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Abstract: Effective doses due to muons produced in dumps or collimator systems and penetrating the soil above the tunnel are estimated. The following processes are considered: coherent pair production from a nucleus without and with form factors, quasielastic production, and inelastic production from a proton. Data for muon transport are taken from the CERN muon shielding experiment. All available data are good enough to deduce an upper limit for the muon dose per year: 1 to 10 μSv , or less than 1 % of the natural radiation background. It is further shown that muons from pion or kaon decay do not contribute.

1. Introduction

It is proposed to build a Linear Collider which collides electron and positron beams with beam energy of 250 GeV and a beam power of 8 MW each. Scientific aspects and accelerator techniques are described in a Conceptual Design Report [1]. A tunnel of 33 km length houses two linear accelerators, beginning at the DESY site, directed towards north-west, and ending near the village Westerhorn. The interaction point and the large detector is at the midpoint of the tunnel. After having passed this region each beam is dumped into an absorber. The absorption of an 8 MW electron beam produces an enormous amount of secondary radiation and radioactivity, therefore each dump will probably not be installed in the tunnel but in a separate room beside of it. The next largest source of secondary radiation is the system of distributed collimators downstream the interaction point. They shield the components of the incoming beamline against the low energy tail of the deflected beam and against beamstrahlung produced in the interaction point. The fraction of the beam which is absorbed by these collimators can be as high as 10 - 20 %.

Two components of the secondary radiation can reach the earth surface: high energy neutrons and muons. Data on neutron doses are already given in the Design Report. In the present paper we estimate doses due to muons produced in the beam dumps and in the collimator systems.

When a high energy electron hits bulk material the electromagnetic cascade is developed. The high energy photons produce muons by pair production. Hadrons are produced by direct interaction or as a result of an intranuclear cascade and can develop a hadronic cascade to some extent. Pions and kaons can escape from the absorber, and if a long flight path in air is available they decay into muons giving a second muon source. Muons will reach the earth surface if their production angle is larger than 50 mrd, and 50-400 mrd are very large angles for a primary energy of 250 GeV. Therefore one can expect that muon doses at earth surface are low. Nevertheless quantitative data or at least upper limits are necessary, they will be given for 5 sources in the following.

2. Muons produced by pair production

2.1. Cross sections

Pair production cross sections are needed for primary energies up to 250 GeV and production angles up to 200 mrd. This is an unusual kinematical region in high energy physics, therefore a possibly complete description of the production process is necessary without too much restrictive approximations. The best available calculations can be found in the papers of Tsai and colleagues.

The simplest approach is the assumption of a nuclear field without form factors (coherent production), it leads to a simple formula for the double-differential cross section [2,3] and is valid for small angles. An improvement is the introduction of form factors to describe the nuclear field. Other contributing processes are: elastic production from a single proton (and neutron), quasielastic production from the nucleus (leading to nuclear excitations), inelastic production from a proton (with meson production) [4,5]. The latter processes are important when dealing with large production angles. A complete description of this treatment is ref. [6]. The cross sections for coherent production with or without form factors can be calculated by means of given formulae. The other processes are not described by simple expressions due to the complexity of the problem. An evaluation is difficult and out of the scope of the present paper, and it is not necessary as seen *a posteriori* from the results.

First we compare the differential cross sections for photoproduction of muons by the mentioned processes. They are displayed in figs. 1 and 2 for the light nucleus ^9Be and for two primary energies 20 GeV and 200 GeV. The two coherent production processes are calculated by means of the final equations in [2] and [4,5,6]*. Numerical data for the complete process, coherent production (with form factors) + quasielastic production + 9 * inelastic production from a proton, are directly taken from Tsai's paper [6]. One can note that the two curves for coherent production are upper and lower limits for the best available description of the pair production process at all angles and all energies. Fig. 3 shows the great overestimation of the cross sections especially at large angles if form factors are not used, and the cross sections calculated with form factors are further reduced if the Coulomb correction is applied [6]. The two limiting cross sections can easily be calculated and are useful for approximate estimations of muon doses. We transfer these conclusions drawn for a ^9Be target to other light target materials.

2.2. Propagation of muons

When the electron beam of the collider hits a dump or a collimator the electromagnetic cascade is developed. Photoproduced muons leave the material, traverse part of tunnel and move through the earth shield to produce a dose at the surface. The whole process can be treated by the Monte Carlo method though long times of calculation are necessary since the production at large angles are rare processes. On the other hand, the interaction of muons in a shield is simple, and it was shown first by W. R. Nelson [3,7] that a simple analytic expression can be derived for muon doses behind a shield if the geometry is not complicated. An application is shown in fig. 4 where a comparison is made between calculations and the only complete muon shielding experiment at an electron accelerator in the GeV region [7]. The calculations using

* A plus sign in eq. 3.23 of [5] and in eq. 3.76 of [6] should be changed to minus, see eq. 13 of [4].

coherent production cross sections without and with form factors are in good absolute agreement with the experiment at not too large angles and are upper and lower limits of the experimental result as stated in the preceding section. The differences between both theoretical results are not so big as in figs. 1-3 since they are screened by multiple scattering in the shield.

The propagation of muons is more complicated at high energies, the Eyges theory taking into account multiple Coulomb scattering and ionization loss is no longer sufficient. Bremsstrahlung production and nuclear processes cause a broader spread. Here we make use of the results from the CERN muon scattering experiment with $E_\mu = 280$ GeV [8]. Fig. 5 shows measured muon doses behind a shield of 292 m soil together with calculated values using the mean square lateral displacement from Eyges theory. If this latter value is increased by a factor of 3 (the σ of the Gaussian distribution multiplied by $\sqrt{3}$) one receives a formal agreement with the experiment (the flattening of the experimental curve at largest angles was attributed to background). We use the increased value in all our calculations.

2.3. Muon doses at earth surface

The main muon sources of the collider are the dumps and the distributed collimators behind the interaction point. The earth profiles relevant for muon shielding above the tunnel are shown in figs. 6 and 7. The distance relative to dump or collimator are indicated together with the internal coordinates (with point zero at the beginning of the e^- linac on the DESY site). The exact positions of dump and collimators are still under discussion. For the e^+ dump we choose two possible positions (I and II in fig. 6); since the geometries for muon shielding are nearly the same we give final results for only one of them. The dumps will probably not be installed in the tunnel but beside of it; the spent beam can be directed down at an angle of 20 mrd, an easy way to reduce secondary radiation at earth surface. Any concrete shielding around the dumps is neglected. The attenuation of muons by the accelerator components along the flight path in the tunnel is unknown at present; we take it into account by adding 1/3 of the flight path as seen in figs. 6 and 7 to the amount of earth shield.

The doses at earth surface are calculated in an approximate way by using the analytical formalism of Nelson though the geometry is not the same as that in [3]: the earth surface is parallel to the beam and not perpendicular to it as in the case of a beam endstop. Therefore a separate calculation is necessary for each angle and the respective total sand shield. Two limiting pair production cross sections (see section 2.1.) and an enlarged scattering distribution (see section 2.2.) are used. A mean fluence-to-effective dose conversion factor is taken as $3.5 \cdot 10^{-10}$ Sv cm^2 [9].

The dumps and the distributed collimators are both simulated by 6 m aluminium. This is also the first scattering medium, the main absorbing medium is sand ($\rho = 2.0$ g/cm³). The primary energy of electrons and positrons is 250 GeV. An operation of 8 MW during 5000 h per year giving $3.6 \cdot 10^{21}$ e/a is assumed for the two dumps and 20 % of this value for the collimators. The muon doses per year are given in tab. 1 for the positions defined by the production angle Θ and figs. 6 and 7. The drastic reduction in the coherent muon production by introducing nuclear form factors is apparent. The best approximation is limited by the values of row 5 and 6 as

outlined in section 2.1., the logarithmic mean of both may be used as a guidance. It shows that the annual doses at all positions are less than 1 to 10 μSv .

3. Muons from pion and kaon decay

Pair production is known to be the main muon source at electron accelerators. Therefore we expect that muons from the decay of pions and kaons will give even smaller doses at earth surface than those estimated in the preceding section. Nevertheless these processes should be examined, and we will prove that they give no contribution.

Muons are produced copiously if a long flight path is available for the pions and kaons to decay. Such a decay path does not exist at the beam dumps since they are surrounded by thick concrete blocks and soil as near as possible. In case of the other main sources, the distributed collimators, the tunnel presents the necessary flight path. Therefore we confine ourselves to these objects.

The Monte-Carlo code FLUKA 97 [10] is used to calculate the production of pions and kaons. We assume a short aluminium target (\varnothing 36 cm * 45 cm) in an otherwise empty tunnel in which the electromagnetic cascade is partially developed. Pions and kaons can escape the target and see a long flight path in the tunnel (\varnothing 5 m) according to their production angle. Again the interesting angles are very large for an incident energy of 250 GeV, 100 mrd and more. Such large angles may be possible as a result of an intranuclear or extranuclear cascade. It was difficult to receive significant results for these rare events, therefore the γ -nucleus cross section was artificially magnified by a factor of ten, and the decay length in air was reduced to 2.5 m. (The weight of a produced muon is reduced correspondingly). A lower energy cut of 10 GeV was applied to all particles.

Fig. 8 gives an example of the results. It shows the muon spectrum from the decay of all secondary particles (mainly pions and kaons) and from the decay of kaons only, for two angular intervals. The ordinate is the muon fluence per logarithmic energy interval at the concrete wall of the tunnel, per one 250-GeV electron. The minimum energy necessary for a muon to penetrate the soil above the tunnel is 130 GeV at 42 mrd and 46 GeV at 137 mrd in case of the e^+ collimator (see fig. 7). Both spectra clearly do not reach the minimum value, and this is also true for other production angles examined. Muons from pion or kaon decay do not produce any dose at the earth surface.

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Absorber	Θ (mrd)	d (m)	E_{\min} (GeV)	Muon dose (Sv/a)	
				Without f. f.	with f. f.
e ⁻ dump	80	350	190	$1.1 \cdot 10^{-6}$	$3.3 \cdot 10^{-10}$
	100	250	130	$1.2 \cdot 10^{-5}$	$1.9 \cdot 10^{-9}$
	120	200	100	$2.7 \cdot 10^{-5}$	$5.0 \cdot 10^{-9}$
	140	150	72	$8.2 \cdot 10^{-5}$	$1.4 \cdot 10^{-8}$
	160	130	62	$1.0 \cdot 10^{-4}$	$1.9 \cdot 10^{-8}$
e ⁺ dump	60	340	180	$6.0 \cdot 10^{-6}$	$6.2 \cdot 10^{-10}$
	80	190	94	$2.1 \cdot 10^{-4}$	$1.4 \cdot 10^{-8}$
	100	140	68	$5.0 \cdot 10^{-4}$	$3.3 \cdot 10^{-8}$
	120	120	56	$5.4 \cdot 10^{-4}$	$4.0 \cdot 10^{-8}$
	140	90	41	$1.3 \cdot 10^{-3}$	$8.1 \cdot 10^{-8}$
	160	80	36	$1.3 \cdot 10^{-3}$	$9.3 \cdot 10^{-8}$
e ⁻ collimator	40	430	230	$2.8 \cdot 10^{-9}$	$1.4 \cdot 10^{-11}$
	60	300	160	$4.8 \cdot 10^{-6}$	$3.7 \cdot 10^{-10}$
	80	230	120	$1.2 \cdot 10^{-5}$	$1.1 \cdot 10^{-9}$
	100	180	88	$2.3 \cdot 10^{-5}$	$2.4 \cdot 10^{-9}$
	120	150	72	$3.1 \cdot 10^{-5}$	$3.6 \cdot 10^{-9}$
	140	130	62	$3.7 \cdot 10^{-5}$	$4.8 \cdot 10^{-9}$
	160	100	48	$6.5 \cdot 10^{-5}$	$8.1 \cdot 10^{-9}$
e ⁺ collimator	40	280	140	$6.2 \cdot 10^{-5}$	$3.0 \cdot 10^{-6}$
	60	190	94	$1.4 \cdot 10^{-4}$	$1.3 \cdot 10^{-7}$
	80	150	72	$1.7 \cdot 10^{-4}$	$1.5 \cdot 10^{-8}$
	100	120	56	$2.3 \cdot 10^{-4}$	$1.4 \cdot 10^{-8}$
	120	100	48	$2.2 \cdot 10^{-4}$	$1.3 \cdot 10^{-8}$
	140	85	39	$3.3 \cdot 10^{-4}$	$1.9 \cdot 10^{-8}$
	160	75	34	$3.6 \cdot 10^{-4}$	$2.2 \cdot 10^{-8}$

Tab 1. Annual muon doses calculated with coherent pair production cross sections without and with nuclear form factors for positions indicated by production angle Θ and figs. 6 and 7. d is the total soil thickness and E_{\min} the minimum muon energy which produces a dose at the surface.

Figure captions

- Fig. 1. Differential cross sections for muon pair production at 2 muon energies and a primary electron energy 20 GeV. Target is ${}^9\text{Be}$. - - - - - coherent production without nuclear form factor. — — — coherent production with nuclear form factor. ————— coherent production + quasielastic production + 9 * inelastic production from a proton.
- Fig. 2. Same as fig. 1, but primary electron energy 200 GeV.
- Fig. 3. Same as fig. 1, but high primary energy (100 GeV) and large angles. — · — · — Coulomb correction included.
- Fig. 4. Comparison between experiment (————) and calculations. - - - - - coherent production without nuclear form factor. — — — coherent production with form factor.
- Fig. 5. Scattering of 280-GeV muons. σ_1 is the scattering parameter from Eyges theory.
- Fig. 6. Earth profile above tunnel behind the e^- dump and behind 2 possible positions of the e^+ dump. Positions marked by the internal scale are given at the bottom.
- Fig. 7. Same as fig. 6. but for the two collimator systems.
- Fig. 8. Muon fluence at the tunnel wall produced by decay of all relevant particles (————) and by decay of kaons only (- - - - -) for two ranges of production angles and per one 250-GeV electron.

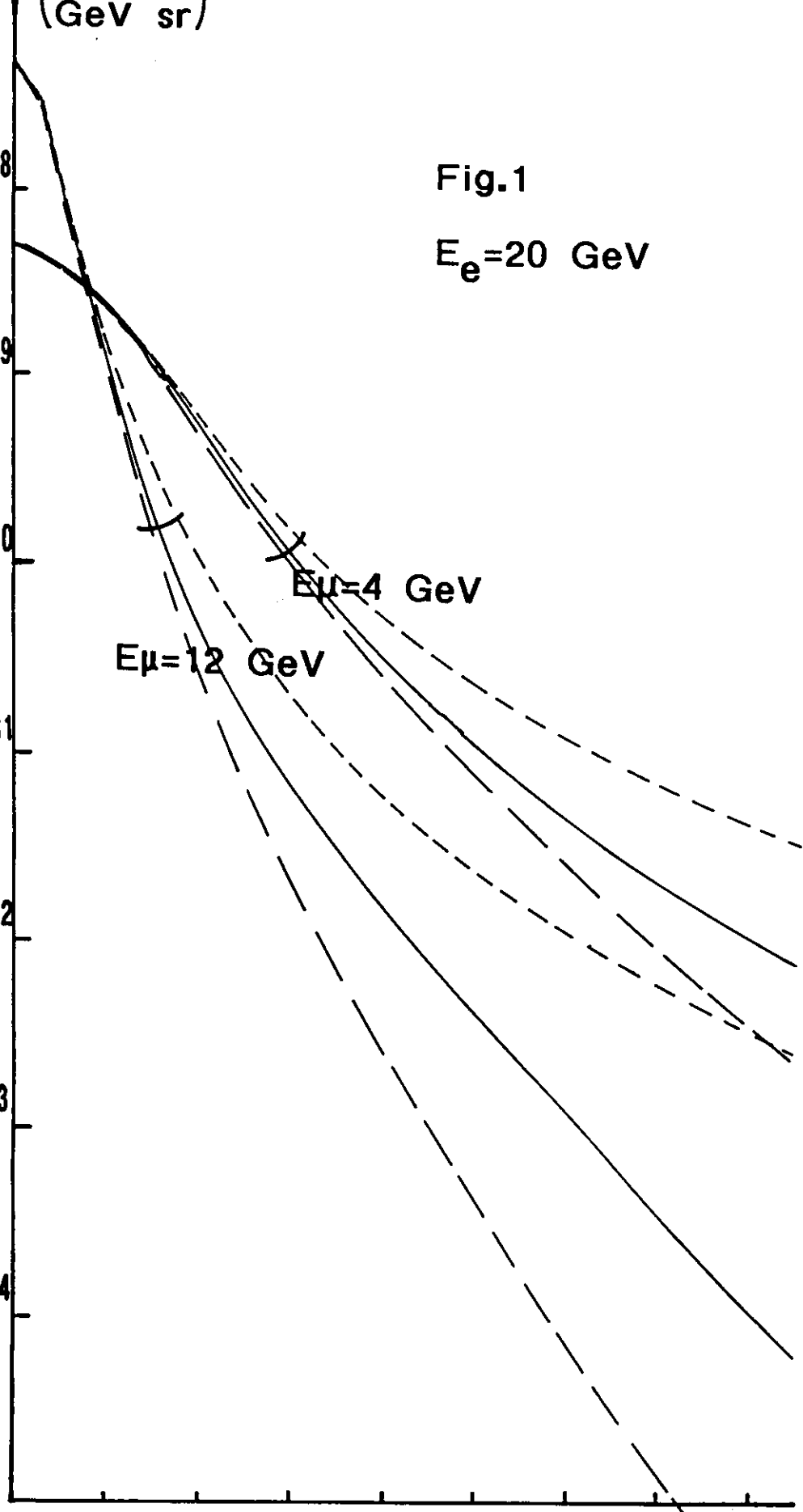
$$\frac{d\sigma}{d\Omega d\phi} \left(\frac{\text{cm}^2}{\text{GeV sr}} \right)$$

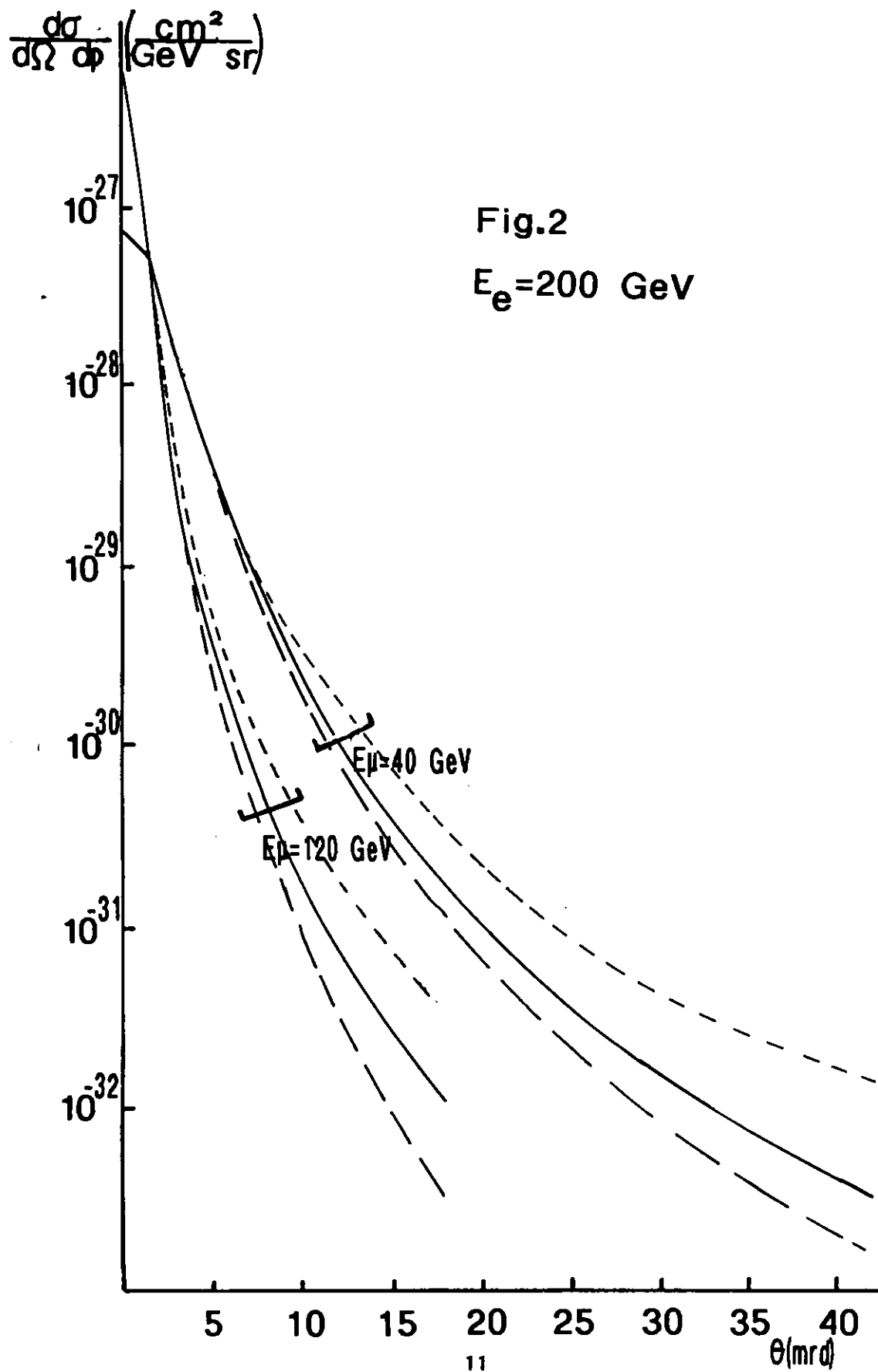
 10^{-28} 10^{-29} 10^{-30} 10^{-31} 10^{-32} 10^{-33} 10^{-34}

Fig.1

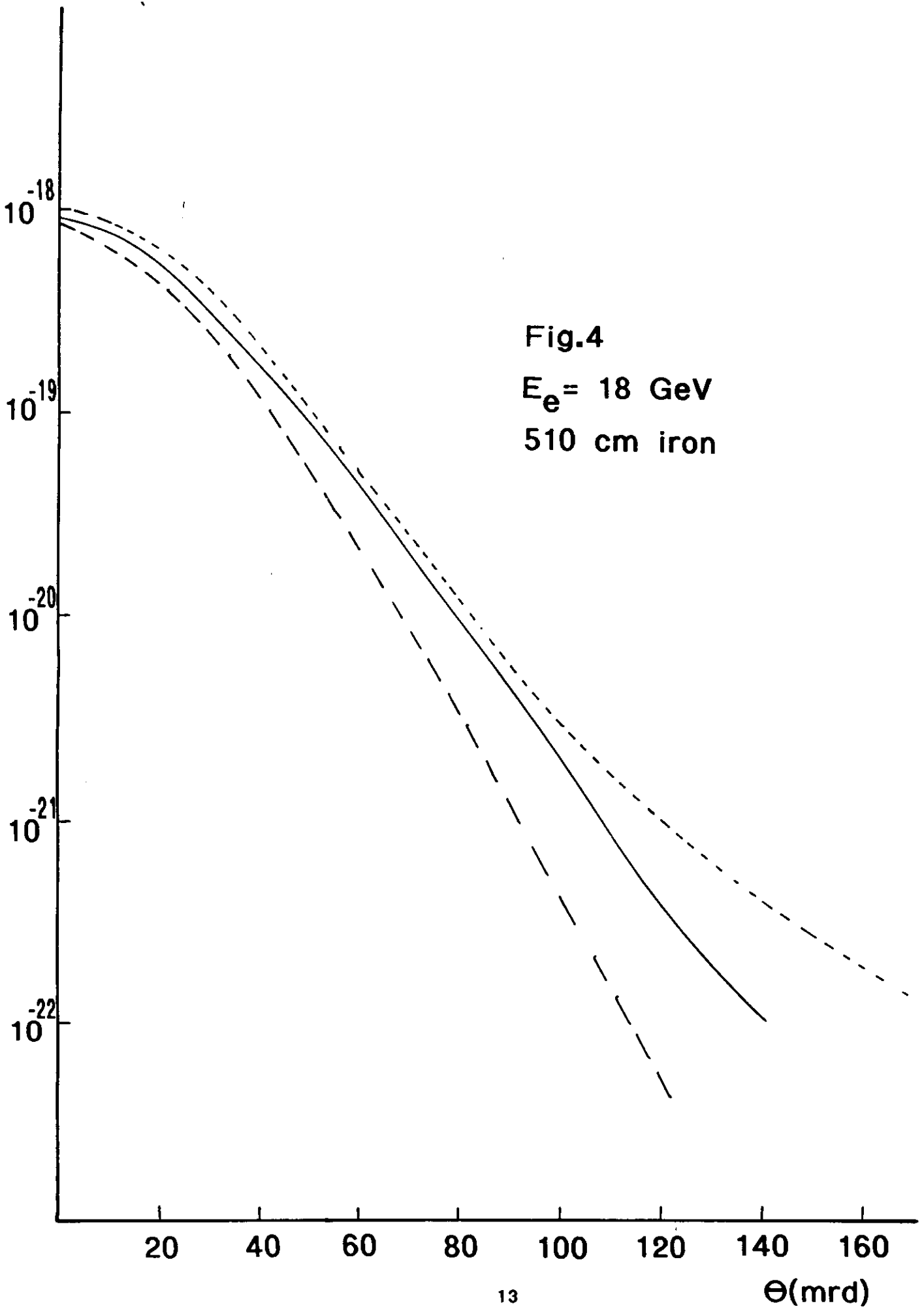
 $E_e = 20 \text{ GeV}$ $E_\mu = 4 \text{ GeV}$ $E_\mu = 12 \text{ GeV}$

20 40 60 80 100 120 140 160

 $\Theta(\text{mrd})$ 



per electron



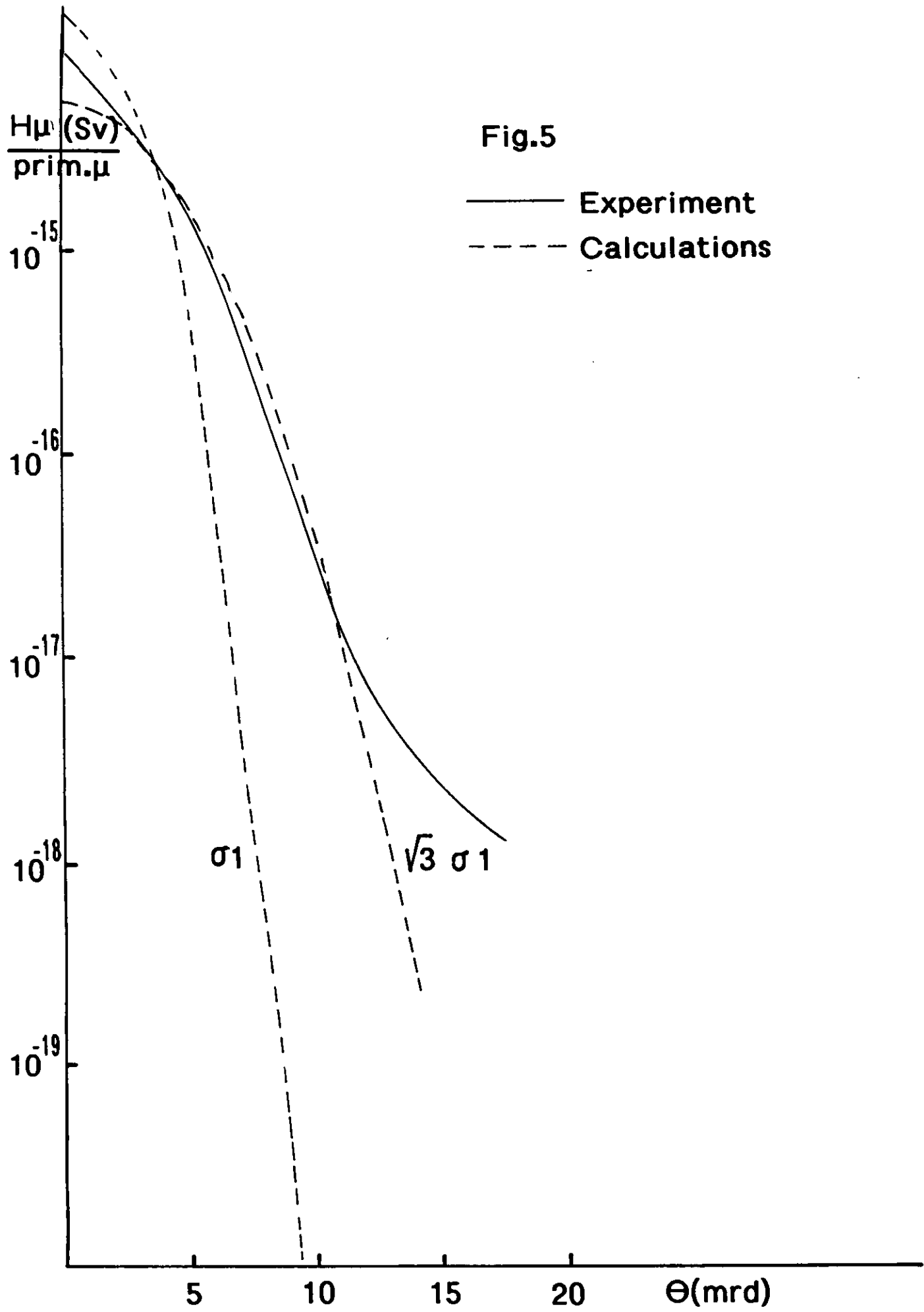


Fig.6

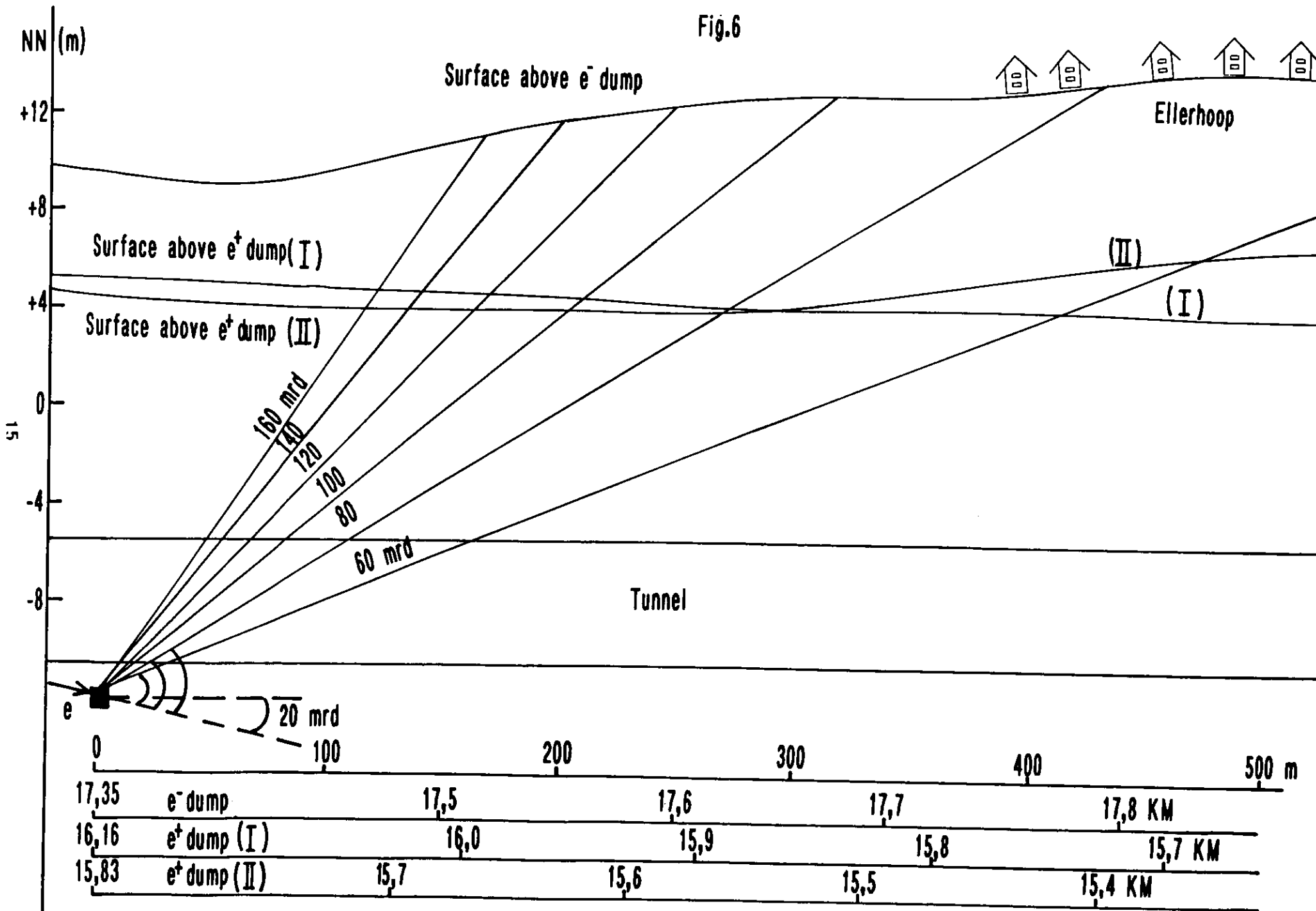


Fig.7

