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SHIELDING FOR CONCENTRIC STORAGE RINGS

by

W.C. Middelkoop and B. de Raad

1. Introduction

This report revises the report AR/Int. SG/62-10/Rev. The revision is made necessary due to the anticipated increase in the CPS intensity if a 200 MeV linac is to be built as a new injector for the CPS. At the same time, this report includes the effects on the shielding due to the tentative fixation of machine structure, of some relevant dimensions of the ISR tunnel and of the ground level on which the ISR will be constructed.

The proposed intersecting storage rings (ISR) (de Raad 1963) make it possible to perform simultaneously 8 different colliding-beam experiments. In addition they can be used to provide d.c. beams of secondary particles by slowly spilling out the injected protons in between successive pulses from the CPS. The most flexible experimental area would therefore be a large annular hall around the ISR, with inner and outer radii of, say, 120 m and 180 m respectively. The ISR would then be shielded with side walls made of concrete blocks and a roof made of concrete beams that could be rearranged so as to suit any specific experiment. Unfortunately such a lay-out requires huge amounts of concrete and is very expensive.

Since, per unit volume, earth shielding is about a factor 30 cheaper than ordinary concrete, one should try to use as much earth as possible for shielding purposes. Burying the ISR in an underground tunnel is the most effective way of achieving this. This solution is in fact imposed by the quality of the ground of the site on which the ISR have to be built. Studies (Soletanche, 1964) of the structure of the underground have shown that the highest level acceptable for the tunnel floor is at 443 m in order to be on stable sandstone along the whole circumference of the ISR. The lowest level of the ground surface around the machine is at about 449 m, while the highest level is at 462 m. A tunnel of 6 m height will therefore have at most its roof on the level of the normal ground surface.

On the other hand, the problem of access to the colliding beam areas has led to the proposal of an excavated road on the 443 m level on the inside of and about concentric with the ISR tunnel as shown in fig. 1. In spite of the fact that earth shielding for the side walls cannot slope down faster than at a rate of 1 : 2.5 for stability reasons, which implies an earth volume of 3.5 times that of a concrete shield, earth shielding remains the only economical proposal. This reasoning also applies to the shielding of the colliding beam experimental halls, of which the sizes have been tentatively fixed at a length of 70 m and a width of 25 m for the intersection points where the ISR beams go towards the inside, at a length of 50 m and a width of 25 m for the points where the beams go towards the outside, and with a height inside the halls of 13 m in both cases.

There are only two cases where an argument can be made in favour of a wall and roof shielding consisting of concrete blocks. The first one is a demountable tunnel section at an intersection point, which allows the construction of a colliding beam hall, the size and shape of which can be decided in the future, without an extensive shut-down period for the ISR. This case will not be treated further in this report. The other case, which will be considered here, is that of a demountable shielding around the part of the ISR to be used for stationary target operation, the whole overcoupled by part of an experimental hall of 50 x 200 m^2 for the use of secondary beams.

In estimating the required shielding thicknesses, we shall whenever possible extrapolate from the existing information about the radiation level around the CPS instead of basing ourselves on less reliable theoretical calculations. Measurements have been made by the CERN Health Physics Group in order to survey the radiation hazards around the CPS. Although these measurements have perhaps not the desired accuracy for our purpose and more extended measurements will have to be made, they offer already the most reliable starting point for estimating the required shielding thicknesses against nuclear radiation. For the muon background estimates based on the known pion production spectra are made.

2. Biological Requirements

We shall base the shielding design on biological requirements and assume that any detector which needs a lower background has its own special shielding. The maximum permissible dose (mpd) for radiation workers is 2.5 mrem/hr (Rossi 1957).

When a beam of strongly interacting high energy particles passes through a concrete shield its intensity decreases by absorption, but after a few mean free paths each surviving primary particle is accompanied by a large number of lower energy particles, most of which are neutrons from nuclear stars and other processes and the biological effects are mainly due to these degraded particles. The degraded radiation emerging from a thick shield usually consists of a mixture of fast neutrons, slow neutrons and γ-rays.

Measurements made by the CERN Health Physics Group (Baarli, 1964 a) indicate the following radiation composition in rem-dose outside the CPS shielding which is about independent of shielding thickness and target location,

thermal neutrons	11 to 12 %
fast neutrons (100 keV - 20 MeV)	50 to 76 %
high energy particles (above 20 MeV)	2 to 25 %
γ-rays + ionization from charged particles	2 to 19 %

Only the number of fast neutrons will be considered in our calculations and it will be assumed that the mpd corresponds to a neutron doserate of 1 mrem/hr. The latter figure is equivalent to 7 fast neutrons /cm^2 sec. (Rossi, 1957).*) This conservative assumption seems justified as the calculations will be mainly based on the neutron measurements made by the proton recoil counter and long counter which are only sensitive to the neutron energy range of (0.1 - 14) MeV (Baarli, 1964 b).

An important part of the background in our case consists of fast muons. We therefore also note (Lindenbaum 1961), that 1mrem/hr corresponds to 9 minimum ionizing particles/cm^2 sec.

In calculating shielding thickness we shall aim at the mpd on top of the roof, where people do not normally work and 0.1 of the mpd in the working areas at both sides of the ISR. We believe that this last figure provides an adequate safety factor against possible errors in our results due to uncertainties in the parameters which enter into the calculation.

3. Sources of Background Radiation

The shielding design should be based on the intensities which might be reached with the CPS in 6 years from now, in order to avoid expensive additions to the shielding after the first period of operation of the ISR.

*) The readers who wish to compare this report with AR/Int. SG/62-10/Rev. will find that in the previous report calculations were based on an mpd of 2 mrem/hr for fast neutrons. This does not reflect a change of policy however, since the measured number of neutrons in the (0.1 - 14) MeV interval was in that case arbitrarily multiplied by a factor of two to account for the higher energy neutrons. In view of the new information about the radiation composition, the authors preferred the formulation given above.

The maximum intensity which one might hope to reach with the CPS with the present 50 MeV linac as injector is

$$N_a = 2 \times 10^{12} \text{ protons/pulse.}$$

This is about 2.5 times the present CPS intensity. If the 50 MeV linac is to be replaced by one of 200 MeV, as is seriously being considered at present, the CPS intensity could go up by another factor of five to

$$N_a = 10^{13} \text{ protons/pulse.}$$

The maximum current expected to be stacked in each of the ISR is

$$N_s = 4 \times 10^{14} \text{ protons (= 20 Amp).}$$

For the purpose of estimating the shielding thickness however, we shall assume a maximum stacked current of

$$N_s = 4 \times 10^{15} \text{ protons (= 200 Amp).}$$

In spite of this last assumption it will be shown that the required shielding thickness is not determined by the colliding beam experiments but by the use of the ISR to provide d.c. beams of secondary particles for the orthodox way of experimentation. The shielding calculation for this last case will be based on the injection of 10^{13} protons per pulse into the ISR.

For the purpose of shielding calculations we assume a pressure of 10^{-8} mm Hg in the ISR. The beam lifetime is then 1.2×10^{5} sec = 33 h and the number of protons lost from each SR is 3×10^{10} protons/sec. The radiation from a point target is smeared out over some 40 m along the ISR circumference of 940 m. Therefore the beam loss from both ISR due to gas scattering gives close behind the shielding wall about the same background as a point source of 3 x 10^9 protons/sec. Lindenbaum (1961) reports that when the Cosmotron was accelerating 2 x 10^9 protons/sec at 3.0 GeV, with barrier shielding, but without roof shielding, the sky shine radiation level was already 3 mrem/hr which is slightly above the mpd. It appears therefore that even under quite ideal conditions the ISR are not such clean devices as one might think at first sight.

Suppose that the beam in the ISR is renewed after 24 hours. The injected beam must pass as close as possible to the vacuum chamber wall in order to use effectively the total horizontal aperture. Moreover one may spill, say, 25 % of the protons from the RF bucket during stacking. Finally the surviving beam after 24 hours must be disposed of before a fresh beam can be stacked. We shall be somewhat generous and assume that during all these manipulations each ISR is allowed to spill out 10 % at any place around its circumference. This gives an extra source strength of 9 x 10^9 protons/sec.

Although we may assume that normally one can dispose of the beam in a well shielded place, it might occasionally happen that the beam is lost somewhere else before it can be dumped, due to some minor accident, like vacuum or magnet trouble. These troubles are likely to be associated with an experimental set-up in the interaction region, so that the beams of both ISR would be lost at approximately the same place. This gives rise to a large instantaneous radiation level. Let us assume that the total dose received by a person working behind the shielding at that moment can be treated as if it had been accumulated over a period of 4 weeks with 40 working hours per week. This then corresponds to a source strength of 14 x 10^9 protons/sec.

Adding up we find a total equivalent source strength of 2.6 x 10^{10} protons/sec for the case of colliding beam experimentation with the ISR.

One might argue that these estimates are somewhat exaggerated regarding stored proton intensity and prevailing pressure. However, if the ISR are used for 25 GeV experiments the interaction rate in the target is about $\underline{3 \times 10^{12} \text{ protons/sec.}}$ A 3 $^{o}/o$ spill-out at any place (or over some 40 m length) due to injection and targetting together would correspond to a source strength of 10^{11} protons/sec. A total spill-out of about 70 $^{o}/o$ over the whole circumference of the machine is not excessive since the proposed vertical aperture of the ISR is only 52 mm instead of 70 mm for the CPS. This reduces the number of multiple traversals through a target, and thus the target efficiency, and increases the beam loss.
On the other hand, it is expected that the machine contamination will prevent the continuous use of internal targets at the maximum intensity foreseen. This will make imperative the use of fast or slow ejected beams in some 80 $^{o}/o$ of the non-colliding beam experiments, and the internal beam loss may be expected to be reduced to at most 20 $^{o}/o$ under those conditions.

We see that the required shielding thickness is determined by stationary target operation, in spite of the somewhat generous beam loss assumptions for the case when the ISR are used for colliding beam experiments. The beam loss estimates outside the target region would be about the same for both situations if the use of the 200 MeV linac was not taken into consideration.

The average beam loss near the injectors under normal working conditions should of course be small compared to that in the targets. However, during the starting up process when the initial attemps are being made to circulate the beam, it is possible that most of the beam might get lost in the injector region, so that it looks desirable to shield it for the full beam intensity.

For shielding design we shall take a source strength of

10^{11} protons/sec	everywhere around the tunnel
3×10^{12} protons/sec	in the region of the target and the injectors.

4. <u>Shielding aganist Strongly Interacting Particles</u>

Measurements have been made by the CERN Health Physics Group of the background on top of the CPS tunnel at 7.5 m above an uranium target operating in straight section 82. The beam intensity was 4.1×10^{11} protons per burst at 5 sec. intervals, with a proton energy of 26 GeV. The fast neutron level had a maximum value of 16 neutrons/cm^2 sec. right above the target and gradually decreased to half this value at about 20 m downstream of the target. Other measurements, with other target materials and at different positions, give similar results. Qualitatively one can explain this behaviour by noting that although most of the secondaries are produced at small angles to the primary beam, they are partially shielded by the steel of the CPS magnet and hit the roof under such small angles, that their effective path in it is several times the perpendicular thickness.

Geibel et al (1963) have made a theoretical estimate of the target efficiency by a Monte Carlo procedure. Their results indicate that values as high as 70 $^o/o$ can be expected in case of beryllium targets and up to 40 $^o/o$ for copper targets. No absolute experimental values are reported by them however. Neale (1962) has analyzed the data for some CPS external beams and found that with beryllium targets the efficiency lies between 25 and 40 $^o/o$ if the elastic proton-proton scattering is included.

Targets with larger Z have more coulomb scattering and therefore tend to have a lower efficiency. We shall assume that in the measurement reported above the target efficiency was 25 %. This then gives 8 neutrons/cm^2 on the tunnel roof per 10^{10} interacting protons/sec.

In the following we shall express all shielding thicknesses as equivalent thickness in concrete. The roof thickness of the CPS tunnel is 40 cm of concrete (2.4 g/cm^3) plus 3.2 m earth (1.7 g/cm^3) which is equivalent to 2.66 m concrete. The radiation level on the tunnel roof then is 20 fast neutron/cm^2 sec. for a source of 2.5 x 10^{10} protons/sec., which is about three times the mpd.

It might be argued, that on top of the roof a neutron flux larger than the mpd would be allowed, since access to the roof can be restricted or forbidden when the ISR operate. However, it is well known that the neutrons are scattered back from the air and give rise to a general background radiation (skyshine) which is approximately inversely proportional to the distance from the source (Lindenbaum 1961). The radiation level allowed for the general population is about 44 times smaller than the mpd for radiation workers. Therefore we consider it advisable that the neutron flux on top of the roof does not exceed the mpd. Moreover, it is difficult to add roof shielding at a later stage, since the roof strength would not be sufficient. Also for this reason we consider it advisable to be somewhat on the conservative side in the choice of the roof thickness.

Since the preliminary accepted height for the ISR beam tunnel is 6 m against 4.5 m for the CPS, the ISR tunnel width 15 m against 6 m for the CPS and since we anticipate a thicker shielding for the ISR than for the present CPS, we shall calculate the roof and inner side wall shielding for a chosen radiation dose at 10 m distance from the beam everywhere around the tunnel while this distance will be taken 12 m for the target and injector regions. The different distances from the beam are accounted for by the inverse r^2 law, where r is the distance to the source.

Hence, we allow a level of 7 neutrons/cm^2 sec. on top of the roof. The mean free path in concrete for removal of nuclear particles around 1 GeV such as are produced at large angles is 130 g/cm^2. Starting from the measurements of the Health Physics Group we then find a roof thickness of 3.7 m concrete for a source of 10^{11} protons/sec. and 5.3 m for a source of 3 x 10^{12} protons/sec.

The inside wall of the shielding is exposed to radiation in much the same way as the roof. To reduce the background to 0.7 neutron/cm^2 sec. we need 4.9 m concrete for a source of 10^{11} protons/sec. and 6.6 m concrete for a source of 3 x 10^{12} protons/sec.

For the outside wall the situation is quite different. The average inelasticity of high energy collisions is not more than 50 °/o so that quite often the primary proton retains most of its energy. The average transverse momentum of the secondaries is about 400 MeV/c. Then there are the elastically scattered protons and the high energy neutrons which are strongly peaked in the forward directions. The majority of these high energy secondaries produced at small angles will hit the outside shielding wall, which must therefore be thicker than the roof and the inner wall. Accurate calculations are difficult in this case, but it will be shown below that the thickness of the outside shielding wall is mainly determined by the muons. We shall therefore restrict ourselves to an approximate pessimistic calculation of the thickness required for the outside shielding wall to reduce the fast neutron level to 0.1 of the mpd. For the moment we shall neglect the effect of the magnet yokes.

Let us assume that half of the energy of the primary proton is carried away by high energy secondaries which are contained in a cone with half opening angle 2^{0} and that the other half is distributed over low-energy secondaries produced at much larger angles, up to 90^{0}. The latter half is taken care of by the same shielding thickness as we had found for the inner wall, so that we only consider the forward cone. We assume the geometry shown in Fig. 3. Each high energy secondary of the forward cone develops a nuclear cascade in the shielding wall. If all degraded particles went in the forward direction, their effective path in the concrete would be very long. We take for the removal the mean free path at these high energies in concrete 170 g/cm^{2} and assume a fast neutron build-up factor 100 per 25 GeV proton. Finally, we assume that the nuclear cascade in the concrete forms a uniformly filled cone with half opening angle 30^{0}. To reduce the fast neutron background to 0.7 neutron/cm^{2} sec., we then need a concrete thickness of 6.3 for a source strength of 10^{11} protons/sec. and 7.6 m for a source of 3×10^{12} protons/sec.

5. Shielding against Muons

The mean free path for decay of a π-meson is 55 p metres, where p is the momentum in GeV/c. A 10 GeV/c π-meson has a 1.8 $^{0}/_{0}$ probability to decay in a flight path of 10 m, so that the high energy muon flux is, roughly speaking, a few per cent of the high energy π-meson flux. However, the muons are not absorbed by nuclear interactions but are only slowed down due to energy loss by ionisation. Only those muons are suppressed, whose range is smaller than the shielding thickness.

The energy spectra of π-mesons produced by 25 GeV protons are reasonably well known (Baker et al., 1961, Diddens et al., 1962, Cocconi 1961). For the given π-meson momentum p_π the muon momentum p_μ has approximately an equal probability to have any value in between 0.57 p_π and p_π. We shall assume therefore that the momentum of all muons is 0.79 times the momentum of the parent π-meson. The momentum of the muon in the rest frame of the π-meson is about 30 MeV/c so that in the laboratory system the muon has essentially the same direction as the π-meson. The angular distribution of the π-mesons is strongly peaked in the forward direction. The most realistic figure for a shielding design is the muon flux, averaged over a suitably chosen area. We have therefore integrated the π-meson spectra over all angles and calculated the total number of muons, per interacting proton, whose momentum exceeds a value p_{min}, assuming a π-meson decay path of 10 m. The result is shown in Fig. 2.

The high energy muons are produced approximately tangentially to the ISR, so that they only influence the shielding thickness on the outside of the ISR. The attenuation of the muons depends strongly on the geometry of the shielding and the ISR magnets. If the ISR beam level will be on 444.5 m there will essentially be only a muon problem in the hall for secondary beams from stationary target operation. Since the lowest surface ground level encountered around the ISR is about 449 m (the highest about 462 m), all muons will be stopped in the surrounding earth. We shall therefore treat only the case of the secondary beam hall where a demountable shielding of concrete blocks around the machine is foreseen. The lay-out is shown in Fig. 3.

We want to determine the shielding thickness necessary to reduce the muon flux to 2.5 muons/cm^2 sec., i.e. 0.1 of the mpd, behind the shielding wall at a distance of 50 m from the target. For simplicity we assume that all muons come from the internal target. For all calculations in this section we shall make the following assumptions:

a) The number of interacting protons is 3×10^{12} per sec. Half of the π-mesons are absorbed in the vacuum chamber wall or collimators close to the point of production, so that they do not contribute to the muon flux.

b) The average flight path of the π-mesons is 10 m. We average the total number of muons as derived from Fig. 2 over a cone with a half opening angle of 50 mrad and neglect the detailed influence of the magnet stray field.

c) We consider all negative muons and only 50 °/o of the positive muons, since roughly half of the latter will be deflected inward by the downstream magnet units and consequently strike the side walls under small angles, which increases proportionally their path length inside the shielding, and are moreover smeared out over a large length of the shielding wall.

d) The average momentum loss of the muons in collimators, beam transport, downstream magnet yokes, etc is 3 GeV/c. The equivalent of 2.1 m of steel is needed for this energy loss, if we assume $\frac{dE}{dx} = 1.8$ MeV per g/cm^2.

Under those conditions the total number of muons of one sign per interacting proton with $p_\mu > p_{min}$ for 10 m decay path of the π-mesons has to be smaller than 1.7×10^{-7}. Extrapolating the trend of Fig. 2 we estimate that all muons with momentum smaller than 15 GeV have to be stopped. Allowing for an energy loss of 3 GeV in the target area, the shielding in the forward direction has to be sufficient to stop 12 GeV/c muons, which corresponds to 6.7×10^3 g/cm^2 i.e. 8.55 m of steel (ρ : 7.8 g/cm^3) or 19.0 m of barytes (ρ : 3.5 g/cm^3). It is obviously advantageous to place the shielding wall so that it provides maximum path length in the 0^0 direction. On the other hand, if a 5 tons crane is required in the target area as in the other parts of the ISR tunnel, its shielding has to be constructed as a continuation of that tunnel. With the shielding lay-out as shown in Fig. 3 a wall thickness of 7.6 m of baryte is sufficient for the required path length in the 0^{o} direction. It may be noted that this thickness provides 40 removal mean free paths ($\lambda \sim 170\ g/cm^{2}$) for the high energy strongly interacting particles in the forward direction.

For muons which originate upstream from the target we assume a point source strength of 10^{11} interacting protons and calculate the shielding thickness at 60 m from the source. The other conditions remaining the same we calculate a path length of 14.3 m of baryte along the appropriate 0^{o} production direction. For this a shielding wall thickness of 5.85 m of baryte is required. However, a decrease of beam loss in this region by appropriately placed beam catchers in the ISR could be attempted. Moreover, space requirements in the ISR tunnel upstream from the target may be less strignent so that some additional baryte shielding could be provided near to the ISR inner arc straight sections in order to prevent pion decay and to slow down muons. A wall thickness of 5 m of baryte is therefore proposed for the longest part of the outside shielding wall.

The thickness of the inner wall is chosen as 4.5 m of baryte and that of the roof as 5.3 m of concrete since they are determined by the attenuation of the nuclear cascade as treated in section 4. The choice of baryte as shielding material for the size walls was made on space considerations. Cost considerations could still lead to the choice of an equivalent thickness in concrete for a large part of the shielding wall in the hall for secondary beam experiments. The fact that this shielding is demountable allows its adaptation to the actual beam intensities injected into the ISR at a given moment.

6. Conclusions

The following table summarizes the shielding thicknesses for the inner wall and the roof calculated in the previous sections

Source strength	10^{11} protons/sec.			3×10^{12} protons/sec.		
Part of shielding	earth	concrete	baryte	earth	concrete	baryte
Roof mpd ~~at 10 m from source~~ (allowed)	5.2 m	3.7 m	2.5 m	7.5 m	5.3 m	3.6 m
Inside wall 0.1 mpd ~~at 12 m from source~~ (allowed)	6.9 m	4.9 m	3.4 m	9.2 m	6.5 m	4.5 m
Outside wall	See section 5.					

For the outside wall no figures are mentioned since the tunnel floor is at least 6 m below the lowest ground surface level, by which automatically an adequate earth shielding is provided. This is not the case for the secondary beam hall. Here the shielding thickness is determined by the required attenuation of the muon flux, as it always is for the outside wall for our primary proton energies. An estimate for the shielding thickness adapted to this particular situation is given in section 5 while the lay-out is shown in Fig. 3.

As the thickness estimate for the outside and inside shielding walls is based on 0.1 mpd behind the wall in the experimental area and on a maximum CPS intensity which might be a factor 2 higher than realistically can be hoped for, we have a safety factor of 20 against errors resulting from the uncertainties in the experimental data for the parameters on which the calcualtion is based. It is our opinion that this safety factor is sufficient, but not exaggerated. Better data about the effectiveness of the CPS shielding could lead to some reduction in this safety factor, thereby ..

reducing the required shielding thicknesses. The accuracy of the estimate for the thickness of the outside wall is limited by the dependence of the muon flux on the lay-out of collimators, beam transport etc in the target area.

The critical evaluation of the calcualtion for the roof shielding is complicated by the requirement to have the mpd for the general population at the boundary of the CERN site. This dose in mrem/hr is 44 x smaller than that for radiation workers. It is difficult to make a reliable estimate for the dose at larger distances which is determined by the sky shine radiation, but preliminary estimates show that this condition is met for the proposed shielding. More extensive measurements on the CPS radiation level at larger distances could serve as a welcome guide on this point however.

Acknowledgements

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Distribution: (open). Scientific Staff AR Division.

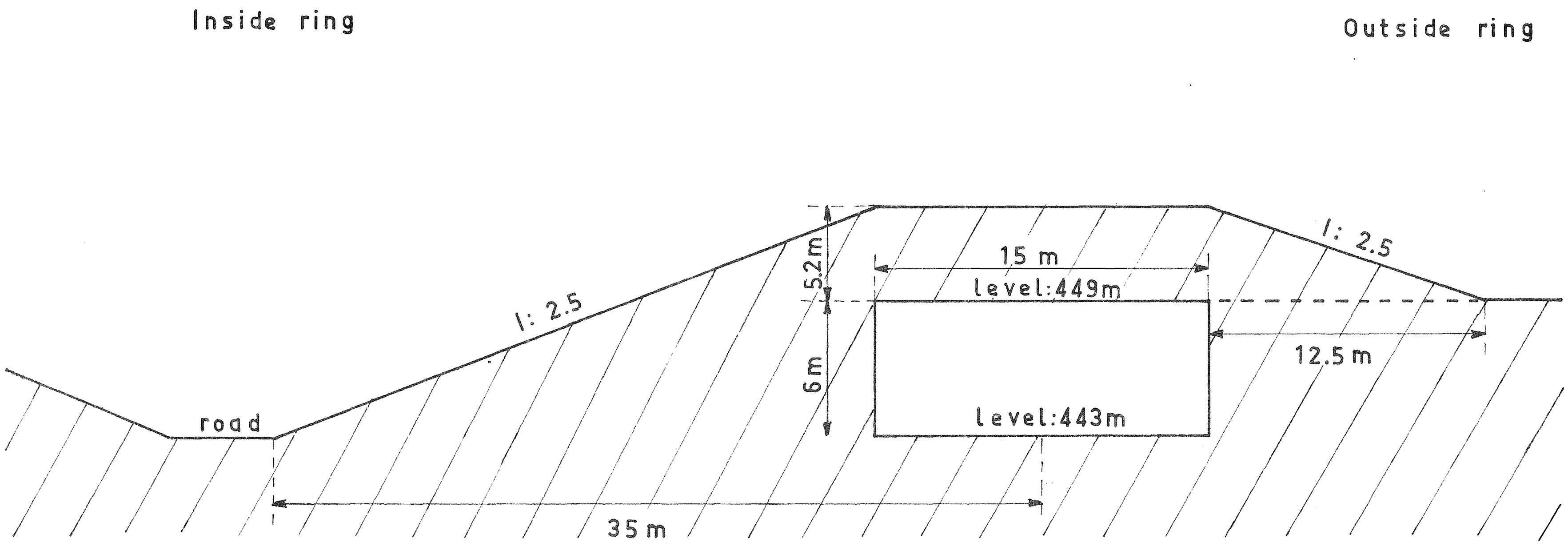

Fig. 1. TYPICAL SHIELDING LAY-OUT AROUND ISR TUNNEL.

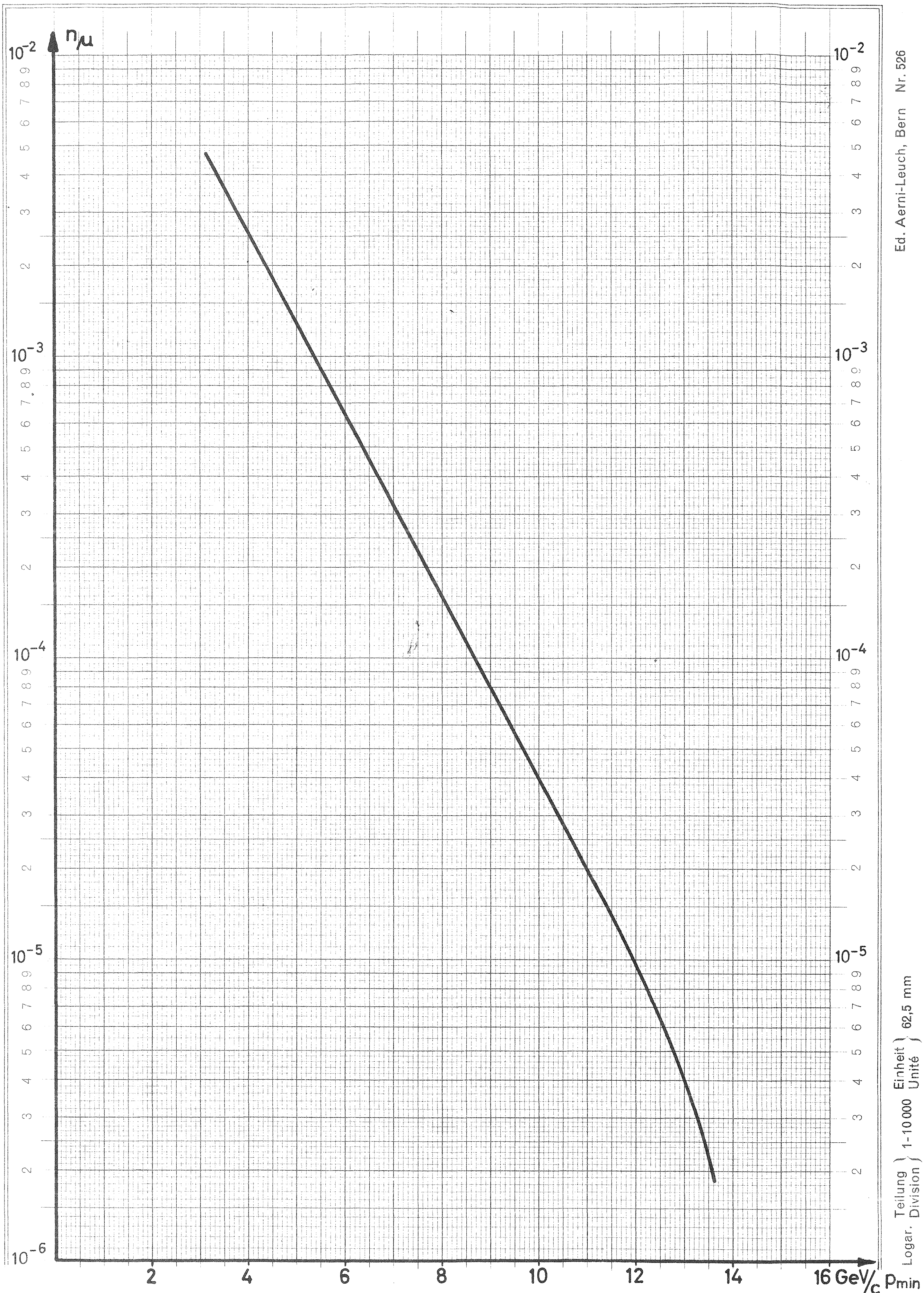

Fig. 2. Total number of μ's of one sign per interacting proton with $p_\mu > p_{min}$ for a 10m decay path of the π-mesons.

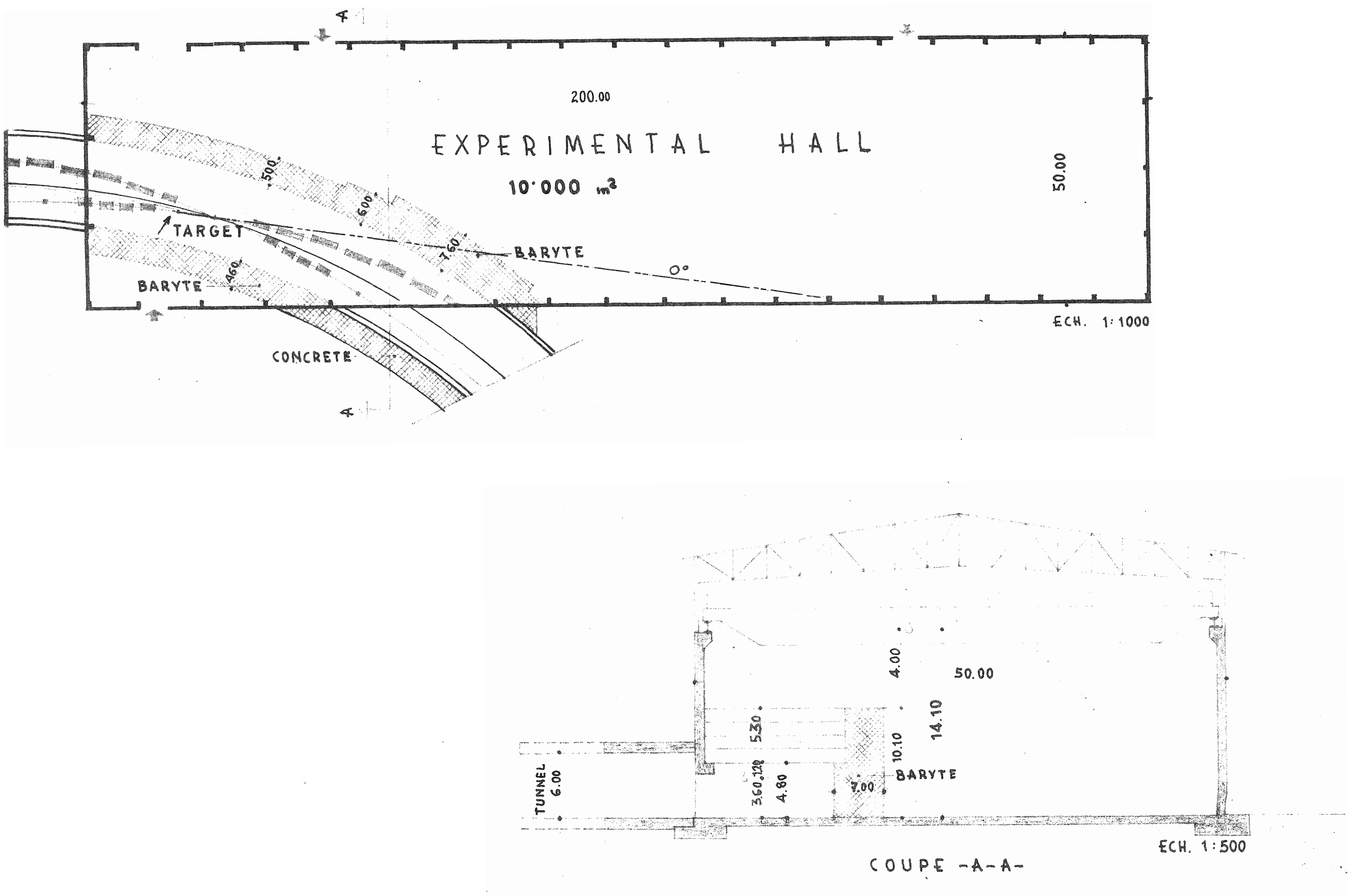

FIG. 3 SHIELDING LAY - OUT IN THE HALL FOR SECUNDARY BEAMS