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Neutrino radiation hazard at the planned CERN neutrino factory

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Abstract

This note briefly discusses the radiation hazard which may be posed by the neutrino radiation generated in the decay of an intense 50 GeV muon beam circulating in the storage ring of a future Neutrino Factory. Of the various options which are being considered for the decay ring, for the present estimate the triangle-shaped one, with three arms of equal length, was taken into account. The neutrinos emerging from the ground along a direction which is the prolongation of the arm pointing towards the surface may represent a local radiation hazard. Assuming 10^{21} muons per year, the annual dose equivalent will exceed 15 mSv.

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1. Introduction

The present design of a future Neutrino Factory to be possibly built at CERN after the LHC era includes a proton driver producing a 4 MW beam of 2.2 GeV protons, a pion production target, a system to capture and focus the pions, a muon focussing and cooling system, two muon accelerators to raise the muon energy to 50 GeV and a muon decay ring (see, for example, ref. [1]). In the latter the muons circulate at constant energy and their decay originates an intense neutrino fluence. These neutrinos are aimed at one or more far-located detectors, at typical distances of a few hundreds to a few thousands of kilometres.

The radiation protection issues of such a high-intensity proton accelerator complex are (at least) comparable to those posed by state-of-the-art spallation neutron sources. Before such a facility can be built a throughout study will have to be conducted to define shielding requirements, assess induced radioactivity in accelerators, targets and auxiliary equipment, evaluate the risk of ground water activation and the environmental impacts due to prompt radiation streaming through the access and ventilation shafts as well as to releases of radioactive air and fluids. Also, the amount of radioactive waste to be handled at the time of the facility's decommissioning will have to be assessed. At CERN these aspects have been addressed until now only in a very preliminary way and limited to the proton driver [2-4].

In addition to the above "conventional" radiation issues a more exotic problem may be posed by the neutrino beam itself. This aspect was first investigated for high-energy muon-muon colliders [5-7], where it was shown that above about 1.5 TeV per beam the neutrino-induced secondary radiation emerging from the ground even at very large distances (tens of kilometres) from the machine would pose a serious hazard (both radiological and political). In spite of the fact that in a Neutrino Factory the muon energy is much lower than in a muon-muon collider (50 GeV in the CERN reference scheme), a potential radiation hazard from the neutrino beam may still be present because of the intensity of the circulating muon beam. The present CERN design of a neutrino factory foresees the production of 10^{21} neutrinos per year. Of the various options which are being evaluated for the decay ring, for the purpose of the present estimate we shall here consider the triangle-shaped one, with three arms of equal length. The machine will be located underground and tilted in such a way that two arms of the triangle (at slopes of 22% and 5.6%, respectively) point towards two far-located neutrino detectors, whilst the third arm, needed to close the storage ring, points towards the surface at a slope of 23.3%. The minimum depth at which the ring will be located is about 20 m (at the starting point of the first "detector arm", which coincides with the end point of the "return arm"). These construction parameters provide a minimum shielding of earth of 100 m for muons lost in the storage ring. Under this circumstance all muons are stopped before reaching the surface. Since the return arm has the same length as the two detector arms, the same number of neutrinos (approximately one third of the total) are produced in this section of the ring. These neutrinos, emerging from the ground along a direction which is the prolongation of the arm, may represent a local radiation hazard, as discussed in this note.

2. Neutrino induced radiation

The attenuation length (λ) of a neutrino of energy E_ν in a material of density ρ is approximately given by [6]:

$$\lambda = 0.5\cdot 10^6 \text{ km } (1 \text{ TeV}/E_\nu)\cdot(3 \text{ g cm}^{-3}/\rho) \quad (1)$$

Neutrinos have a very small interaction cross-section. Interactions of muon neutrinos (ν_μ) can be reduced to two categories: Charged Current, when they weakly interact through the exchange of a W-boson to form muons, and Neutral Current, when they produce uncharged particles through the weak exchange of Z-particles. A hadronic shower accompanies both reaction types. The ν_μ induced radiation hazard thus comes from two sources: secondary muons and secondary hadronic shower products. The latter have a much shorter range than the muons produced in the neutrino interactions, but on the other hand the number of particles produced in the cascade is very large.

We shall follow here the same simple model used for assessing the radiation hazard of the neutrino radiation from a high-energy muon-muon collider [6], using the fluence to dose equivalent conversion coefficients of Cossairt *et al.* [8]. These data show that the radiological hazard is much larger (up to three orders of magnitude at TeV energies, two orders of magnitude at 50 GeV and still almost an order of magnitude at 1 GeV) if the neutrino beam is “shielded” rather than left “unshielded”. This is because of the secondary radiation produced in the shielding material (in practice, earth, if the accelerator is installed underground). As stated above, the secondaries with the longest range are the muons, the maximum energy of which cannot obviously exceed the energy of the muons circulating in the decay ring. The machine must be shielded and the shield must be thick enough to absorb the muon beam circulating in the ring in case of a full beam loss. It follows that the shield must be thicker than the maximum range of all secondaries, i.e. the neutrino radiation emerging from the shield will automatically be in equilibrium with its secondary radiation. It has been shown that, down to a few GeV, the data of Cossairt *et al*. do not differ substantially from those of Mokhov calculated with the MARS Monte Carlo code [5].

The increasing energy and increasing number of the secondaries is the main reason for a rising fluence to dose equivalent conversion coefficient with increasing neutrino energy for shielded neutrino radiation. Another reason is the energy dependence of the neutrino attenuation length, which decreases with increasing energy of the primary neutrinos (see expression 1 above).

3. Assessment of the produced neutrino radiation

In the decay ring of the Neutrino Factory the circulating muons will produce 10^{21} neutrinos per year. The energy distribution (or differential fluence) of these neutrinos in the laboratory system, averaged over all production angles, is given by [6]:

$$\frac{dN(E_\nu)}{dE_\nu} = \frac{2}{E_0}\cdot\left(1-\frac{E_\nu}{E_0}\right)\cdot\Phi \quad (2)$$

where $N(E_\nu)$ is the number of neutrinos per cm^2, E_ν is the neutrino energy, E_0 is the energy of the primary muons and Φ is the integral neutrino fluence (N_ν cm^{-2}, where N_ν is the total number of neutrinos).

Here we shall just consider the case in which the neutrinos have traversed a shield sufficiently thick to have reached secondary particle equilibrium, i.e. the "shielded" case. In the neutrino energy range from 0.5 GeV to 10 TeV, the fluence to dose equivalent conversion coefficients as given by Cossairt *et al.* [8] can be fitted by the expression [6]:

$$C(E_\nu) = 10^{-15} E_\nu^2 \qquad (3)$$

in which $C(E_\nu)$ is the fluence to dose equivalent conversion coefficient ($\mu Sv \cdot cm^2$) and E_ν is the energy of the neutrinos (GeV).

To calculate the dose equivalent (H) induced by an energy dependent neutrino radiation spectrum, one has to sum up the radiation effects over the relevant energy range:

$$H = \int_0^{E_0} \frac{dN(E_\nu)}{dE_\nu} \cdot C(E_\nu)\, dE_\nu = \frac{1}{6} \cdot 10^{-15} \cdot E_0^2 \cdot \Phi \qquad (4)$$

where H is expressed in μSv, E_0 in GeV and Φ in N_ν cm^{-2}.

The neutrino fluence (Φ) is the number of neutrinos crossing a given surface behind the shielding. This surface is determined by the divergence of the neutrino beam and by the distance *r* from the neutrino source. The divergence of the neutrino beam (the opening half-angle) induced by the decay (expressed in radians) is the inverse of the relativistic factor:

$$\theta = 1/\gamma = 1/(10 \cdot E_0) \qquad (5)$$

in which θ is the opening half-angle in radiant of the decay cone, γ is the relativistic factor and E_0 is the energy of the primary muon in GeV.

Hence, the neutrino fluence at a given distance *r* from the muon decay point is given by the expression:

$$\Phi = N_\nu/((\theta \cdot r)^2 \cdot \pi) \qquad (6)$$

With expression 4, 5 and 6 the neutrino-induced dose equivalent as a function of the primary muon energy and of the distance to the muon decay point can be estimated as:

$$H = 5.3 \cdot 10^{-15} \cdot E_0^4 \cdot N_\nu / r^2 \qquad (7)$$

in which H is the dose equivalent in μSv, E_0 is the primary muon energy in GeV and N_ν is the number of produced neutrinos.

Expression 7 provides the dose equivalent if all muons decay at the same point. Since the muons actually decay all around the storage ring with the same probability, the dose equivalent has to be calculated as an integral over the length of the return arm of the decay ring:

$$H = 5.3 \cdot 10^{-15} \cdot E_0^4 \int_d^{d+l} \frac{N_\nu}{l} \cdot \frac{1}{r^2}\, dr = 5.3 \cdot 10^{-15} \cdot E_0^4 \cdot \frac{N_\nu}{l} \cdot \left(\frac{1}{d} - \frac{1}{(d+l)}\right) \qquad (8)$$

in which H is the dose equivalent in µSv, E_0 is the primary muon energy in GeV, N_ν is the number of produced neutrinos, *l* is the length of the return arm of the storage ring (cm) and *d* is the distance (cm) from the end of the return arm to the surface, along the direction of the arm.

The radius of the produced neutrino beam at surface level is 140 cm, thus generating a whole body exposure. In order to calculate the expected annual dose equivalent at the point where the radiation emerges from the ground, the parameters listed in Table 1 have been chosen:

Table 1. Basic parameters assumed for the estimate of the annual dose equivalent from neutrino radiation.

Parameter	Value
Energy of the muons in the storage ring, E_0	50 GeV
Length of the return arm pointing towards the surface, *l*	60000 cm
Thickness of material traversed by the neutrino beam between the end of the return arm and the surface, *d* (approximate minimum thickness of earth needed to absorb the 50 GeV circulating muons in case of total beam loss)	10000 cm
Number of neutrinos produced in the return arm of the decay ring, N_ν	$10^{21}/3$ per year

Using the above figures, equation 8 gives a dose equivalent of 16 mSv per year. This has to be compared with an annual CERN limit of 15 mSv for occupational exposed workers and of 1 mSv for workers who are not under individual dosimetric control. The value of ambient dose equivalent caused by ionising radiation emitted by CERN beyond the boundaries of its site must not exceed 1.5 mSv per year [8]. The radiological impact on the environment of a Neutrino Factory built at or nearby CERN will have to comply with these limits.

4. Conclusions

This note has shortly addressed the radiological hazard which may be posed by the neutrino radiation from a future CERN Neutrino Factory. The magnitude of such an hazard is strongly dependent on the energy and intensity of the muon beam circulating in the decay ring, on various machine parameters as well as on the shape and siting of the accelerator. Here only the energy and intensity of the muon beam was taken into consideration, along with a preliminary information on the shape and tilting of the ring and on the depth at which it will be installed. The value of annual dose equivalent of 16 mSv here calculated for an integral number of 10^{21} muons per year decaying in the storage ring will scale linearly with the muon intensity. Although limited to a relatively small area, the radiation hazard is such that, if the decay ring is not sited on CERN territory, the area where the radiation emerges from the ground must be within the CERN perimeter.

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