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**EVALUATION OF RADIATION SKYSHINE FROM THE MAIN RINGS
OF THE DAΦNE PROJECT**

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Abstract

To properly design the roof shielding for the Main Rings of the DAΦNE Project, the dose equivalents due to the skyshine effect as a function of distance from the machine building and of the altitude have been evaluated.

The calculations, for both neutrons and photons, were performed in two steps: source definition and radiation transport. For the first step the code used was FLUKA. The transport of the emitted particles was simulated using the CERN version of the MORSE code.

From the results obtained two alternatives are suggested:

- a roof covering the sections of the machine without local shields;
- the removal of the windows existing in the building housing the machine.

1. INTRODUCTION

It is well known that particle accelerators with insufficient top shielding may become important sources of skyshine. This term designates any radiation emitted upwards on the Earth's surface, which is backscattered downwards by collisions with air nuclei.

Depending on the type and energy of accelerated particles, photons or neutrons contribute to this phenomenon, or even both. At large distances (several hundred meters), skyshine is likely to give the highest contribution to the radiation field near low and medium-energy accelerators.

A general analytical treatment of this effect has never been developed because of the large number of parameters involved. As the neutrons is concerning, a semi-empirical theory was formulated by Lindenbaum (Li57). This theory was found to be in good agreement with the experimental data. Later on, many studies have been published (Th62, Ki62, La68, Na75, Mi77, Al81, Na81a, Na81b, Ha84, Uw87), several of which were performed by means of computer simulations. A review of available information on skyshine from proton accelerators can be found in (St84). Photon studies have also been reported in the literature (NCRP77, Na81c), although electromagnetic radiation is, in general, of minor radiological interest around high energy particle accelerators.

To make a realistic assessment of skyshine contribution, it is often necessary to take into account the specific features of each installation, including the ground profile of the surroundings. Computer simulations become then a mandatory tool.

Such is the case of the Adone e^+e^- storage ring of the Laboratori Nazionali di Frascati. The peculiar characteristics of the building housing that facility require an ad hoc treatment rather than extrapolation from reported experimental or calculated data referring to standard situations. Adone is located inside a hall having no proper shielded roof, but rather a concrete vault of 30 cm average thickness, interrupted at about 10 m height by large windows. In the past, to avoid radiation streaming to the environment through these windows, a concrete shield 50 cm thick was installed on top of the ring. That kept radiation below measuring levels everywhere around the facility.

According to LNF programs, Adone should be phased out at the end of April 1993. At its location, inside the same building, it is planned to install the Main Rings of a Φ -factory (DAΦNE), which will operate with stored e^+ and e^- 510 MeV beams.

The installation of the new machine will require a verification of the effectiveness of existing shielding, and its upgrade if needed. In particular, it will be necessary to decide whether shielding has to be provided for upwards-emitted radiation, and how.

To account for the peculiar characteristics of the machine building, it has been decided to study the skyshine effect by a computer simulation.

2. DESCRIPTION OF THE CALCULATIONS

The skyshine calculations, for both neutrons and photons, were performed in two steps: source definition and radiation transport. For the first step the program used was FLUKA (Aa86, Aa93a, Aa93b), a hadron transport code which has been recently provided with an improved module for electron-photon transport (Fe92) replacing to a large extent the original EGS4 interface (Ne85). The transport of the emitted particles was simulated using the CERN version of the MORSE code (Em75, Fa87).

2.1 SOURCE

Points around the new machine where significant beam losses are likely to occur will be locally shielded with lead bricks in which the electro-magnetic cascade is expected to develop. Therefore, in order to define the photon source, a 510 MeV electron beam was assumed to hit a cylindrical lead target of 10 cm diameter and 10 cm length. The target position was assumed to be near one of the injection septa.

The lower cut-off limit used in FLUKA when calculating the photon yield was 5 MeV for electron and positron transport and 10 keV for photons. The calculated number of photons escaping from the target surface was 5.43 per incident electron, with an energy spectrum as shown in Fig. 1.

For the sake of simplicity, the actual spatial and angular distributions of the emitted photons were neglected. Emission was assumed to be perpendicular to the target axis, uniformly distributed in azimuthal angle and equally probable over the whole target length. Such an approximation is unlikely to bias the results, since the spatial distribution of the emitted photons is restricted to a source that can be considered pointlike compared to the size of the region in which transport takes place. On the other hand, possible angular effects should be largely nullified by scoring average doses over concentric circumferences.

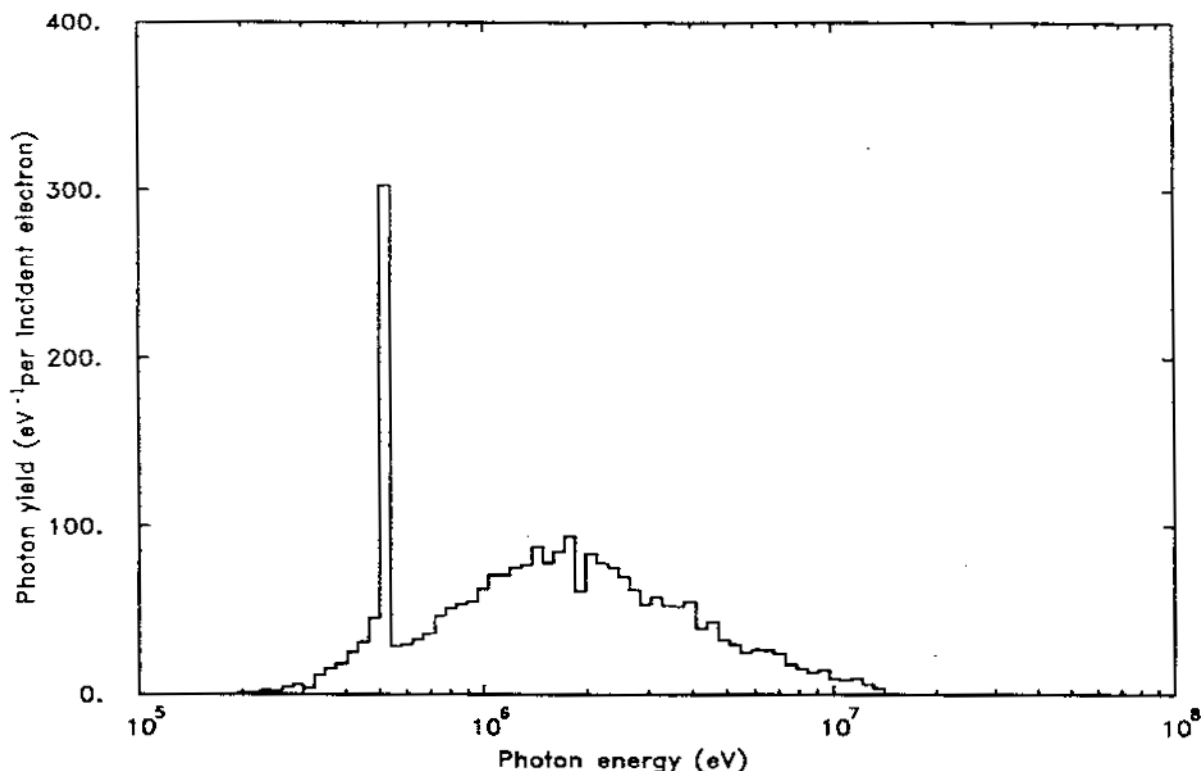


FIG. 1 - Energy spectrum of the photons escaping from the target surface.

Concerning the neutron source, the photon fluence (differential in energy, per incident electron) was first calculated in 10 concentric cylindrical regions of the target. To save computer time, an energy cut-off of 7 MeV, corresponding approximately to the photoneutron production threshold in lead, was applied to both electrons and photons. The number of neutrons produced per incident electron in each of the regions was then evaluated by folding the corresponding spectrum over the lead giant resonance cross-section. To this purpose, the excitation function was represented analytically by a Lorentz curve:

$$\sigma(E) = \frac{\sigma_m}{1 + \frac{(E^2 - E_m^2)^2}{\Gamma^2 E^2}} \quad (1)$$

where $\sigma(E)$ is the photon cross-section as a function of the electron energy E (MeV), E_m (MeV) is the resonance energy, σ_m (mb) the peak cross-section and Γ (MeV) the curve full width at half maximum. The numerical values used in the calculation for the various parameters are: $E_m = 13.48$ MeV, $\sigma_m = 602$ mb, $\Gamma = 4.20$ MeV (Di88).

The resulting total number of neutrons produced in the target per incident electron was 0.1534. More than 90% of these were produced in a central cylindrical target region of 1.5 cm radius. Neutron emission was assumed to be isotropic. For the energy distribution, a Maxwellian spectrum of 0.98 MeV "temperature" (Sw88) was adopted, as shown in Fig. 2.

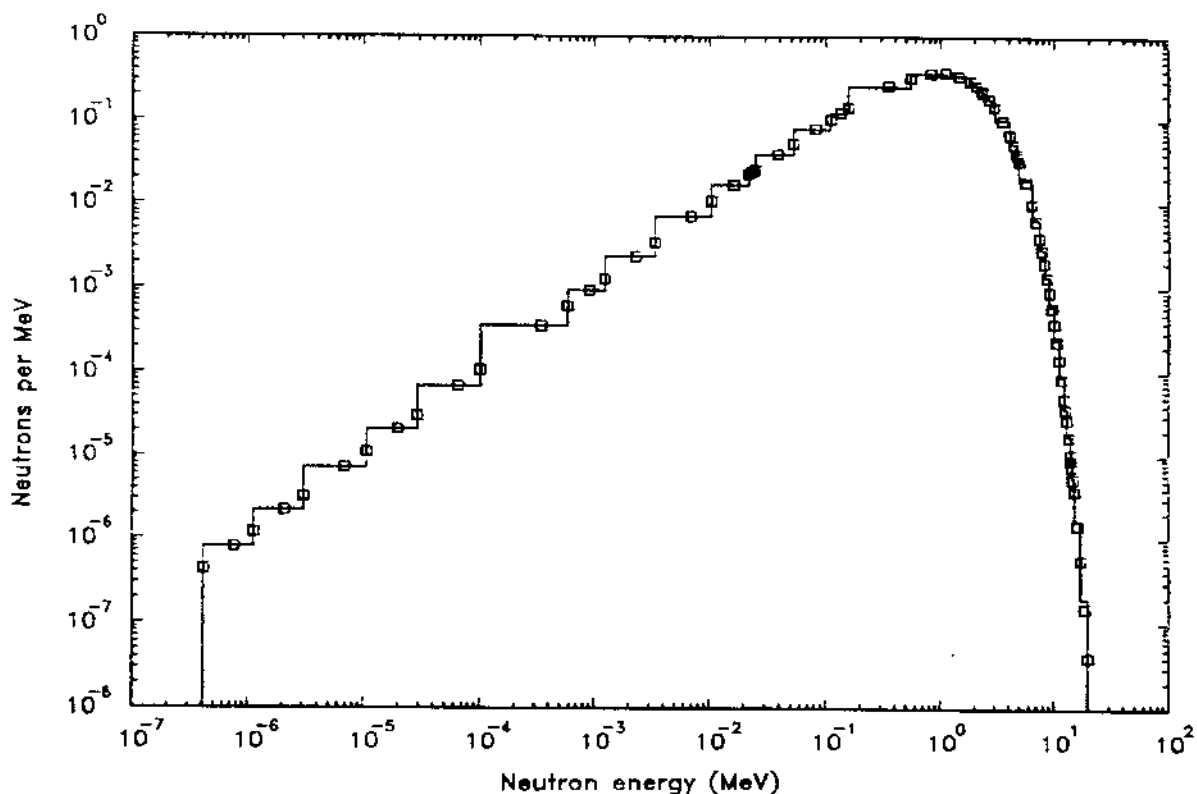


FIG. 2 - Energy spectrum of the photoneutrons produced in lead.

2.2 TRANSPORT

The DLC-31 multigroup cross-section library (Ba77) was used to transport both neutrons and photons by means of the MORSE code. The library has 37 energy groups between 20 MeV and thermal neutrons (but the calculation was stopped at 0.4 eV, ignoring the thermal group), and 21 photon groups between 14 MeV and 10 keV. The materials employed were air, concrete and lead (for the target).

The Adone building was represented in a combinatorial geometry as shown in Fig. 3. Both the base of the building and the external ground were simulated by a concrete slab 10 cm thick. The actual ground profile was not taken in account. For transport in air a cylinder 2000 m high and of 400 m radius was considered, concentric with the building. The fluence was determined as the average track-length density in 49 air regions defined by 7 heights above ground and 7 radial distances from the building. The corresponding dose equivalent was obtained by integrating the differential fluence multiplied with the appropriate energy-dependent conversion coefficient.

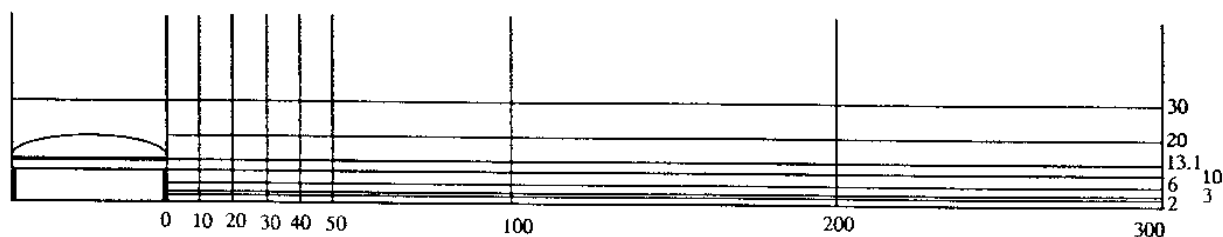


FIG. 3 - Representation of the Main Rings building in combinatorial geometry.

Several kinds of statistical weighting were used to gain calculation speed. The source was biased both in energy and in angle distribution. Energy biasing was achieved by sampling from a fictitious spectrum having a shape similar to that of the energy-dependent fluence-to-dose equivalent conversion coefficient. In this way, particles contributing mostly to dose equivalent were preferentially sampled, their statistical weight being automatically adjusted to get a correct average. In a similar way, angular emission in the upward direction was favoured by reducing to one-half (a quarter of total) the number of particles emitted downwards. Their statistical weight was obviously doubled.

Transport biasing was obtained by applying the classical Russian Roulette and splitting techniques. Each combination of spatial zone and energy group was assigned a "weight window" (maximum allowed weight fluctuation around a value inversely proportional to the importance of that phase space region in terms of contribution to the final result). Weight control was triggered at each collision and at each boundary crossing.

The dose levels obtained must be considered as average values in the corresponding region. In reality, since the source position is not in the centre of the building, there could be variations along each circumference considered. The statistical error of the calculation ranged between 1 and 6 per cent depending on location.

Both neutron and photon calculations required about 7 minutes cpu time of an IBM 3090/E computer (equivalent to one hour of IBM 370/168-3).

3. FLUENCE TO DOSE EQUIVALENT CONVERSION

At the present time a non negligible difficulty in dosimetry evaluations resides in the choice of conversion coefficients to be used when transforming calculated results of physical quantities (particle fluences) into dose values (expressed in Sv, no matter what selected quantity). The situation has further worsened as ICRP replaced Publication 26 recommendations (ICRP77) with those of Publication 60 (ICRP90). The latter have adopted the quantities introduced by ICRU (ICRU85) for external exposure control, however without specifying at which depth in the ICRU sphere they should be defined, and consequently without providing the necessary coefficients. The most recently available coefficients refer to Publication 51 (ICRP87), issued at a time when quality factors were still in force. Now these factors have become both conceptually and numerically outdated.

Concerning the situation in Italy, a further source of confusion is to be found in the obsolete national regulations, referring to radiation protection quantities which have been internationally abandoned and to conversion coefficients going back to 1971.

Therefore, as the photons is concerning, dose equivalent evaluated using ICRP Publication 21 conversion coefficients (ICRP71) could be justified as well as ambient dose equivalent according to Publication 51 (ICRP87).

The situation is even more complex for neutrons: in addition to the above two quantities at least two more might be proposed. These are, on one hand dose equivalent, or rather equivalent dose, based on Publication 60 radiation weighting factors; on the other one, ambient dose equivalent again, but evaluated in terms of conversion coefficient derived from the new relationship between quality factor and LET which is defined in the Publication 60.

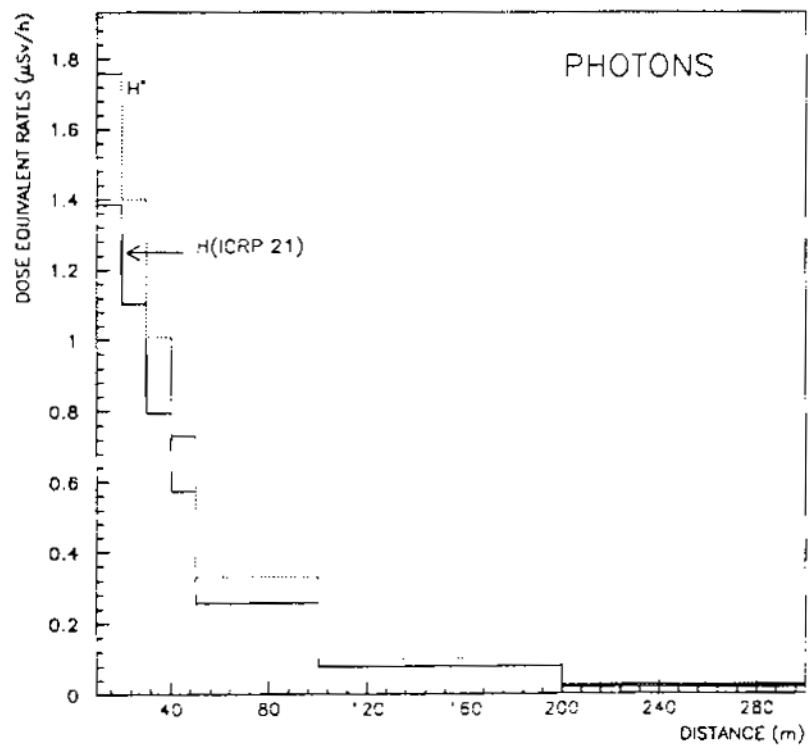


FIG. 4 - Photon dose equivalent rates versus distance from the machine building wall at a height between 0 and 2 m from ground.

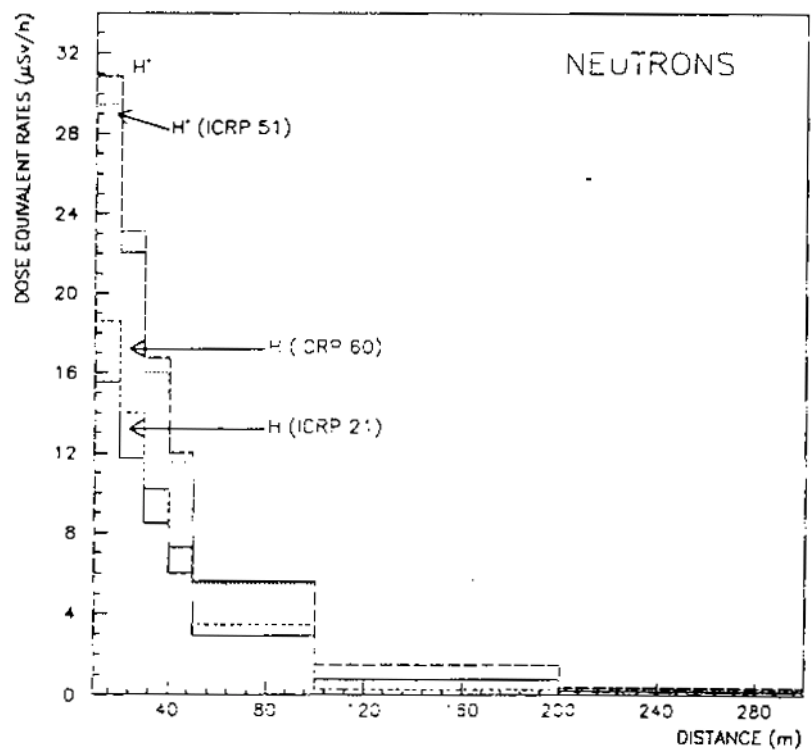


FIG. 5 - Neutron dose equivalent rates versus distance from the machine building wall at a height between 0 and 2 m from ground.

The differences arising between extreme choices are not completely negligible, especially for the neutron component. As an example, they are shown for both photons and neutrons in Fig. 4 and 5, where calculated doses are reported as a function of distance from Adone wall at a height between 0 and 2 m from ground. On the graphs, H^* denotes ambient dose equivalent evaluated by means of Publication 51 conversion coefficients corrected to account for quality factor dependence on LET as defined in Publication 60. The difference of about a factor 2 for neutrons between H^* and H defined according to Publication 21 can be attributed about entirely to the doubling of quality factors which has occurred at low energies.

In the following, in order to be conservative but also to anticipate the most likely legislation trends, the quantity H^* evaluated as explained above will be taken systematically as a reference.

4. RESULTS

The results of the calculations are shown in Fig. 6, 7 and 8, normalized to a beam intensity of 10^{11} e^-/s incident onto the lead target.

In Fig. 6 and 7, for photons and neutrons respectively, ambient dose equivalent rate is reported as a function of height at various distances from the machine building wall. As it can be noticed, curves have a different shape than what could be expected from a simple skyshine contribution. The relatively large value found at a certain height is probably due to direct radiation streaming through the windows which exist in the building wall at a height of 10 m.

In Fig. 8, doses are shown as a function of distance from the building wall at two characteristic elevations. The first, between 0 and 2 m, is of direct interest for dose assessment to possibly exposed personnel. The second, between 13.1 and 20 m, represents the highest dose levels obtained and could possibly concern other buildings on the site.

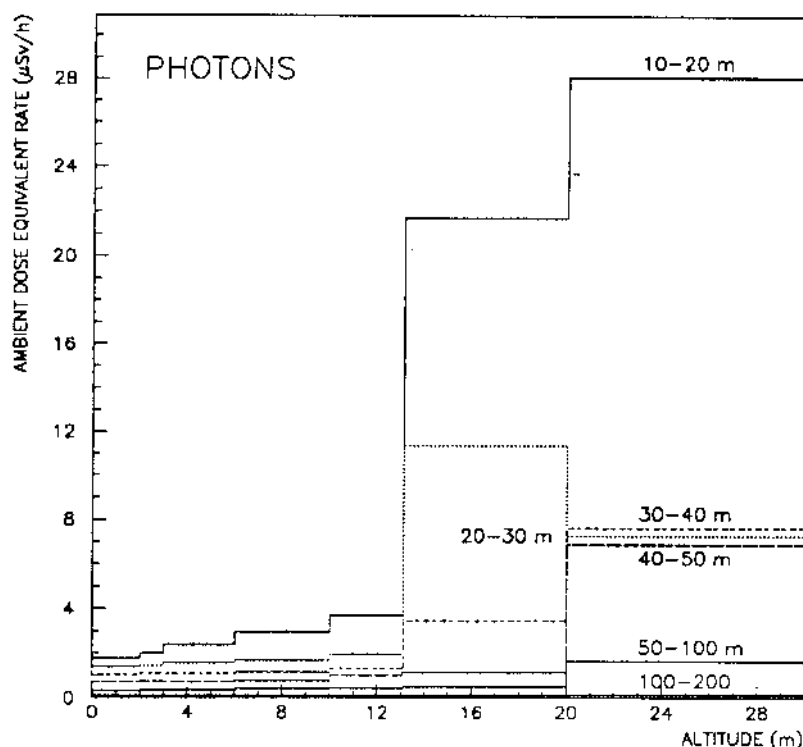


FIG. 6 - Photon ambient dose equivalent rates as a function of height at various distances from the machine building wall.

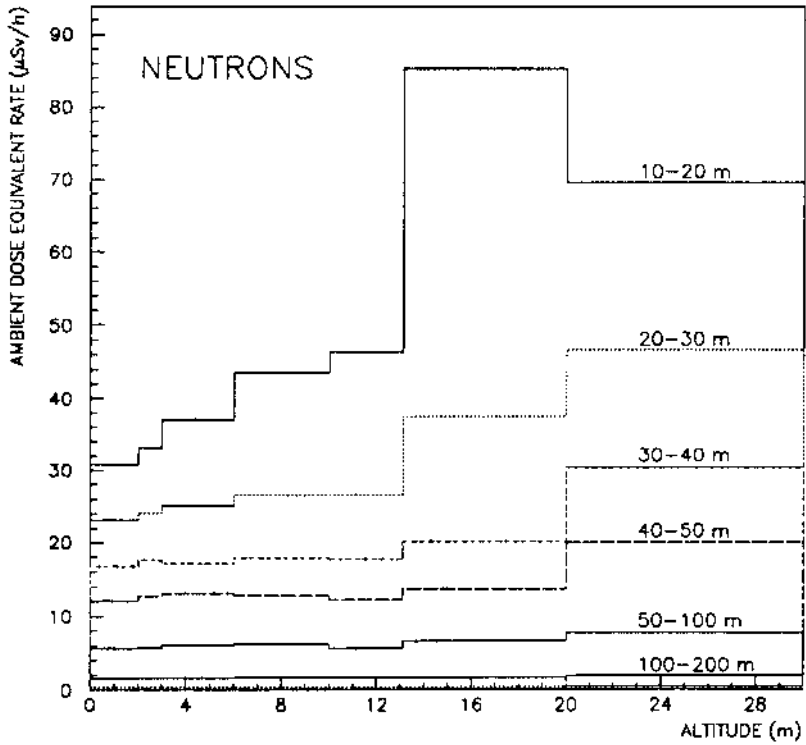


FIG. 7 - Neutron ambient dose equivalent rate as a function of height at various distance from the machine building wall.

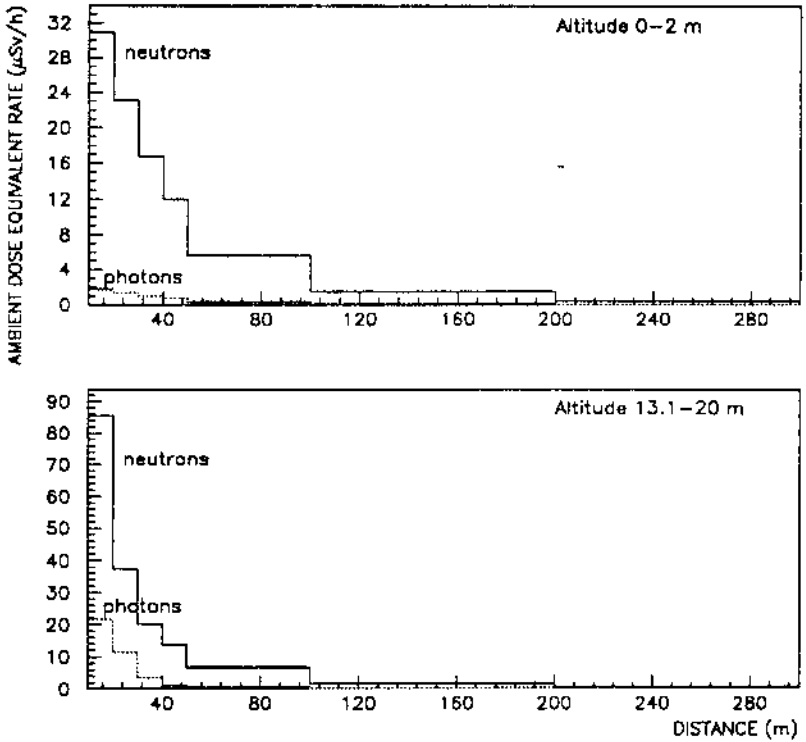


FIG. 8 - Ambient dose equivalent rate as a function of distance from the machine building wall at different elevations.

5. RADIATION PROTECTION CONSIDERATIONS

The dose levels shown in the figures of the previous section are not well representative of doses expected during normal machine operation.

Beams injected into the Main Rings will have an intensity of $9.38 \cdot 10^{10}$ e⁻/s, only 5% of which is expected to contribute to losses; the latter will mostly occur in correspondence with the injection septa and will be certainly top-shielded, since at least 50 cm concrete will be required to protect various premises located above ground (Control Room, Counting Room, Detector Control Room).

As a consequence, the doses shown in the figures could arise only in the unlikely occurrence of a full loss of the injected beams in areas different from the injection regions and not shielded on top. Even when considering such an event, it would not last long enough to give rise to accumulated doses of concern.

On the other hand, in case only beam losses of the order of 5% would be considered, doses at ground level would result so low that no particular action would be required to reduce them further. Taking into account that losses should occur in top-shielded areas anyway, it can be concluded that skyshine contribution to doses due to the injection into the Main Rings, in normal DAΦNE operating conditions, will be completely irrelevant.

The skyshine doses produced by the continuous loss of the circulating beams deserve, instead, a more careful look. The photon and neutron contributions have been estimated from the data shown in fig. 6 and 7 respectively. The calculation has been made assuming 6000 operating hours per year with both beams at the maximum intensity. The resulting dose equivalent is about 2700 μSv/year at a distance of 10-20 m. This figure decreases to about 490 μSv/year between 50 and 100 m and to about 135 μSv/year between 100 and 200 m. The nearest boundary is located at about 100 m distance.

Although the dose equivalent at a distance of 10-20 m would exceed the shielding design objectives of <1 mSv/y by a factor 2 or 3 and at some height the doses can be higher by a further factor 2 or 3, they could be considered acceptable. Indeed the values thus calculated, being based on very conservative assumptions, represent an upper bound for the actual expected doses. In addition, no account has been taken of the local shields installed above the injection septa and of the self-shielding due to the experimental apparatus which will be assembled around the straight sections of the machine.

However, with the aim to kept the doses as low as possible, we suggest to consider the following two alternatives:

- a roof covering the sections of the machine without local shields;
- the removal of the windows existing in the building.

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