Environmental radiation issues at the neutrino factory

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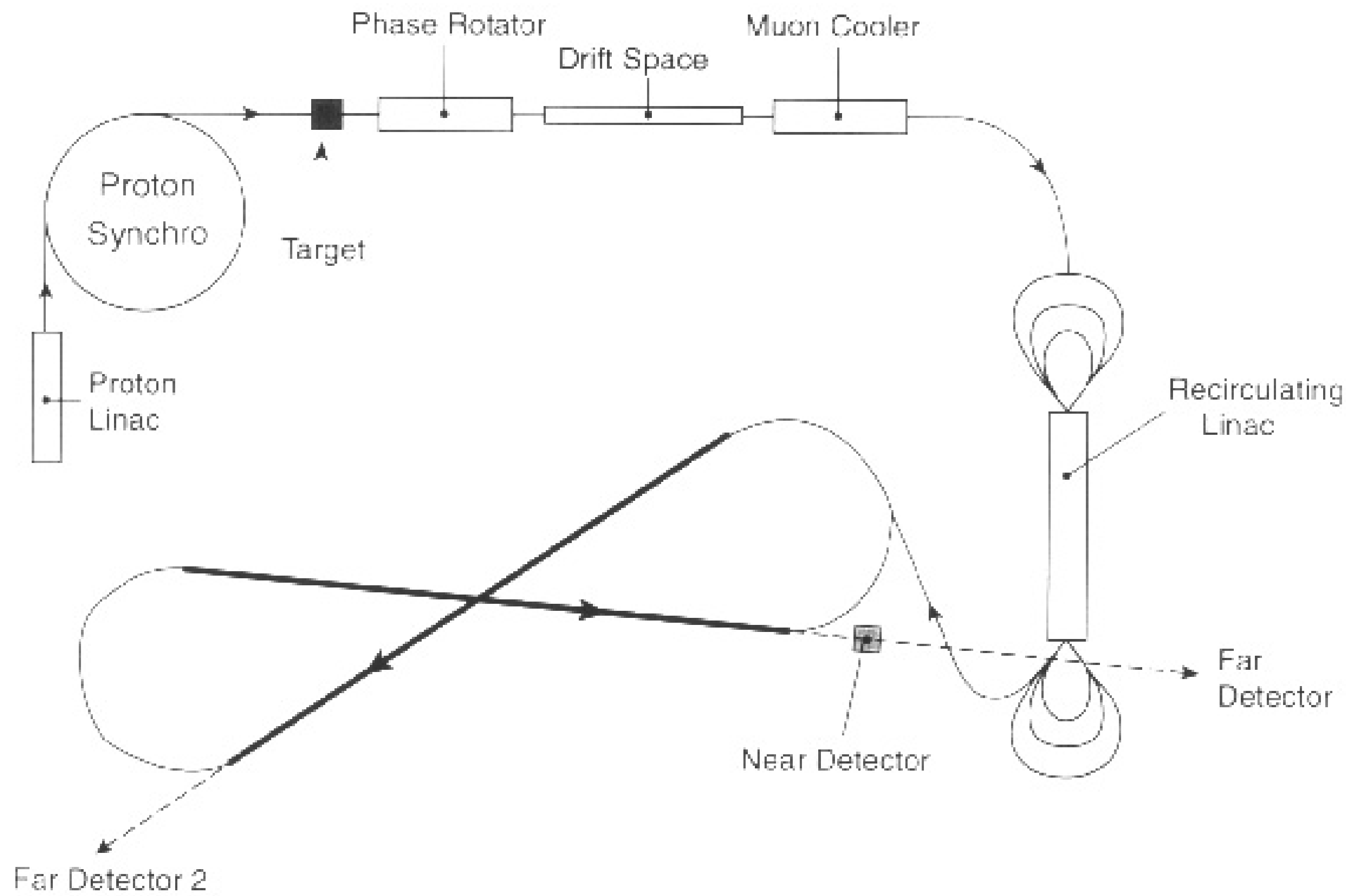
Neutrino Factory

- proton linac
- proton synchro
- target, pion capture, proton dump
- muon cooling and acceleration
- muon storage and decay

See also:

N Mokhov, talk at Lyon workshop Nufact'99
http://lyopsr.in2p3.fr/nufact99/talks

N V Mokhov and A Van Ginneken
http://www-ap.fnal.gov/~mokhov/papers/1999/pac99/thp52.ps



Phase Rotator
Drift Space
Muon Cooler
Proton
Synchro
Target
Proton
Linac
Recirculating
Linac
Far
Detector
Near Detector
Far Detector 2

1 - Proton linac, proton synchro

The problem: 1000 x CERN-PS

Rule of thumb:
1 m of dirt = one order of magnitude reduction

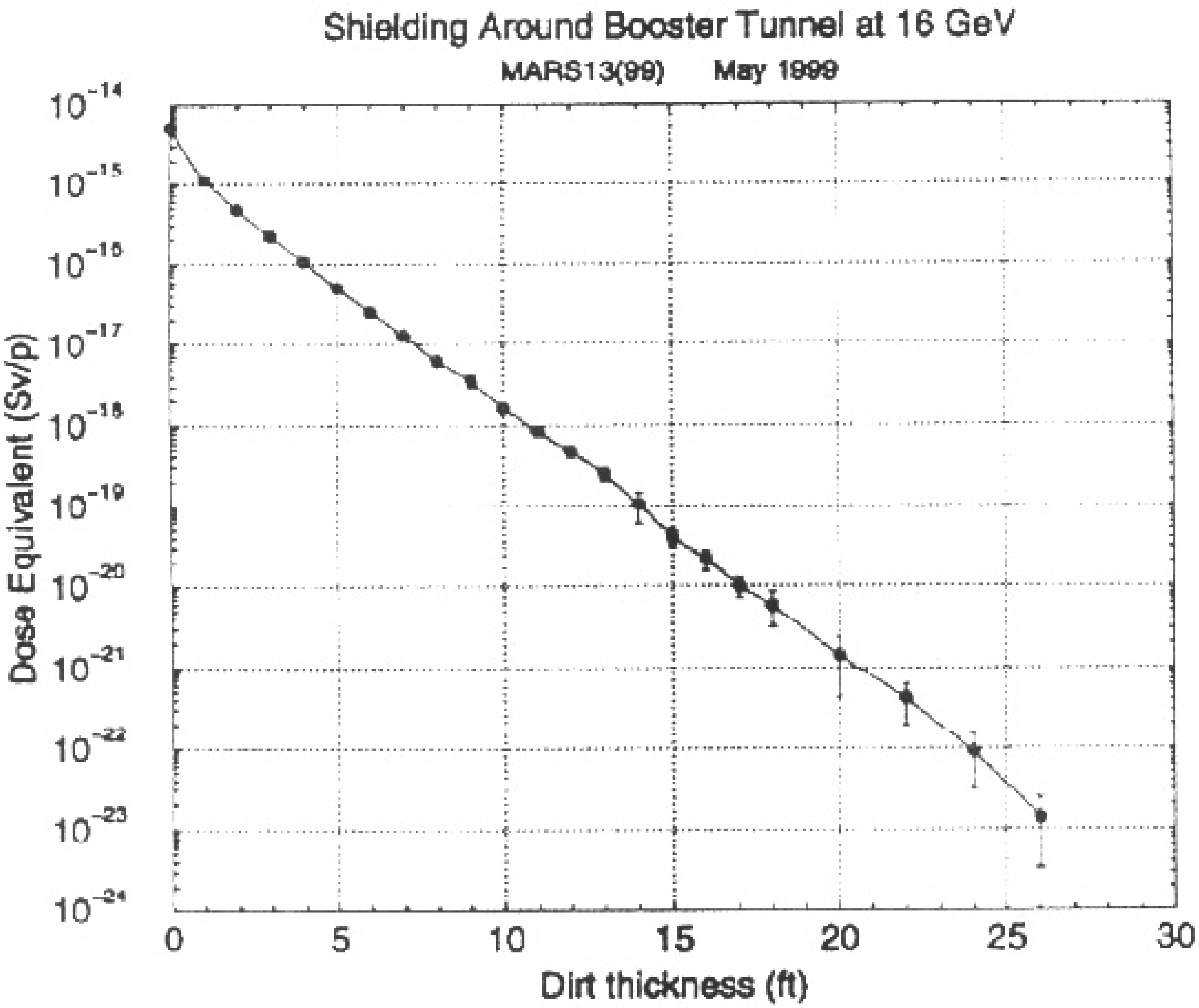
===> direct radiation from protons and proton-induced cascades is no environmental problem (but may cause problems for machine maintenance)

However, potential environmental problems arise from

- gaseous (^{13}N, ^{14}O, ^{15}O...)
  and aerosol (^{7}Be...) radioactivity
- ground water activation (^{3}H, ^{22}Na,...)

Presently, the maximum dose from CERN activities to the population outside CERN is typically 10% of the allowed limit of 3.10^{-4} Sv (= 30 mrem).

===> special precautions must be taken to reduce radioactivity in the exhausts and avoid aquiferous layers around the machine tunnel.



Shielding Around Booster Tunnel at 16 GeV
MARS13(99) May 1999
Dose Equivalent (Sv/p)
Dirt thickness (ft)
10^-14
10^-15
10^-16
10^-17
10^-18
10^-19
10^-20
10^-21
10^-22
10^-23
10^-24
0
5
10
15
20
25
30

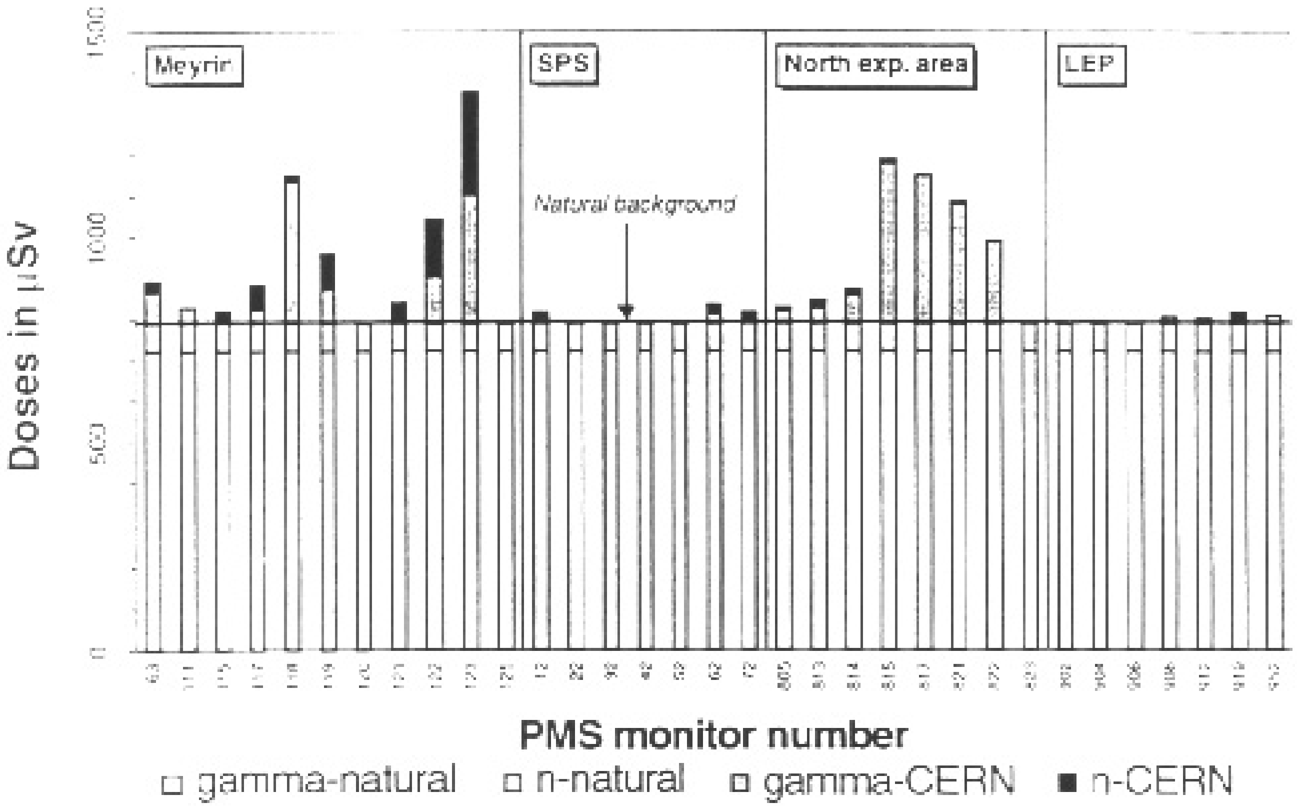


Figure 6: Results of dose measurements by the CERN monitoring stations for the year 1998. The mean natural gamma and neutron backgrounds of 718 µSv and 70 µSv are assumed, respectively.

2 - Lost muons

Rule of thumb:
1m of dirt = 0.5 GeV of energy loss

The pion decay channel, muon capture, muon cooling and muon acceleration are all horizontal.

---> the maximum muon range is 100 m of dirt, easily accommodated by an underground installation

---> as a substantial amount of energy is dissipated, care should be taken to avoid aquiferous layers

3 - Neutrino radiation

Machine parameters

In the following estimate of radiation levels at the Neutrino Factory, the following machine parameters are assumed:

- 10^{16} protons per s = 10^{23} protons per yr
- 0.1 stored muons per proton incident on target
- 50 GeV stored-muon momentum
- 25 % of muons decay in one of the long straight sections

Furthermore, the following definitions, conversion factors and constants are recalled:

- 1 Gy = 1 J/kg (= 100 rad) = 6.24×10^{9} MeV/g
- 1 Sv = 1 Gy × w_R (= 100 rem), where w_R is the radiation weighting factor ($w_R = 1$ for electrons, photons and muons, $w_R = 2$ taken for neutrino-induced final-state hadrons)
- 1 GeV = 1.6×10^{-10} J
- $\rho_{rock} = 2.5$ g/cm^3
- $\lambda_{abs}^{rock} = 100$ g/cm^2 = 40 cm
- $N_A = 6.022 \times 10^{23}$ Avogadro's number
- $\sigma = \sigma_0 \times E_\nu = 0.65 \times 10^{-38} \times E_\nu$ [GeV]
  Charged-current neutrino cross section per nucleon

Annual dose from neutrino radiation

With 0.1 stored muons per incident proton there are per year

$$2.5 \times 10^{21}$$

muons decaying into one electron and two neutrinos along one of the straight sections of the Neutrino Factory. The dominant neutrino radiation hazard is along the direction of the straight sections. In the following, the maximum radiation dose per year from neutrino radiation in the very forward direction is estimated.

50 % of the neutrinos are emitted within a forward half-cone angle of $\theta = 1/\gamma = 2.1$ mrad. Although their energy drops from the full muon momentum at the cone centre to half of this value at the outer cone edge, all neutrinos are taken with full energy. The neutrinos outside the cone are ignored.

Sending a neutrino beam from CERN to Gran Sasso means a downward angle of the straight section of 3.3 degrees (slope = 5.6 %). However, with a racetrack geometry of the muon storage ring, the neutrino radiation which is potentially dangerous is in the *reverse* direction, which surfaces at a distance of 860 m if the middle of the straight section of the Neutrino Factory is at a depth of 50 m.

The number of pairs of neutrinos and antineutrinos per cm^2 and year at 860 m, averaged over the half-cone angle of 2.1 mrad (= radius of 180 cm) is

$$N_\nu = \frac{0.5 \times 2.5 \times 10^{21}}{180^2 \times \pi} = 1.2 \times 10^{16}$$

An average energy E_ν of one third of the energy of the stored muon is assumed for every neutrino. In the neutrino interaction, this energy is shared between the final-state hadrons and final-state leptons. Conservatively, it is assumed that both the neutrino and antineutrino contribute. The cross-section weighted average energy deposited by the final-state hadrons is then (with simplified nucleon structure functions)

$$5E_\nu/8 \; ,$$

while the same average for the final state leptons is

$$7E_\nu/8 \; .$$

Furthermore, as a worst case scenario, an equilibrium situation is assumed: exposure of the human body to radiation directly at the exit from the surface.

Annual dose from the final-state hadrons

A priori, the final state hadrons contribute to the radiation dose if the neutrino interaction takes place up to 10 λ_{abs} before exiting from underground, that is a rock layer with a thickness of 1000 g/cm^2 (= 4 m).

At closer inspection, however, it turns out that the thickness of the rock is immaterial for the calculation of the radiation dose. The thicker the rock layer which is needed to dissipate the energy of the final-state particles, the larger is the pathway along which neutrino interactions are to be taken into account. Therefore, the thickness of the rock layer cancels. In the equilibrium limit, only the energy transferred by the interacting neutrino to the final-state hadrons, muons and electrons is relevant.

It is important to notice that the neutrino radiation dose arising from a straight section scales with the fourth power of the stored-muon momentum. Two powers come from the size of the forward cone, one power from the rising neutrino cross section, and yet another power from the dissipated energy.

For the radiation dose from the final-state hadrons, a factor of 4/3 is applied to take into account the effect of neutral-current interactions.

This results in the average energy deposition from final-state hadrons in MeV/g:

$$4/3 \times N_\nu \times N_A \times \sigma_\nu \times E_\nu \times 5E_\nu/8 \times 1000 = 1.1 \times 10^7 \text{ MeV/g}$$

This corresponds with a radiation weighting factor of $w_R = 2$ to an annual dose of

$$350 \times 10^{-5} \text{ Sv } (= 350 \text{ mrem})$$

Annual dose from the final-state muons and electrons

The calculation of the annual dose from the final-state muons is analogous to the case of hadrons. The very different length in rock of a penetrating muon and an electromagnetic shower is immaterial for the calculation of the radiation dose in the equilibrium case as argued above.

That results in the energy deposition per g:

$$N_\nu \times N_A \times \sigma_\nu \times E_\nu \times 7E_\nu/8 \times 1000 = 1.2 \times 10^7 \text{ MeV/g}$$

This corresponds with a radiation weighting factor of $w_R = 1$ to an annual dose of

$$180 \times 10^{-5} \text{ Sv } (= 180 \text{ mrem})$$

Total annual dose from neutrino radiation

The total annual dose from neutrino radiation under the specified conditions is then:

$$530 \times 10^{-5} \text{ Sv } (= 530 \text{ mrem})$$

For comparison, the annual dose from natural radioactivity at the CERN site is

$$80 \times 10^{-5} \text{ Sv } (= 80 \text{ mrem})$$

The annual dose for the population outside CERN is

$$30 \times 10^{-5}\ \text{Sv}\ (= 30\ \text{mrem})$$

The annual dose limit for persons working at CERN is

$$100 \times 10^{-5}\ \text{Sv}\ (= 100\ \text{mrem})$$

The annual dose limit for professional radiation workers at CERN is

$$1500 \times 10^{-5}\ \text{Sv}\ (= 1500\ \text{mrem})$$

Summary

1. The neutrino factory must be built deep in the molasse (20 m seem safe). Aquiferous layers and gaseous radioactivity are the dominant problems

2. The neutrino radiation dose is comparable to the one from natural radioactivity. A 'nearby' exiting neutrino beam must either exit within a designated radiation zone, or be avoided altogether