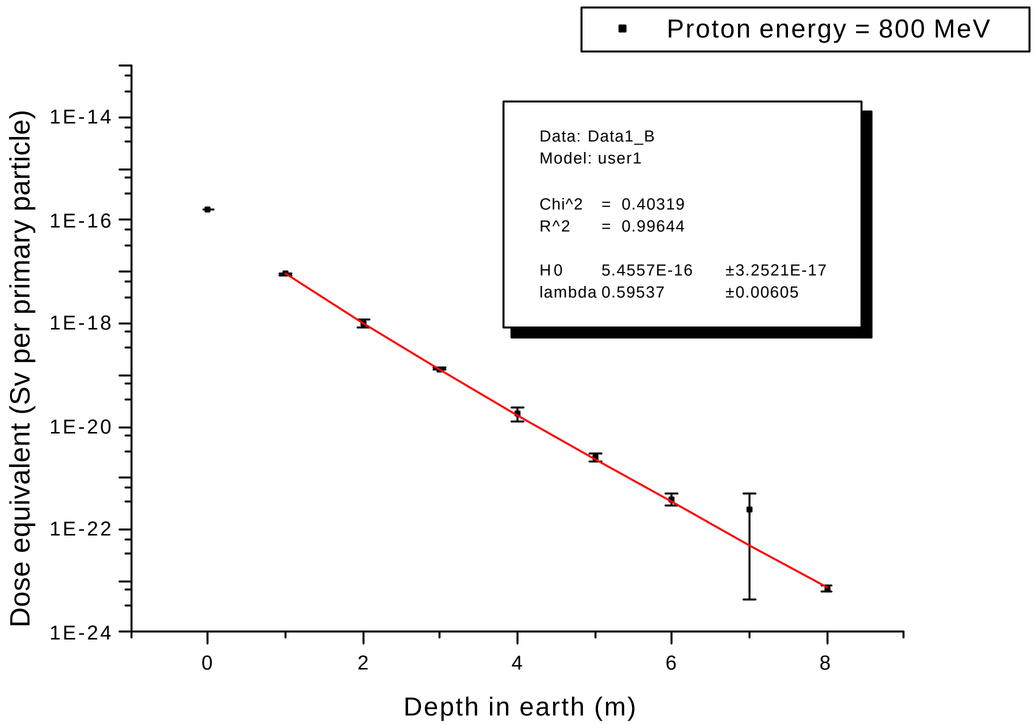
Attenuation curves in moraine for secondary neutrons produced by monoenergetic protons in the energy range 50 MeV to 2 GeV interacting inside the RF module as modelled in Fig. 1. Beam losses at inter-cells gaps are simulated by the "multi-ring" source described in section 4. Note that in the range 50 – 200 MeV the horizontal scale in the graphs is in centimetres rather than in metres and the H_0 values resulting from the fit are scaled by a factor of 10^4 with respect to data in Table 2. In the graphs the attenuation length is in centimetres and should be multiplied by the density of moraine (ρ = 1.9 g/cm^3) to obtain the values listed in Table 2.

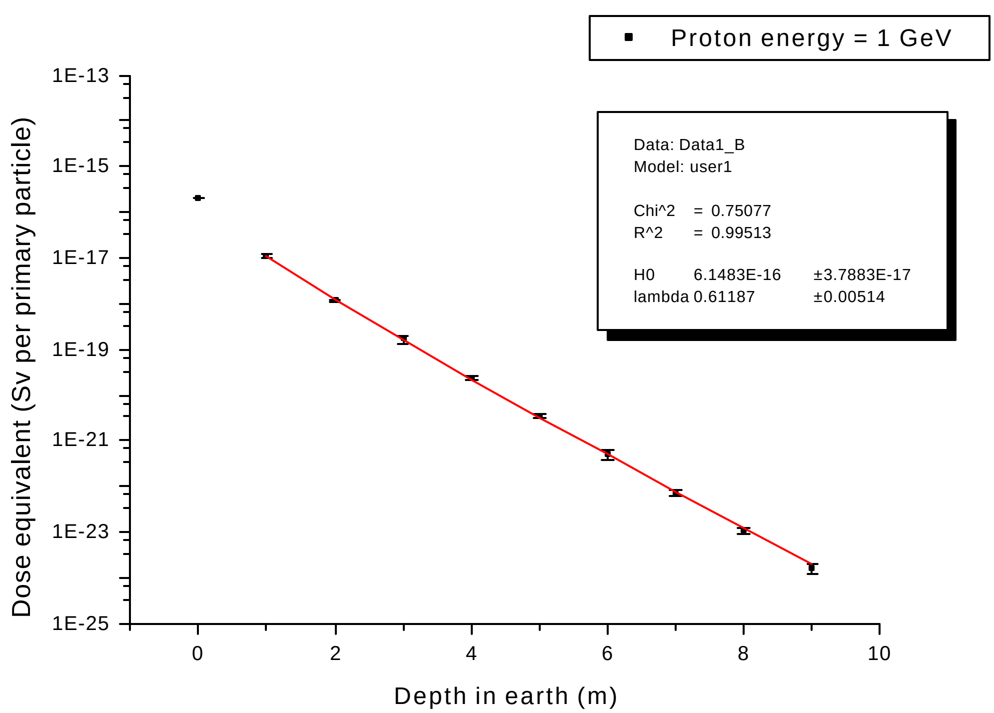

Proton energy = 50 MeV
Data: LINAC50MEV_B
Model: user1
Chi^2 = 1.53536
R^2 = 0.97971
H0 8.0982E-14 ±4.4154E-15
lambda 15.90565 ±0.19389
Dose equivalent (Sv per primary particle)
1E-15
1E-16
1E-17
1E-18
1E-19
1E-20
1E-21
1E-22
1E-23
1E-24
1E-25
1E-26
0
50
100
150
200
250
Depth in earth (cm)

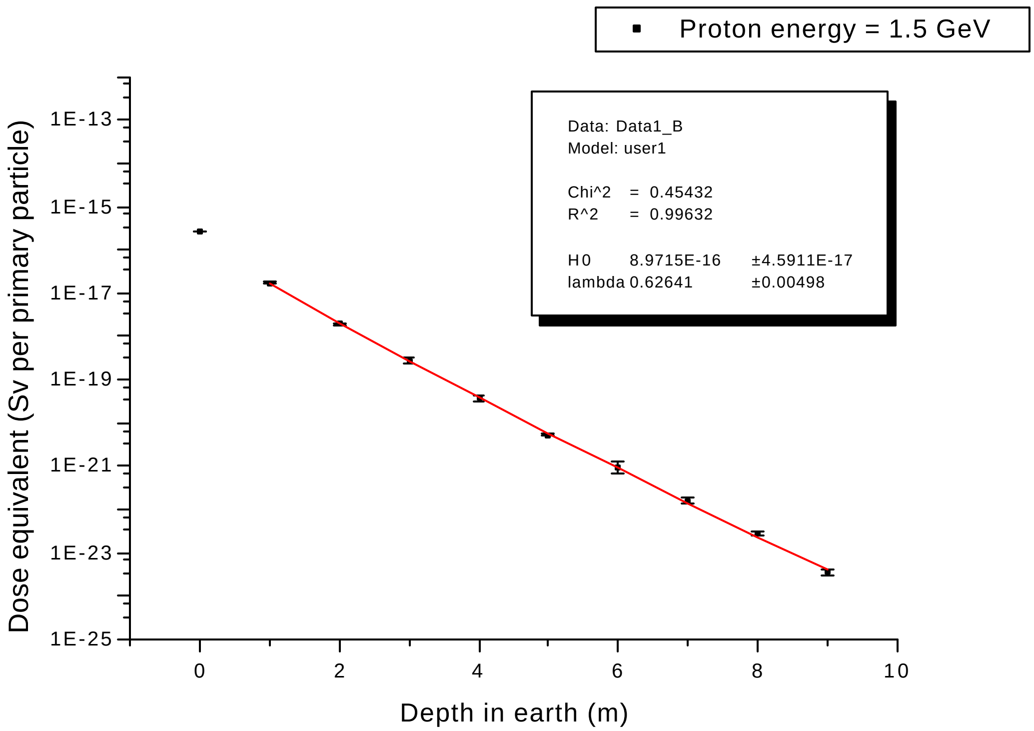

Proton energy = 100 MeV
Data: LINAC100MEV_B
Model: user1
Chi^2 = 5.69504
R^2 = 0.96275
H0 9.9629E-14 ±5.4858E-15
lambda 29.26116 ±0.16504
Dose equivalent (Sv per primary particle)
1E-14
1E-15
1E-16
1E-17
1E-18
1E-19
1E-20
1E-21
1E-22
1E-23
1E-24
1E-25
1E-26
1E-27
0
100
200
300
400
500
Depth in earth (cm)


Proton energy = 200 MeV
Data: LINAC200MEV_B
Model: user1
Chi^2 = 5.01913
R^2 = 0.99253
H0 5.567E-13 ±1.2748E-14
Lambda 42.61683 ±0.09793
Dose equivalent (Sv per primary particle)
1E-16
1E-17
1E-18
1E-19
1E-20
1E-21
1E-22
1E-23
1E-24
0
100
200
300
400
500
Depth in earth (cm)

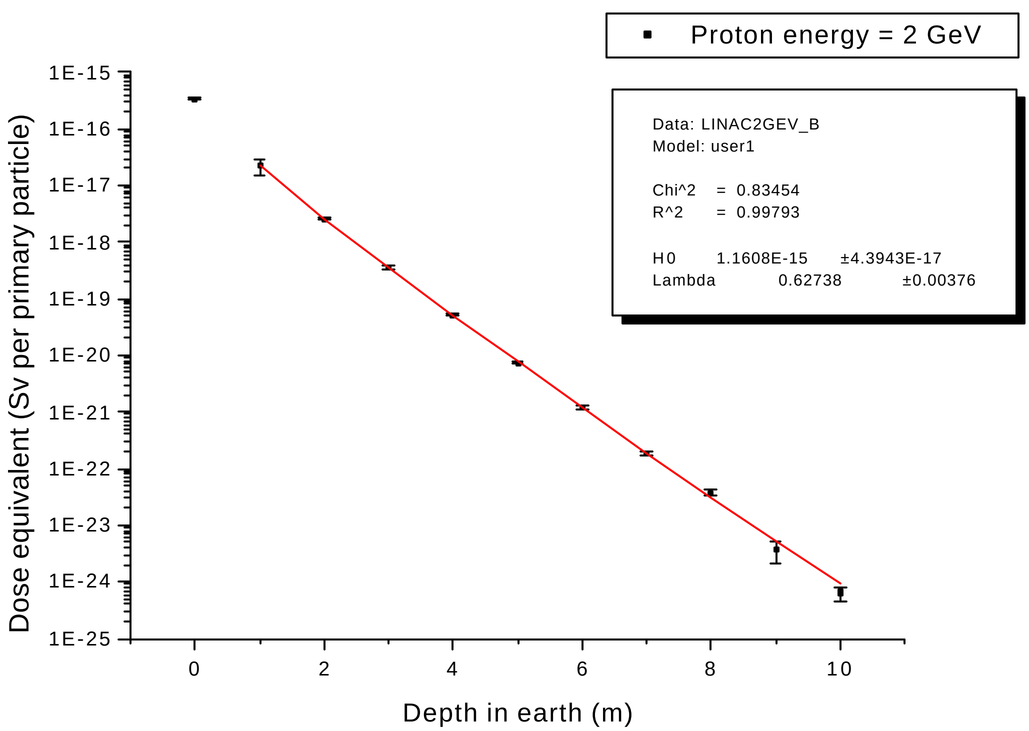

Proton energy = 400 MeV
Data: Data1_B
Model: user1
Chi^2 = 0.61734
R^2 = 0.99811
H0 2.5737E-16 ±1.2637E-17
lambda 0.53974 ±0.0061
Dose equivalent (Sv per primary particle)
1E-14
1E-16
1E-18
1E-20
1E-22
1E-24
1E-26
0
2
4
6
8
10
Depth in earth (m)


Proton energy = 800 MeV
Data: Data1_B
Model: user1
Chi^2 = 0.40319
R^2 = 0.99644
H0 5.4557E-16 ±3.2521E-17
lambda 0.59537 ±0.00605
Dose equivalent (Sv per primary particle)
1E-14
1E-16
1E-18
1E-20
1E-22
1E-24
0
2
4
6
8
Depth in earth (m)


Proton energy = 1 GeV
Data: Data1_B
Model: user1
Chi^2 = 0.75077
R^2 = 0.99513
H0 6.1483E-16 ±3.7883E-17
lambda 0.61187 ±0.00514
Dose equivalent (Sv per primary particle)
1E-13
1E-15
1E-17
1E-19
1E-21
1E-23
1E-25
0
2
4
6
8
10
Depth in earth (m)



Proton energy = 1.5 GeV
Data: Data1_B
Model: user1
Chi^2 = 0.45432
R^2 = 0.99632
H0 8.9715E-16 ±4.5911E-17
lambda 0.62641 ±0.00498
1E-13
1E-15
1E-17
1E-19
1E-21
1E-23
1E-25
0
2
4
6
8
10
Dose equivalent (Sv per primary particle)
Depth in earth (m)



Proton energy = 2 GeV
Data: LINAC2GEV_B
Model: user1
Chi^2 = 0.83454
R^2 = 0.99793
H0 1.1608E-15 ±4.3943E-17
Lambda 0.62738 ±0.00376
1E-15
1E-16
1E-17
1E-18
1E-19
1E-20
1E-21
1E-22
1E-23
1E-24
1E-25
0
2
4
6
8
10
Dose equivalent (Sv per primary particle)
Depth in earth (m)